BIM and DfMA

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The main goal of this study is to explore the adoption of a design for manufacturing and assembly (DfMA) and building information management (BIM) approach during the whole lifecycle of assets. This approach aims to tackle issues inherent in the design of traditional construction methods, such as low productivity and quality, poor predictability and building performance, and energy use, through the implementation of a BIM library of off-site components. In recent years, a renewed interest has been directed to the attempt to provide solutions to these urgent problems through the adoption of new advancements in technologies. However, while there are studies focussing on a BIM-DfMA approach, there is a lack of research regarding how this approach should be adopted during the whole lifecycle of the assets. Furthermore, to the best of our knowledge, defining an efficient way of developing a component-based BIM object library has not yet been included in any of the available studies. A mixed methodology approach has been used in this research. A conceptual framework was developed as the result of an extensive literature review to investigate new advancements in the AEC sector.

building information management (BIM) design for manufacturing and assembly (DfMA)
off-site manufacturing (OSM) design for deconstruction (DfD) circular economy

1. Introduction

Architecture, engineering, and construction (AEC) is widely recognised for its impact as a socio-political-economic driver [1]. Where, for example, construction progress can be seen to be dependent upon the supply and availability of materials, resources, and skills—the culmination of which have ultimately influenced its evolution and subsequent success/failure [2]. Moreover, as a sector, AEC is seen as a barometer of Gross Domestic Product (GDP), and a core influencer of prosperity and global competitiveness [3]. Thus, decisions made in this field (local, national, and international) affect everything we do, from the type of projects procured through to the materials and resources consumed and the wider impact of these on carbon use, sustainability, waste, etc. It is therefore important that AEC considers these implications and repercussions for the whole-life value of these services [4].

Despite the importance and contribution of AEC, historically, a number of recurrent challenges have stifled progression, especially when compared to other sectors such as aerospace, pharmaceuticals, the automotive industry, etc. These challenges have been well documented in literature, especially concerning the high levels of fragmentation and poor levels of performance and productivity. More recently, in the United Kingdom (UK), issues such as low productivity, project delivery uncertainty, skills shortages, and a general lack of data transparency have been of concern [5]. Similar challenges have also been observed in most other countries around the world, including the need to deliver homes to meet the expanding population and housing crisis [3]. To address these issues, AEC has pursued several change strategies, including novel approaches for delivering higher quality homes in less time [6].

Other sector challenges include issues surrounding “process”, where it has been acknowledged that many of these have not been revisited for some time now [4]. The corollary of this has led to: inefficient project planning and methodologies; low productivity; poor project predictability and uncertain delivery times; low quality products; higher costs; and lower value. Skills shortages have also contributed to these challenges, where evidence suggests that this shortage is due (in part) to an ageing workforce and lower numbers of new entrants wishing to join the sector due to poor working conditions [7]. These issues have been captured in numerous reports. For example, Farmer [8] observed that the fragmented sector and "traditional" service delivery models were predominantly cost-focused rather than value-focused; but that these issues could be addressed through new approaches, such as off-site manufacturing. Anecdotally, both off-site and modern methods of construction (MMC) have been proffered as viable solutions for many years now [8][9][10][11][12][13][14].

In parallel with these issues, several new approaches have now emerged, including new tools and technologies to support design and construction. These include advancements in technology and data management, new manufacturing techniques, and advanced digitalisation and automation (construction 4.0). From a housing perspective, a number of promising initiatives offer significant potential [15]. Many other technological solutions have also emerged, from building information modelling (BIM) through to virtual reality (VR), digital twins, and advanced discreet event simulation. While some research has been conducted in this area, little attention has been paid to the assessment of the potential of a BIM-DfMA approach that could offer additional insight into a possible solution to these issues. This assessment would also present a theoretical framework for discussion, highlighting an approach for creating sub-assemblies and component-based systems within a prefabrication construction process, specifically to integrate MMC with BIM and supply chain management (SCM).

