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BIM and DfMA: A Paradigm of New Opportunities

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Abstract: 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. Following the literature review, the framework was tested and validated through a case study based on the production and adoption of a BIM library of off-site components at the design stage of an asset. The architecture, engineering, and construction (AEC) industry has recognised the necessity of a new approach that helps to resolve the well-known issues presented in traditional methods of construction. The conceptual framework and case study proposed presents a valuable new method of construction that support the implementation of a BIM and DfMA approach, highlighting their benefits. This framework has been created using many valuable and reliable sources of information. The result of this research supports the idea of a novel new construction method that focuses on a manufacturing-digital-driven industry, with the use of DfMA in a BIM-integrated approach. This novel method will add significance and be beneficial for a wide range of aspects in the construction sector, contributing to the theoretical and practical domain.

Keywords: 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 [8–14].

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 [22–25]. 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 [9,34–36]).

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. Materials and Methods

The work presented in this paper follows a mixed-method approach which captures both qualitative and quantitative data. Secondary data was gathered from extant literature in order to identify and explore state-of-the-art advancements in AEC and the manufacturing sector. From this, an initial conceptual framework was developed from this exercise. In order to test and validate this framework, an exploratory case study was developed, where, primary data was collected to evaluate performance, features, opportunities, and limitations.

The literature review process included an examination of a wide range of topics and information gathered from journal articles, books, reports, conference papers, and dissertations. Two stages were implemented in the literature review to raise the legitimacy and reliably of the data sources. The first stage used keywords search from databases, such as Springer, Scopus, Elsevier, etc. The second stage refined this process with pattern matching against core publications and reports in light of industry developments, legislation, and emerging technological solutions entering the market. This encompassed the use of proprietary industry databases such as BIM Task Group, Build Offsite, Homes England, National Buildings Specifications, and Construction Leadership Council (CLC). These two stages used Nvivo software to organise and analyse the non-numerical data. The data were classified by topic, including relationships. These findings helped to establish the initial conceptual framework. The exploratory case study phase was then undertaken to critique this framework. Primary data was captured from this case study and used to develop a prototype. This prototype was developed using Autodesk Revit software in order to obtain exhaustive information on the standardisation and automation details required for this new proposed method.

2.1. Design for Manufacture and Assembly: Framework Development

This section presents a DfMA conceptual framework for discussion. This includes aspects of the different approaches analysed in this study, such as OSM, DfMA, and DfD, with BIM as the central connection point. This framework—highlighted in Figure 1—presents all links and dependencies, divided into eight stages following the Royal Institute of British Architects (RIBA) Plan of Work 2013. This was adopted in order to highlight the importance of the approaches that defined this new method of construction. A final stage "end-of-life" section was added to accentuate that this process is cyclical, and component-based systems could be reutilised or reused, thereby encouraging DfMA. Every phase of the framework will be individually explained underlining the key aspects of every stage. Although, every task and activity enclose some level of dependency with each other warranting that the aim of each stage is accomplished.

To facilitate discussion, the framework development process is divided into the following four core parts:

- Preparation phase
- Design and pre-construction phases
- Construction/assembly to close-out phase
- Use and reuse/demolition phases.

2.1.1. Preparation Phase

During the preparation phase (strategic definition; preparation and brief), a strategic brief is developed using a BIM object library based on a set of components (that can be used across different multiple projects). This also considers how CE issues can be implemented. The strategic definition and preparation and brief stages help define the project objectives, including the requirements for DfMA, where the use of smart contracts are contemplated. A