1.1. Digital Tools for the AEC Industry

Digitalisation is continuing to reshape many industrial sectors, including AEC, where digital tools have been gradually implemented for designing, constructing, and operating buildings and infrastructure assets [16]. These initiatives are also opening many exciting opportunities for wider exploitation. One of these major developments has been with BIM. In this respect, several new approaches are now transforming the ways through which AEC leverages this digital platform, particularly through the integration of products and services. Whilst there are several definitions of BIM in extant literature, the following definition is adopted in this paper, where the Construction Project Information Committee (CPIC) defined BIM as:

"…digital representation of physical and functional characteristics of a facility creating a shared knowledge resource for information about it forming a reliable basis for decisions during its lifecycle, from earliest conception to demolition."

[17]

As a digital tool, BIM can be broadly categorised as a computer-generated model for the planning, design, construction, and operational stages of a scheme/project [18]. Where BIM is used to efficiently manage data (creation, maintenance, and utilisation) and information across the whole asset lifecycle by all stakeholders involved [19]. In this respect, this whole-life approach naturally involves people, processes, technology, and standardised processes, and is seen as a viable way of sharing information from one project phase to another [20]. Advocates of this approach have noted higher quality coordination between stakeholders, greater productivity, and improved profit retention [21]. These benefits have also been seen to include: communication and coordination, sustainability, health and safety, and process efficiency savings [22][23][24][25]. However, the adoption and uptake of BIM in AEC seems to have been influenced by country-specific demand. This has changed over the last five years, with the majority of countries now accepting BIM as the preferred approach, in part promoted by governmental pressure. From a UK perspective, Borrmann et al. [16] noted that the British government provided a noteworthy example of this type of approach, highlighting the importance of reducing costs, enhancing efficiency, and lowering the carbon footprint of construction projects, placing the UK "…at the vanguard of a new digital construction era …".

Reflecting on literature in this field, several studies have examined BIM in numerous project scenarios, including off-site. For instance, the synthesis of off-site manufacturing (OSM) and BIM have been seen to serve as beneficial solutions in terms of improved AEC performance [26]. Examples include: Ezcan et al. [12], who noted improvements in speed, modelling time, and quality of construction delivery using BIM; and Babic et al. [27] who highlighted that the use of BIM with industrialised processes could support standardised BIM objects (in BIM object libraries) for greater design flexibility. Moreover, the DfMA concept, has also been useful in the delivery of OSM, especially with BIM, where this relationship has been seen to optimise the design and manufacturing processes, components, and assembly [28]. Moreover, BIM can link DfMA activities (e.g., procurement, fabrication, transport, installation, etc.) to upstream activities such as briefing, appraisals, and conceptual design, thereby improving communication and collaboration with stakeholders [29].

Similar studies by Wang and Skibniewski [30] evaluated BIM in the production of 3D printing models to support engineers and improve construction results. These types of evaluation are particularly useful, as BIM inherently captures rich geometric information. It has also been suggested that this could be blended with scheduling and assembly sequences to support 3D printing robots [31]; and several authors have highlighted this link between BIM and 3D printing [30][32][33]. In summary therefore, whilst a number of advanced digitalisation tools have now started to permeate the market, it is proffered that only a few of these have been purposefully aligned to BIM, OSM, and DfMA.

1.2. Off-Site Manufacturing within AEC

As mentioned earlier, the increased use and application of OSM and MMC in AEC is continuing to grow, evolve, and mature. Increasingly, BIM is now also starting to become part of organisational delivery platforms. OSM provides prefabricated components (from a factory or manufacturing facility), which are then transported to site for assembly [34]. In this respect, the type and level of assembly required on site is dependent upon the type of OSM used (as several options are available, from components through to hybrid options, pods, and fully finished “plug and play” solutions). Notwithstanding this, Abanda et al. [26] explained the advantages of OSM compared to traditional methods. Benefits include: improved quality, improved health and safety, better working conditions, higher tolerances, lower costs, improved productivity, lower labour re-works, reduced waste, consolidated processes, higher levels of sustainability, and greater reliability [9][34][35][36]).

OSM projects tend to follow slightly different delivery approaches compared with traditional projects, particularly across the design, manufacturing, and construction phases. For example, they often use DfMA [9]. This approach is especially suited to OSM, where it is noted that design techniques should be suitably selected and planned to make implementation much simpler [37]. This approach should also be flexible in order to regulate design changes and accommodate levels of automation and standardisation. Intrinsically, whilst the level of OSM varies considerably depending upon the exact method used [38], each approach is based on the principle of assembled parametric components and modules. These require well-organised process control and management systems to be in place, especially to ensure that the design and manufacturing plans coalesce [39]. In this respect, the engagement of BIM with OSM has been seen to improve the design, communication, manufacturing, and assembly approaches [9].

OSM classification is still unfolding [40][41], including taxonomy and links with industry foundations classes (IFC) for example. The Housing Forum [15] guide indicated that several proposals aimed to encourage manufacturers to offer their systems through international and accessible standards such as publicly available specifications (PAS), etc. This standardisation is expected to guide specifiers, designers, and constructors to common and standardised components, thereby improving accessibility and uptake, whilst also reducing incompatibility risks.

In summary, the combination of OSM and BIM presents AEC with a number of valuable solutions to meet industry needs. This integration captures and blends the unique facets of each. For example, BIM supports high levels of accuracy, which directly supports the optimisation of design, manufacturing, assembly, and deconstruction [26]. This resonates with the principles of DfMA used with OSM. It is therefore proffered that this alignment could also help solve many of the integration issues associated with technology, particularly with design changes and logistics [12]. In this respect, BIM is particularly suited to this, as it is able to store specific information on attributes and components throughout the design, manufacturing, and assembly lifecycle processes.

1.3. Design for Manufacture and Assembly

DfMA is an accepted approach for OSM with AEC [42] where it can be used to engage with organisational processes to deliver designs in manufacturing and assembly [43] and thus reduce the level of onsite activity. This methodology emphasises the relevance of design for manufacturing and assembly of components, which ultimately form part the final asset [29]. Broadly speaking, there are two main types of DfMA, notably: design for manufacture (DfM) and design for assembly (DfA). DfM is relates to the process of making individual parts, whereas DfA involves the ways of assembling them [43]. The underlying concepts of DfMA are based on optimisation—where designers maximise the delivery process for clients. This naturally includes all activities, from concept through to automation and logistics. Whilst AEC has only really started to embrace this approach more recently [44], the benefits are particularly encouraging with mass customisation or high repetition. This repeatability or mass customisation enables products to be delivered in volume, thereby embedding value into the production and delivery supply chains and delivery processes [45]. Given this, AEC has now started to meaningfully look at blending this approach with traditional delivery methodologies and digital design practices (of OSM), to radically improve productivity, costs, value, and time.

From a concept perspective, DfMA relies on premise of standardisation, with repeatable processes and designs. Therefore, a key part of any decision (to adopt DfMA) is to establish if the level of standardisation is sufficient to add value to the process (and end product). The challenge here, therefore, is to assess whether this level of standardisation affects (or indeed compromises) the end product, or indeed hinders functionality, the value proposition, etc. In this respect, Digital Built Britain and Bryden Wood [46] advocated that solutions should be interrogated and refined through a process of rationalisation, standardisation, and optimisation. Thus, the decision to adopt DfMA requires some thought regarding, for example, the needs and demands of design, planning, adapting/optimising designs, level of automation, etc., particularly at the early stages, to enable the seamless production of components their subsequent assembly onsite [28]. The methods by which these projects are delivered, the off-site manufactured components used, and the planning/logistics processes involved should also be considered [47].

Whilst literature highlights that the use and application of DfMA can produce products more quickly that are safer and more resource/cost effective [48][49], these benefits are contingent upon having effective systems and procedures in place to support them. For example, a series of “teams” are required dedicated to this methodology. These may be engaged on producing one aspect of a building component (focussing on repetition) under the same conditions, or across a platform of activities (focussing on productivity) to improve value, quality, etc. [4]. This was endorsed by Milestone [50], noting the additional impact on skills, particularly those needed to support technical advancement and innovation; and especially the “need to embrace more productive construction methods” [15].