BEP (BIM execution plan) is then designed to ensure that the asset is designed in accordance with client's requirements. Along with the BEP, constructability issues are established.
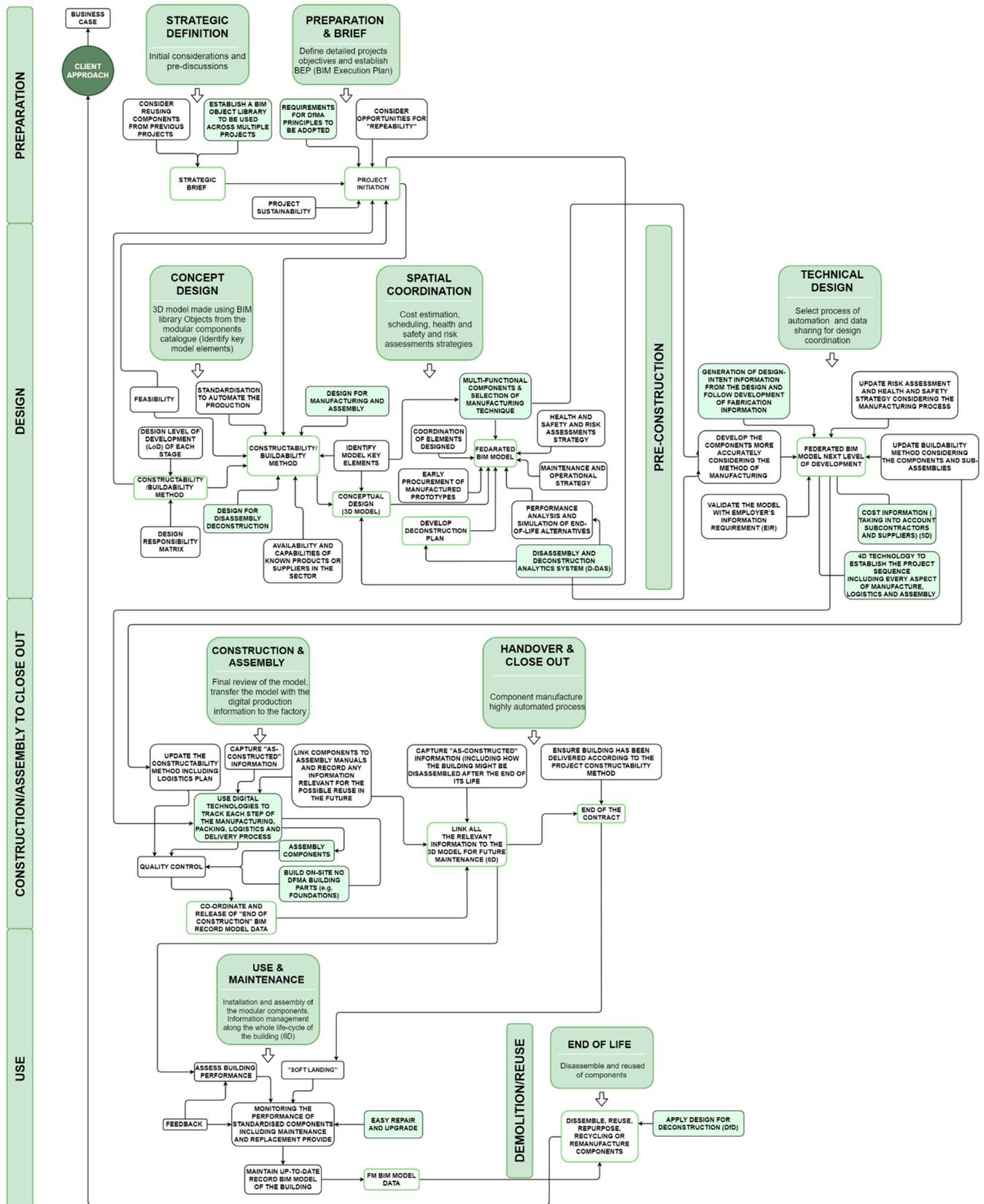
Figure 1. Conceptual framework.

2.1.2. Design and Preconstruction Phases

At the design phase (concept design; spatial coordination), the BIM object library (the development of the BIM object library is discussed later) is used to create a conceptual 3D model. Here the design follows the DfMA and DfD approaches in order to obtain all the benefits that these methods offer, such as: mass-construction, improved productivity, and end-of-life sustainability performance. Buildability is also included, along with the availability and capabilities of known products and suppliers, especially the use of standardisation to automate production. Subsequently, at the Spatial Coordination stage, a federated model is designed. This includes cost estimation, scheduling, health and safety, and risk assessments strategies. These strategies are based on OSM and additive manufacturing environments. This phase also establishes the manufacturing technique and defines the deconstruction plan.

During the technical design stage (pre-construction phase), the federated BIM model reaches the next level of development, where this includes radio-frequency identification (RFID) in selected components. Components are also defined with a higher level of detail (LoD) and level of information (LoI). This includes the process of automation and data sharing to facilitate design coordination. Together, the model is then validated following the employers information requirements (EIR) prior to entering the construction/assembly phase.

2.1.3. Construction/Assembly and Close-Out Phases

During the construction/assembly stage, the final model and digital production strategy is forwarded to the chosen factory. Once the components have been produced and the quality control process completed, the components are then released to site in accordance with logistics and the buildability method. The assembly process then commences on site. During this process, digital tools such as the Internet of Things (IoT) enable stakeholders to track each step of the manufacturing, packing, logistics, and delivery process. At the handover and close-out stage, all information for the maintenance of the asset is linked to the 3D model for conformance. Of particular note, the information captured through these two stages can be linked to peripherals such as IoT-driven products, laser scanners, photogrammetry technology, or drones. Information from these services can then be analysed to for predictive pattern matching (to help to future projects).

2.1.4. Use and Demolition/Reuse Phases

In the use and maintenance stage the asset is continually monitored and aligned with the facilities management (FM) BIM model in order to keep this data up to date. Energy consumption and production is tracked along with the performance of the components (using RFID where available). This continuous tracking also enables components to be analysed, thereby enabling repairs or replacements to occur much sooner than through conventional approaches. This is also particularly advantageous for components with fixed warranty periods. In this respect, this functionality can be embedded into smart contracts at the preparation and brief stage, along with the ownership of components, etc. The use of OSM is also seen as being suited to this stage, as the use of standardised components with easy assembly/disassembly techniques more readily supports design changes, etc. In the final stage of the conceptual framework, the end-of-life stage is presented. This covers how the asset and its components will be disassembled, reused, or recycled. This follows the principles of DfD and CE. In doing so, this helps minimise construction and demolition waste and also supports cradle-to-cradle initiatives (rather than cradle-to-grave).

2.2. DfMA Feasibility Case Study

A case-study method was selected to evaluate the efficacy of the initial framework. In order to get the primary data from the case study, a prototype was developed using Autodesk Revit software to obtain a more exhaustive and comprehensive information on the standardisation and automation of the new proposed method.