In summary, whilst DfMA is partially founded on the assumption that lowest assembly costs can be streamlined, designed, and economically assembled [43], this is contingent upon not only the design of parts per se, but also on the ease with which these can be assembled [51]. However, the real challenge here concerns the effective use of BIM in this process. Where DfMA can be more effectively managed through BIM, this includes a number of activities, from procurement, through to: manufacturing, logistics, assembly, construction processes (briefings, appraisals, conceptual design etc); however, the wider acceptance and understanding of contributing project stakeholders must be present [28]. Moreover, from a technology perspective, the engagement of BIM and DfMA requires a certain mindset, particularly to support the adoption and uptake of digital technologies into the manufacturing process [52]. In doing so, data-rich DfMA models are seen as an essential part of this process, where “…BIM has a role in making the project less risky by allowing the project team to simulate the construction virtually to identify potential pitfalls way before the actual construction begins” [29].

1.4. Design for Deconstruction/Disassembly

Further to the discussion on DfMA, a number of research initiatives have now started to investigate the use of this approach at end life of an asset's lifespan. In particular, solutions for dealing with deconstruction, disassembly, and disposal. This forms part of the wider AEC debate on sustainability. In this respect, DfMA can include decommissioning processes, as components or even whole buildings (in the majority of cases) can be reverse engineered to accommodate this—commonly known as design for deconstruction/disassembly (DfD) [49].

DfD is increasingly being used to prompt designers to think about procedures supporting reuse and recycling, including preventive measures to avoid waste being unnecessarily produced [53]. This encouragement of thinking about DfD from the outset for end-of-life reuse is becoming very important within AEC [54]. Traditionally, there are only really two real options available at the end of an asset's lifecycle: demolition or deconstruction. Demolition is used as a fast approach to asset removal, whereas, deconstruction is in many respects the polar opposite, requiring considerable thought on the recuperation of building materials for reuse, recycling, and remanufacturing [55]. Thus, DfD can be seen as a detailed process where assets are specifically designed to facilitate not only adaptation and renovation, but also the reuse of building materials and components [56]. This approach requires an effective strategy to be engineered into the design from the outset, with consideration paid to building materials, connections, loads, etc., insofar as the intrinsic design supports deconstruction/disassembly, with chosen materials being recyclable and harmless after the recycling process [57]. This requires developing a sustainable deconstruction plan which examines all these factors, including cost, energy use, and carbon emissions [58].

Other initiatives in this area include the disassembly and deconstruction analytics system (D-DAS), a method of utilising information modelling and decision support tools to achieve effective end-of-life sustainability performance [59]. This approach plays an important role at the design stage where deconstruction strategies are developed and assessed in order to consider changes in the design and the fabrication of the components (and the impact these may have on results). This type of thinking and approach supports the wider efforts of supporting the circular economy (CE), where DfD offers opportunities for developing components for reuse, remanufacture, or recycling [60].

In conclusion, DfMA and DfD have been seen to be particularly useful in addressing sustainability concerns. If appropriately designed from the outset, these approaches can minimise disposal and reduce end-of-life waste [59]. Moreover, the impact of DfMA and DfA has the potential to deliver other benefits, including lower assembly and manufacturing costs, improved sustainability, and lower environmental impacts.

2. Current Researches and Discussion

2.1. General Case Study Findings

During the development of this case study, a BIM object component-based library was developed following a process of rationalisation, standardisation, and optimisation. This followed standards and protocols concerning coding convention. The use of this library mirrored the strategic definition stage and adopted the principles of DfMA. These findings aligned with standard agreements. From this, a conceptual design was developed utilising the BIM object component-based library. Prior to the design of this, key model components were identified and used to create this library. Findings from this case study helped achieve a deeper understanding as to how the conceptual design phase aligns to DfMA principles. Specific findings are discussed further in the following sections.