2.2.1. Core Components Identification

The proposed framework introduces the utilisation of a BIM object library formed by a set of core components. These components were specially selected for this case study and were identified by a process of rationalisation, standardisation, and optimisation (Figure 2).
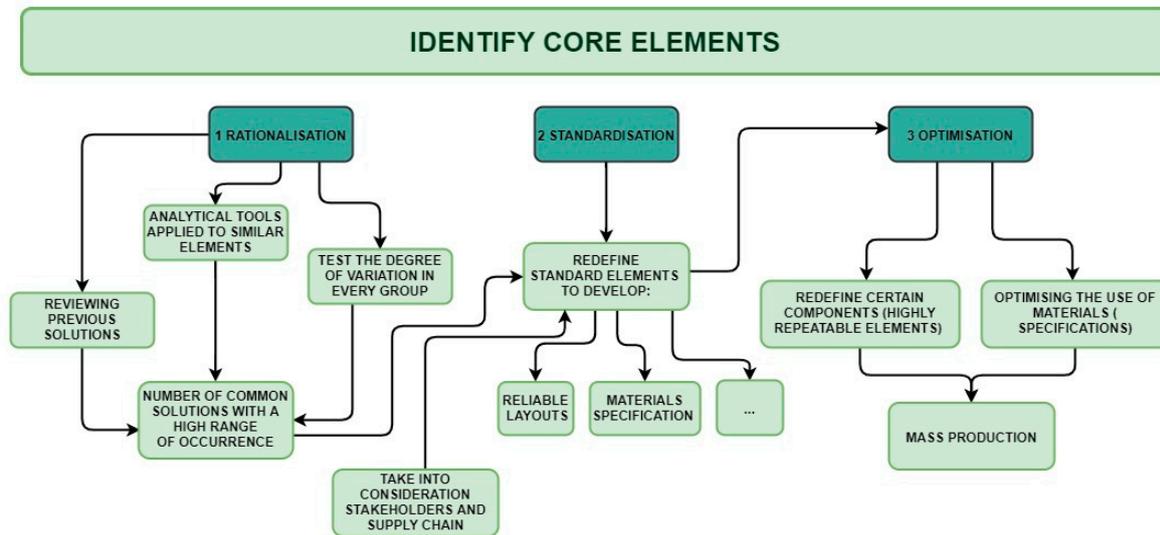
Figure 2. Identification of core elements.

During the rationalisation phase, analytical tools were applied to select similar elements in order to determine the degree of variation in order to satisfy a number of common solutions with a high degree of occurrence. The second stage involved redefining elements to achieve reliable layouts along with specified materials and other requirements. Whereas the third stage (optimisation) entailed analysing components in order to obtain repeatable elements, whilst also optimising the use of materials. The results from this three-stage process generated a set of components suitable for mass production.

2.2.2. BIM Object Library Development

BIM library components should be defined and classified in a format that enables and facilitates information transfer. This classification process should therefore be clear and in a form readily understood by AEC professionals; and more importantly, each component should be uniquely named and described. Given this, a library for international use and common data standards was adopted for developing the coding convention. Standards such as BS 8541-1, BS EN ISO 19650, BS EN ISO 13567, and UNICLASS 2015 were implemented together with the American Institute of Architects (AIA) Framework to indicate the level of detail (LoD) and level of information (LoI). Figure 3 presents the BIM library coding convention created for this case study.

The general classification of components was primarily based on their functionality, ergo structural elements, walls (non-structural), floors, and roofs. For the purpose of this study, components were designed to LoD300 (detailed design), although given the new method of construction, the BIM library should include LoD400 components (where information for manufacturing and assembly are specified). All components were treated as generic objects, insofar as their novelty or distinctiveness was not attributable to any specific library or manufacturer. Focusing on their type, components were classified through standards; mechanical, electrical, and plumbing (MEP); and aesthetics (where components included an aesthetic feature such as a door or window). Whilst developing this case study, a fourth type was added—where the same component presented MEP and aesthetic characteristics. Of note, the subtype indicates the location of the component: external, internal, or assembled to foundations in the case of floors. In addition, as part of this case study, another coding system (alphabetically based) was added to similar

components where needed in order to highlight different attributes such as the length of walls, etc. From this, a set of standardised components was concluded. These were considered more optimal and favourable elements for use in the BIM library (given the proposed new method of construction). These components can be seen as follows:

- EF_20_10-300-AEST-EXT
- EF_20_10-300-AEST-INT
- EF_20_10-300-MEP&A-EXT
- EF_20_10-300-MEP-EXT
- EF_20_10-300-STND-EXT
- EF_20_10-300-STND-INT
- EF_20_10-300-MEP-INT
- EF_25_10-300-MEP&A-INT
- EF_25_10-300-STND-INT
- EF_25_10-300-MEP-INT
- EF_25_10-300-AEST-INT
- EF_30_10-300-STND
- EF_30_20-300-MEP
- EF_30_20-300-MEP-FDATION
- EF_30_20-300-STND
- EF_30_20-300-STND-FDATION

Figure 3. BIM library coding convention.

Table 1 presents the BIM library component descriptions used in this case study.

Table 1. BIM library components descriptions.

1	EF_20_10-300-AEST-EXT	Element/Function	Structural element	
		LoD	Detailed design	
		Source	Generic object	
		Type	Aesthetic	
		Subtype	Exterior	
2	EF_20_10-300-AEST-INT	Element/Function	Structural element	
		LoD	Detailed design	
		Source	Generic object	
		Type	Aesthetic	
		Subtype	Interior	
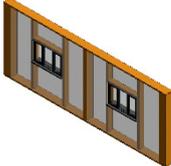
Table 1. *Cont.*

3	EF_20_10-300-MEP&A-EXT	Element/Function	Structural element	
		LoD	Detailed design	
		Source	Generic object	
		Type	With mech., elect., and plumbing and aesthetic features	
		Subtype	Exterior	
4	EF_20_10-300-MEP-EXT	Element/Function	Structural element	
		LoD	Detailed design	
		Source	Generic object	
		Type	With mech., elect, and plumbing	
		Subtype	Exterior	
5	EF_20_10-300-MEP-INT	Element/Function	Structural element	
		LoD	Detailed design	
		Source	Generic object	
		Type	With mech., elect, and plumbing	
		Subtype	Interior	
6	EF_20_10-300-STND-EXT	Element/Function	Structural element	
		LoD	Detailed design	
		Source	Generic object	
		Type	Standard	
		Subtype	Exterior	
7	EF_20_10-300-STND-INT	Element/Function	Structural element	
		LoD	Detailed design	
		Source	Generic object	
		Type	Standard	
		Subtype	Interior	
8	EF_25_10-300-MEP&A-INT	Element/Function	Wall (non-structural)	
		LoD	Detailed design	
		Source	Generic object	
		Type	With mech., elect., and plumbing and aesthetic features	
		Subtype	Interior	
9	EF_25_10-300-STND-INT	Element/Function	Wall (non-structural)	
		LoD	Detailed design	
		Source	Generic object	
		Type	Standard	
		Subtype	Interior	
10	EF_25_10-300-MEP-INT	Element/Function	Wall (non-structural)	
		LoD	Detailed design	
		Source	Generic pbject	
		Type	With mech., elect., and plumbing	
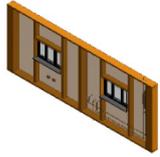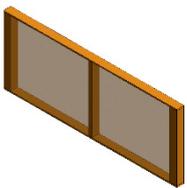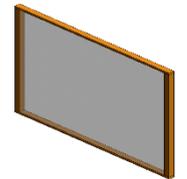
Table 1. *Cont.*

		Subtype	Interior	
11	EF_25_10-300-AEST-INT	Element/Function	Wall (non-structural)	
		LoD	Detailed design	
		Source	Generic object	
		Type	Aesthetic	
		Subtype	Interior	
12	EF_30_10-300-STND	Element/Function	Roof	
		LoD	Detailed design	
		Source	Generic object	
		Type	Standard	
13	EF_30_20-300-MEP	Element/Function	Floor	
		LoD	Detailed design	
		Source	Generic object	
		Type	With mech., elect., and plumbing	
14	EF_30_20-300-MEP-FNDTN	Element/Function	Floor	
		LoD	Detailed design	
		Source	Generic object	
		Type	With mech., elect., and plumbing	
		Subtype	Assembled to foundations	
15	EF_30_20-300-STND	Element/Function	Floor	
		LoD	Detailed design	
		Source	Generic object	
		Type	Standard	
16	EF_30_20-300-STND-FNDTN	Element/Function	Floor	
		LoD	Detailed design	
		Source	Generic object	
		Type	Standard	
		Subtype	Assembled to foundations	

2.2.3. Technical Specifications for Standard Type Components

Four main types of components were developed for this case study. Standard components were used as a basis for the creating the other main types. Whilst structures were not expressly included in this case study, the walls, roofs, and floors were designed to comply with such issues as stability, logistics management, etc. In addition, materials and standardised components were carefully chosen to satisfy standards and building regulations ergo insulation and sound proofing properties. The technical specifications of these are presented as follows:

- EF_20_10-300-STND-EXT: External standard structural walls components were designed to be 7.5 m long, within three structural columns, and a selection of layers (including insulation and waterproof membrane). For visualisation purposes, some layers were set up with a grade of transparency.
- EF_25_10-300-STND-EXT: Internal standard non-structural walls components were designed to be a maximum of 4 m long with layers that guaranteed the correct

level of insulation. For visualisation purposes some layers were set up with a grade of transparency.

- EF_30_10-300-STND: Standard roof was designed considering logistics and the most efficient way to transport and assemble this component. Components not exceeding 9–10 m were considered suitable for this purpose. For visualisation purposes some layers were set up with a grade of transparency.
- EF_30_20-300-STND: Standard floors were designed following the same criteria for roofs regarding logistics. For visualisation purposes some layers were set up with a grade of transparency.

2.2.4. Prototype Design Based on DfMA

Revit 2020 software was used to create a working prototype in order to corroborate the effectiveness of the components in the design stage. A set of components proposed in the BIM library were used to design a two-bedroom house. This building was semi-detached and divided into two floors in order to utilise a variety of components. Figure 4a presents the layout of the ground floor and Figure 4b presents the layout of the first floor. This arrangement consisted of a living room, open-plan kitchen to dining room, and a toilet. Prefabricated stairs were located in the living room leading to the first floor. This consisted of two double bedrooms and a bathroom.