2.2. BIM and DfMA Strategy Findings

The decision to adopt BIM methodology was made on the basis that this seemed to be the fundamental principle adopted in AEC. This was not only reinforced in the literature but has also been acknowledged through several different studies and numerous worldwide governmental reports. Given this, the doctrine of BIM was uniquely embedded in all stages of the conceptual framework, particularly to ensure effective delivery. This also helped in managing information and decision-making through transparent coordination processes and a common data environment. From a findings perspective, this also supported the early involvement of manufacturer(s), enabling cross references to be made with the EIR as part of the design process. From this case study, a component-based BIM object library was developed in accordance with standard coding conventions, supported by a 3D model, where for example, through the BIM library, relevant data can be edited and updated during the asset's lifecycle. In this respect, the findings highlighted that BIM was particularly suitable for enabling this new method of construction.

That being said, it is equally important to acknowledge that (after analysing all data), the successful implementation of a new method such as this (based on manufacturing) requires people with appropriate levels of skills and knowledge to make this happen. In particular, there is a specific need to engage stakeholders from the outset. Early engagement and collaboration are key in every part of the process. In this respect, BIM can help, as this technology-driven solution is uniquely placed to support digital design and digital manufacturing methods.

From a technical perspective, the proposed component-based BIM library was perfectly suited to OSM, where the set of components proposed in this paper were expressly designed to be standardised (to enable mass production). In doing so, this library supports automation, whilst also being flexible enough to incorporate some degree of customisation.

In this research it has been proven that a component-based library offers the majority benefits of standardisation and also a degree of adaptability that the new method of constructions needs to succeed. This approach provides to the client the choice to select from a standardised set of components, guaranteeing in this way a degree of adaptability and bespoke products as requested by the industry, along with solutions for traditional construction approach problems such as unforeseen environment conductions, lack of predictability, and poor productivity.

In summary, the findings from this research demonstrated that incorporating DfMA and DfD principles into the early stages of a project is possible. The component-based BIM library can be created to follow DfMA principles. In doing so, designs can be optimised to support assembly (and disassembly).

2.3. Discussion

This research reflected on the wider challenges facing AEC and the need to reflect on issues such as OSM, BIM, DfMA, etc. In doing so, it was evident from that the outset that whilst a number of significant developments have been made in these areas, that there were still several areas that require further work, particularly to harvest the benefits of OSM and DfMA with technology driven tools such as BIM, the IoT, Blockchain, etc. The case study presented in this paper highlighted a number of challenges and opportunities. It is also important to note that not all of these issues could be resolved due to project scope and complexity, aesthetic requirements, logistics, component spans, design typologies, etc. Notwithstanding these issues, the use of parametric and generative design was considered a good starting point of departure for this study.

The development of this conceptual framework provided an opportunity to develop, test, and validate some of the theoretical underpinning this work. For example, the time spent designing the parametric BIM library was particularly beneficial, as it presented an opportunity to evaluate what could and could not be achieved. This was especially important, as AEC needs to have tools that are "fit for purpose", especially when transitioning from traditional working practices to those more manufacturing-oriented. It was therefore important to not only capture and "absorb" these into the finished product, but to try and exploit these opportunities in line with AEC needs—cognisant of a number of high-level challenges, including: process inefficiencies, waste, health and safety, communication, automation, predictability, quality, etc.

Reflecting upon these core challenges, the conceptual framework was designed to support collaboration and coordination, especially in the early design stage. In particular, the ability to simulate processes through 3D, 4D, 5D, and 6D BIM models was seen as particularly beneficial. That being said, it was acknowledged through this case study that in order to fully maximise these benefits, a certain degree of workforce upskilling would be required. This includes the involvement of digital specialists and design teams conversant in DfMA. It is also recommended that these skillsets also embrace Blockchain, Smart contracts (including integrated procurement methods), advanced digital platforms, and strategists capable of levering innovation from these new systems and technologies.

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