| (**a**) | (**b**) |
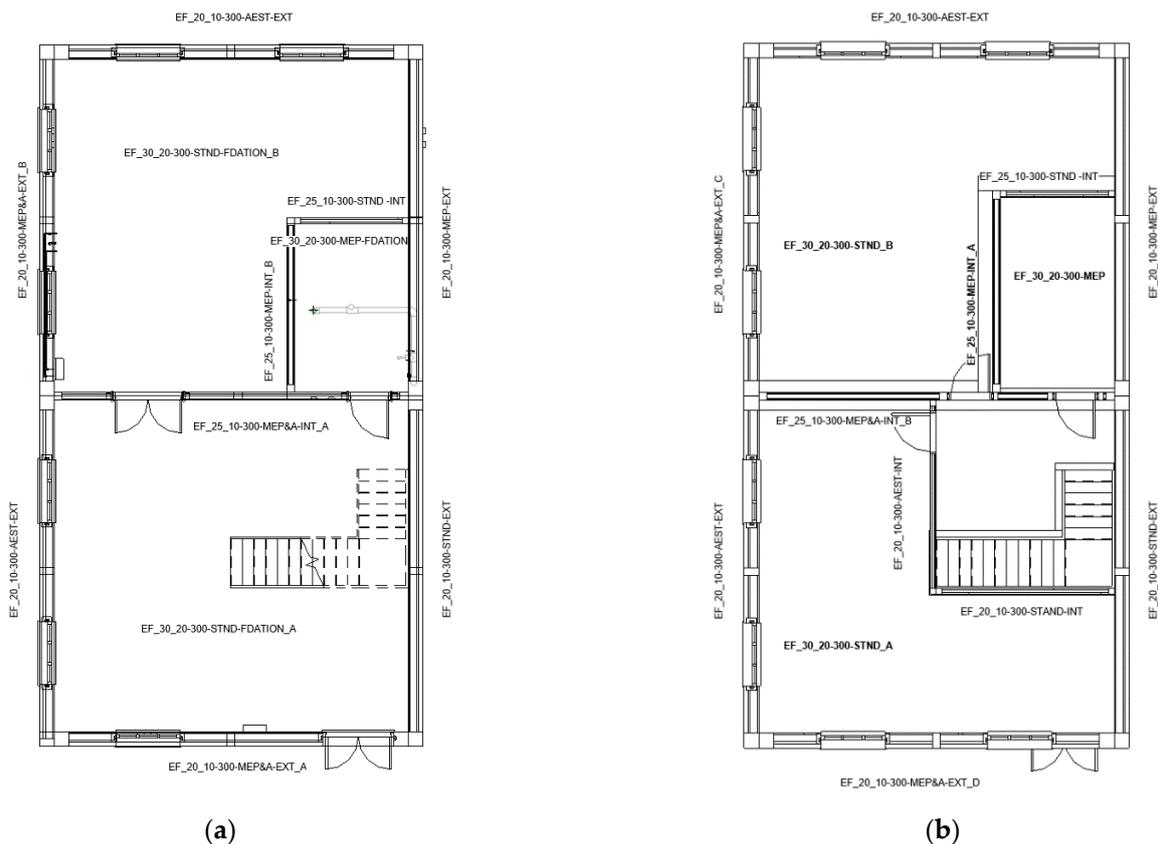
Figure 4. (**a**) Ground floor two-bedroom house; (**b**) first floor two-bedroom house.

Through Revit components were renamed to add extra information; specifically, smalls changes made to original components such as location or sizes. This extra information was added using letters A–D. The following set of components were used in this case study:

- 4 × EF_20_10-300-AEST-EXT
- 1 × EF_20_10-300-AEST-INT
- 1 × EF_20_10-300-MEP&A-EXT_A
- 1 × EF_20_10-300-MEP&A-EXT_B

- 1 × EF_20_10-300-MEP&A-EXT_C
- 1 × EF_20_10-300-MEP&A-EXT_D
- 2 × EF_20_10-300-MEP-EXT
- 1 × EF_20_10-300-STAND-INT
- 2 × EF_20_10-300-STND-EXT
- 1 × EF_25_10-300-MEP&A-INT_A
- 1 × EF_25_10-300-MEP&A-INT_B
- 1 × EF_25_10-300-MEP-INT_A
- 1 × EF_25_10-300-MEP-INT_B
- 2 × EF_25_10-300-STND-INT
- 1 × EF_30_10-300-STND_A
- 1 × EF_30_10-300-STND_B
- 1 × EF_30_20-300-MEP
- 1 × EF_30_20-300-MEP-FNDTN
- 1 × EF_30_20-300-STND-FNDTN_A
- 1 × EF_30_20-300-STND-FNDTN_B
- 1 × EF_30_20-300-STND_A
- 1 × EF_30_20-300-STND_B

The final prototype of this two-bedroom house can be seen in Figure 5.

(**a**)　　　　　　　　　　　(**b**)
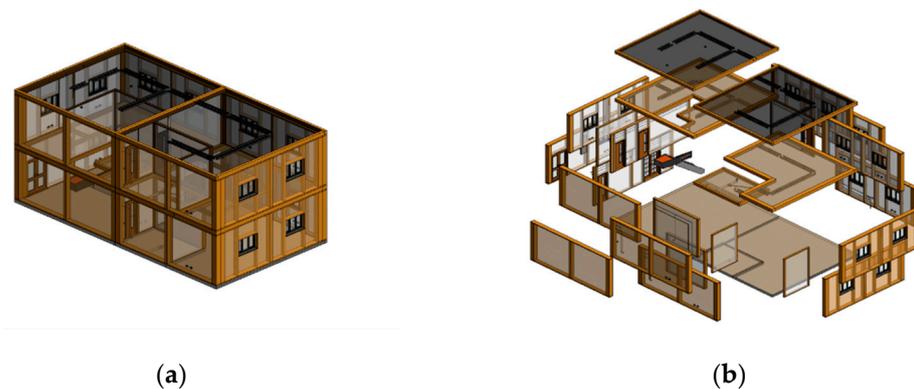
Figure 5. (**a**) Two-bedroom house perspective; (**b**) two-bedroom house displacements.

3. Results & Discussion

3.1. 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.

3.2. 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).

3.3. 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.

4. Conclusions

This paper highlighted a number of recurrent challenges facing AEC. In doing so, OSM was suggested as one possible solution. This was expanded to include DfMA, including the need to embrace technologies such and BIM and GD. From this, a conceptual framework was presented for discussion, covering four main phases (preparation; design and pre-construction; construction/assembly to close-out; and use and reuse/demolition). These phases were discussed along with the technical requirements needed. This included the creation of a BIM object component-based library, along with a worked example prototype based on a two-bedroom house. The findings highlighted a number of significant advantages in using this approach. It also highlighted a few technical challenges; but (arguably) more important perhaps, the need for AEC upskilling. Whilst this work is still embryonic, it is therefore recommended that any generalisation, inference, or future replication is countered by the inclusion of additional test data and case study work in order to improve the veracity of these findings.

Finally, it is proffered that AEC is now entering a new technological era, where almost anything is possible. This statement is made from a somewhat halcyon perspective, insofar as technological solutions are possible whenever or wherever a need exists. This requires considerable effort from all. The old adage of "limited job security, harsh working conditions, and poor health and safety" may still exist in some parts of the industry. However, the obverse is equally true, evidenced through many innovative companies pioneering OSM—most of which are showcasing highly flexible and value-laden solutions. These companies have already resolved many of the challenges raised earlier in this paper. Moreover, they are championing new products and divested services through OSM. This is very encouraging given the transition to Industry 4.0. The findings from this case study provide an important step in this direction, particularly through the use of bespoke BIM libraries, DfMA methodologies, and GD-driven solutions.

References

1. HM Government. Industrial Strategy. In *Construction Sector Deal*; OGL: London, UK, 2017. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/731871/construction-sector-deal-print-single.pdf (accessed on 5 May 2021).
2. Spence, W.P.; Kultermann, E. The construction industry: An overview. In *Construction Materials, Methods and Techniques*, 4th ed.; Cengage Learning: Boston, MA, USA, 2016; ISBN 987-1-3050-8627-2.
3. World Economic Forum. Shaping the Future of Construction. A Breakthrough in Mindset and Technology. 2016. Available online: http://www3.weforum.org/docs/WEF_Shaping_the_Future_of_Construction_full_report__pdf (accessed on 3 May 2021).
4. Mills, F. Construction's Digital Manufacturing Revolution. The B1m Website. 2019. Available online: https://www.theb1m.com/video/constructions-digital-manufacturing-revolution (accessed on 3 May 2021).
5. KPMG. Smart Construction Report: How Offsite Manufacturing Can Transform Our Industry. UK. 2016. Available online: https://assets.kpmg/content/dam/kpmg/pdf/2016/04/smart-construction-report-2016.pdf (accessed on 15 May 2021).

6. Goodier, C.; Pan, W. The Future of UK Housebuilding Report Prepared by RICS. London. 2010. Available online: https://repository.lboro.ac.uk/articles/conference_contribution/The_future_of_offsite_in_housebuilding/9432068/1 (accessed on 5 May 2021).

7. Whysall, Z.; Owtram, M.; Brittain, S. The new talent management challenges of Industry 4.0. *J. Manag. Dev.* **2019**, *38*, 118–119. [CrossRef]

8. Farmer, M.; The Farmer Review of the UK Construction Labour Model. Modernise or Die Report 2016 Prepared by Construction Leadership Council (CLC). Available online: https://www.cast-consultancy.com/wp-content/uploads/2016/10/Farmer-Review-1.pdf (accessed on 3 May 2021).

9. Arif, M.; Goulding, J.; Rahimian, F.P. Promoting Off-Site Construction: Future Challenges and Opportunities. *J. Archit. Eng.* **2012**, *18*, 75–78. [CrossRef]

10. Blismas, N.; Pasquire, C.; Gibb, A. Benefit evaluation for off-site production in construction. *Constr. Manag. Econ.* **2016**, *24*, 121–130. [CrossRef]

11. Egan, J. *Rethinking Construction Report 1998 Prepared by UK Department of the Environment, Transport and the Regions*; HMSO: London, UK, 1998; Available online: http://constructingexcellence.org.uk/wp-content/uploads/2014/10/rethinking_construction_report.pdf (accessed on 1 May 2021).

12. Ezcan, V.; Isikdag, U.; Goulding, J.S. BIM and Off-Site Manufacturing: Recent Research and Opportunities. In *CIB World Building Congress*; Queensland University of Technology: Brisbane, QLD, Australia, 2013; pp. 5–9.

13. Latham, M.; Constructing the Team Final Report 1994 of the Government/Industry Review of Procurement and Contractual Arrangements in the UK Construction Industry. HMSO, London, UK. Available online: http://constructingexcellence.org.uk/wp-content/uploads/2014/10/Constructing-the-team-The-Latham-Report.pdf (accessed on 15 May 2021).

14. Nadim, W.; Goulding, J.S. Offsite production: A model for building down barriers: A European construction industry perspective. *Eng. Constr. Archit. Manag.* **2011**, *18*, 82–101. [CrossRef]

15. The Housing Forum. MMC for Affordable Housing Developers. A Housing Forum Guide to Overcoming Challenges and Barriers, Fifteenth Report of Session 2017–2019. Available online: https://mmc.lhc.gov.uk/wp-content/uploads/2020/01/mmc-guide-2019.pdf (accessed on 3 May 2021).

16. Borrmann, A.; Konig, M.; Koch, C.; Beetz, J. Building Information Modeling: Why? What? How? In *Building Information Modelling. Technology Foundations and Industry Practice*; Springer International Publishing: Cham, Switzerland, 2018; pp. 1–24. [CrossRef]

17. Construction Project Information Committee (CPIC). Drawing is Dead, Long Live Modelling. 2008. Available online: https://www.cpic.org.uk/publications/drawing-is-dead/ (accessed on 4 May 2021).

18. Eadie, R.; Browne, M.; Odeyink, H.; McKeown, C.; McNiff, S. BIM implementation throughout the UK construction project lifecycle: An analysis. *Autom. Constr.* **2013**, *36*, 145–151. [CrossRef]

19. Eynon, J. *Construction Manager's BIM Handbook*; John Wiley & Sons: Chichester, UK, 2016; ISBN 978-1-118-89647-1.

20. Dawood, N.; Vukovic, V. Whole lifecycle information flow underpinned by BIM: Technology, process, policy and people. In Proceedings of the 2nd International Conference on Civil and Building Engineering Informatics, Tokyo, Japan, 22–25 April 2015.

21. Sun, C.; Jiang, S.; Skibniewski, M.J.; Man, Q.; Shen, L. A literature review of the factors limiting the application of BIM in the construction industry. *Technol. Econ. Dev. Econ.* **2017**, *23*, 764–779. [CrossRef]

22. Hardin, B.; McCool, D. Why Is Technology So Important to Construction Management? In *BIM and Construction Management: Proven Tools, Methods and Workflows*, 2nd ed.; John Wiley & Sons: Indianapolis, IN, USA, 2015; ISBN 978-118-9427-5.

23. Ibrahim, H.S.; Hashim, N.; Jamal, K.A.A. The Potential Benefits of Building Information Modelling (BIM) in Construction Industry. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2019; Volume 385.

24. Mesároš, P.; Mandičák, T. Exploitation and benefits of BIM in construction project management. In *IOP Conference Series: Materials Science and Engineering*; IOP Publishing: Bristol, UK, 2017; Volume 245.

25. Saxon, R. *BIM for Construction Clients: Driving Strategic Value through Digital Information Management*; RIBA Enterprises: London, UK, 2016; ISBN 10-1859466079.

26. Abanda, F.H.; Tah, J.H.M.; Cheung, F.K.T. BIM in off-site manufacturing for buildings. *J. Build. Eng.* **2017**, *14*, 89–102. [CrossRef]

27. Babic, N.C.; Podbreznik, P.; Rebolj, D. Integrating resource production and construction using BIM. *Autom. Constr.* **2010**, *19*, 539–543. [CrossRef]

28. Alfieri, E.; Seghezzi, E.; Sauchelli, M.; Di Giuda, G.M.; Masera, G. A BIM-based approach for DfMA in building construction: Framework and first results on an Italian case study. *Archit. Eng. Des. Manag.* **2020**, *16*, 247–269. [CrossRef]

29. Building and Construction Authority (BCA); Bryden Wood. BIM for DfMA (Design for Manufacturing and Assembly) Essential Guide. Singapore. 2016. Available online: https://www.corenet.gov.sg/media/2032999/bim_essential_guide_dfma.pdf (accessed on 3 May 2021).

30. Wang, K.; Skibniewski, M.J. Feasibility Study of Integrating BIM and 3D Printing to Support Building Construction. In Proceedings of the Creative Construction Conference University of Technology and Economics, Budapest, Hungary, 29 June–2 July 2019; pp. 845–850. Available online: https://repozitorium.omikk.bme.hu/handle/10890/13298 (accessed on 3 May 2021).

31. Teizer, J.; Blickle, A.; King, T.; Leitzbach, D.; Guenther, D.; Mattern, H.; Konig, M. BIM for 3D Printing in Construction. In *Building Information Modeling: Technologische Grundlagen und Industrielle Praxis*; Borrmann, A., König, M., Koch, C., Beetz, J., Eds.; Springer International Publishing: Cham, Switzerland, 2018; pp. 421–500. [CrossRef]

32. Ashraf, M.; Gibson, I.; Rashed, M.G. Challenges and prospects of 3d printing in structural engineering. In Proceedings of the 13th International Conference on Steel, Space and Composite Structures, Perth, WA, Australia, 31 January–2 February 2018.

33. Sakin, M.; Kiroglu, Y.C. 3D Printing of Buildings: Construction of the Sustainable Houses of the Future by BIM. *Energy Procedia* **2017**, *134*, 702–711. [CrossRef]

34. Hu, X.; Chong, H.Y.; Wang, X.; London, K. Understanding stakeholders in off-site manufacturing: A literature review. *J. Constr. Eng. Manag.* **2019**, *145*, 03119003. [CrossRef]

35. Smith, D.; Sweets, R. The standardisation dynamic: Could a design code for prefabricated housing help offsite take off? *Constr. Res. Innov.* **2018**, *9*, 32–37. [CrossRef]

36. Durdyev, S.; Ismail, S. Offsite Manufacturing in the Construction Industry for Productivity Improvement. *Eng. Manag. J.* **2019**, *31*, 35–46. [CrossRef]

37. Arashpour, M.; Wakefield, R.; Abbasi, B.; Arashpour, M.; Hosseni, R. Optimal process integration architectures in off-site construction: Theorizing the use of multi-skilled resources. *Archit. Eng. Des. Manag.* **2019**, *14*, 46–59. [CrossRef]

38. Ginigaddara, B.; Perera, S.; Feng, Y.; Rahnamayiezekavat, P. Typologies of offsite construction. In Proceedings of the 8th World Construction Symposium: Towards a Smart, Sustainable and Resilient Built Environment, Colombo, Sri Lanka, 8–10 November 2019; pp. 567–577.

39. O'Connor, J.T.; O'Brien, W.J.; Choi, J.O. Industrial project execution planning: Modularization versus stick-built. *Pract. Period. Struct. Des. Constr.* **2016**, *21*, 04015014. [CrossRef]

40. Abosaod, H.; Underwood, J.; Isikdag, U.; Barony, S.A. Classification System for Representation of Off-Site Manufacturing Concepts through Virtual Prototyping. In Proceedings of the 9th International Detail Design in Architecture Conference, University of Central Lancashire, Preston, UK, 4–5 April 2010.

41. Ayinla, K.O.; Cheung, F.; Tawil, A. Demystifying the concept of off site manufacturing method towards a robust definition and classification system. *Constr. Innov.* **2019**, *20*, 223–246. [CrossRef]

42. Lu, W.; Tan, T.; Xu, J.; Wang, J.; Chen, K.; Gao, S.; Xue, F. Design for manufacture and assembly (DfMA) in construction: The old and the new. *Archit. Eng. Des. Manag.* **2021**, *17*, 77–91. [CrossRef]

43. Gao, S.; Jin, R.; Lu, W. Design for manufacture and assembly in construction: A review. *Build. Res. Inf.* **2020**, *48*, 538–550. [CrossRef]

44. Yin, X.; Liu, H.; Chen, Y.; Al-Hussein, M. Building information modelling for off-site construction: Review and future directions. *Autom. Constr.* **2019**, *101*, 72–91. [CrossRef]

45. Jensen, K.N.; Nielsen, K.; Brunoe, T.D. Mass customization as a productivity enabler in the construction industry. In Proceedings of the IFIP International Conference on Advances in Production Management Systems (APMS), Seoul, Korea, 26–30 August 2018; pp. 159–166.

46. Digital Built Britain; Bryden Wood. Delivery Platforms for Government Assets 2017 Report. Available online: https://www.cdbb.cam.ac.uk/system/files/documents/delivery_platforms_screen.pdf (accessed on 4 May 2021).

47. Pasquire, C.L.; Connolly, G.E. Design for Manufacture and Assembly. In Proceedings of the 11th Annual Conference of the International Group for Lean Construction, Blacksburg, VA, USA, 22–24 July 2003; pp. 184–194.

48. RIBA. RIBA Plan for Work 2013. Designing for Manufacture and Assembly. Plan of Work. Royal Institute of British Architects. London: RIBA Enterprises Ltd. 2016. Available online: http://consig.org/wp-content/uploads/2018/10/RIBAPlanofWorkDfMAOverlaypdf.pdf (accessed on 5 May 2021).

49. Buildoffsite. BIM and DfMA. 2020. Available online: https://www.buildoffsite.com/publicationsguidance/bim-dfma/ (accessed on 3 May 2021).

50. Milestone, N. BIM and DfMA—The Future of Construction. 2017. Available online: https://www.pbctoday.co.uk/news/bim-news/bim-dfma-future-construction/32775/ (accessed on 3 May 2021).

51. Stoll, H.W. Design for manufacture: An Overview. *Appl. Mech. Rev.* **1986**, *39*, 1356–1364. [CrossRef]

52. Staub-French, S.; Poirier, E.A.; Calderon, F.; Chikhi, I.; Zadeh, P.; Chudasma, D.; Huang, S. *Building Information Modeling (BIM) and Design for Manufacturing and Assembly (DfMA) for Mass Timber Construction*; BIM TOPiCS Research Lab, University of British Columbia: Vancouver, BC, Canada, 2018.

53. Barrit, J. An Overview on Recycling and Waste in Construction. *Constr. Mater.* **2016**, *169*, 49–53. [CrossRef]

54. Adams, K.T.; Osmani, M.; Thorpe, T.; Thornback, J. Circular economy in construction: Current awareness, challenges and enablers. *Waste Resour. Manag.* **2017**, *170*, 15–24. [CrossRef]

55. Akinade, O.; Oyedele, L.; Oyedele, A.; Davila Delgado, J.M.; Bilal, M.; Akanbi, L.; Ajayi, A.; Owolabi, H. Design for deconstruction using a circular economy approach: Barriers and strategies for improvement. *Prod. Plan. Control* **2020**, *31*, 829–840. [CrossRef]

56. Kanters, J. Design for Deconstruction in the Design Process: State of the Art. *Buildings* **2018**, *8*, 150. [CrossRef]

57. Akinade, O.; Oyedele, L.; Moteso, K.; Aiayi, S.O.; Bilal, M.; Owolabi, H.A.; Alaka, H.A.; Ayris, L.; Looney, J.H. BIM-based deconstruction tool: Towards essential functionalities. *Int. J. Sustain. Built Environ.* **2016**, *6*, 260–271. [CrossRef]

58. Akbarnezhad, A.; Ong, K.C.G.; Chandra, L.R. Economic and environmental assessment of deconstruction strategies using building information modelling. *Autom. Constr.* **2014**, *37*, 131–144. [CrossRef]

59. Akanbi, L.A.; Oyedele, L.O.; Omoteso, K.; Bilala, M.; Akinade, O.O.; Ajayi, A.O.; Davila Delgado, J.M.; Owolabi, H.A. Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy. *J. Clean. Prod.* **2019**, *223*, 386–396. [CrossRef]

60. Guy, B.; Shell, S.; Esherick, H. Design for Deconstruction and Materials Reuse. *Proc. CIB Task Group* **2006**, *39*, 189–209.