Big Data for Design Options Repository: Towards a DFMA Approach for Offsite Construction

Abstract

A persistent barrier to the adoption of offsite construction is the lack of information for assessing prefabrication alternatives and the choices of suppliers. This study integrates three aspects of offsite construction, including BIM, DFMA and big data, to propose a Big data Design Options Repository (BIG-DOR). The proposed BIG-DOR system will connect BIM clients to manufacturers/supplier's information such as prefab component cost and production lead times. In this study, we propose a framework for integrating BIG-DOR into the process of offsite construction delivery. The design of the BIG-DOR system architecture, as well as the key components such as the DFMA option-based 3D objects classifier, is presented. The contribution to the knowledge of this study is the successful integration of BIM, big data, DFMA and offsite construction in a single framework and the development of a design alternatives assessment system for offsite construction adoption using this framework.

Keywords: Offsite construction, big data, DFMA, BIM, Big-DOR

1 Introduction

Although, the global construction market is expanding and forecasts show that it will grow by over 70% by 2025 and contribute up to 14.7% of global economic output by 2030, but the industry has remained unremarkable for poor productivity with only 1% growth over the last 20 years [1]. As identified in the UK government construction strategy, an estimated productivity savings of about £1.7 billion is targeted by 2020 through the adoption of modern approaches, digital technologies and the pervasive use of big data in the Architecture, Engineering, Construction and Operations (AECO) industry [2]. Conventionally, the AECO industry is significantly less productive than the manufacturing industry because of the complexities in construction operations, which generates enormous volumes of disparate data [3]. Big data is generated throughout the various phases of construction such as design, scheduling, costing, resources planning, logistics, construction, and facilities management; and occurs in various formats such as DWG (short for drawing), DXF (drawing exchange format), DGN (short for design), RVT (short for Revit), ifcXML (Industry Foundation Classes XML), ifcOWL (Industry Foundation ClassesOWL), DOC/XLS/PPT (Microsoft format), RM/MPG (video format), and JPEG (image format) [4]. Despite the availability of the big data sources in the AECO industry, the use of big data for design optimisation and construction process planning is inefficient, and this problem results from the disparate nature of construction processes [5].

The enduring challenge of low productivity and inefficient use of big data in construction has necessitated the adoption of manufacturing approaches such as offsite construction [3]. However, with offsite construction contributing only 7% to the UK construction market, the reluctance of construction investors against offsite construction has been linked to the lack of adequate information to evaluate the potential benefits and constraints of using offsite construction [6]. There is a mutually causal relationship between "low uptake of offsite construction" and the "inefficient use of big data" [7]. While the AECO industry has lagged in the efficient use of the big data for transforming and standardising construction processes, there have been improvements over the years through the implementation of frameworks such as Building

Information Modelling (BIM) [8, 9]. BIM has helped to improve building designs through efficient 3D visualisations, clash detection and collaborative planning [10]. BIM has also helped to enhance the collaborative approach for industry professionals to populate an nD federated model, where n denotes the levels and types of information such as geometry (3D), schedule (4D) and cost (5D) [11].

Despite the positive impacts of BIM on traditional construction approaches, there has been no proportionate positive impact of BIM adoption on offsite construction adoption [2]. While there are attempts to further improve the adoption of BIM-driven offsite construction through the introduction of Design for Manufacturing and Assembly (DFMA), there has been a little positive impact due to the lack of relevant information during design consideration for offsite construction. DFMA is an approach, which originated in the manufacturing industry, for evaluating and improving product design for optimal manufacturing and assembly [12]. The adoption of DFMA principles in the construction industry allows a designer to enhance the buildability of construction products through early-stage design consideration [13]. During early-stage design consideration, the client needs to consider various options of adopting offsite construction with regards to available prefabricated products, ease and cost of manufacture and supply as well as supply chain capabilities. At the point of the early-stage design, the design manager and client/owner must consider the appropriateness of offsite design options to ensure pricing accuracy, significant risk mitigation, more straightforward contracts and better payment arrangement with supply chain [14]. Currently, the combination of BIM and DFMA helps in consideration of alternatives for offsite construction. However, there is a limitation of access to vital information to answer questions such as the 'manufacturability of BIM design components', 'availability of existing off-shelf prefab components' and the 'capability of manufacturers/supplier' to deliver bespoke designs [15]. There remains a significant impediment to the adoption of offsite construction, which is caused by the lack of semantic homogeneity between BIM design authoring tools and manufacturer-based Product Information Models (PIM)/big data sources for DFMA implementation [5].

Existing platforms such as NBS National BIM Library, MODLAR and Revitcity provide data integration capabilities for designers, specifiers and manufacturers by hosting thousands of downloadable BIM objects from prefab manufacturers. However, these platforms do not provide the necessary big data engineering characteristics that are necessary for offsite alternatives analytics. DFMA in construction involves the massive design iterations, alternative BIM objects combinatorial optimisation for efficient offsite construction. Design options in BIM are the vast number of possible choices, including the configuration of building elements, geometry (shapes and sizes), and materials of design parts and component. The consideration of offsite construction during early-stage design involves the assessment of design options through the implementation of DFMA. DFMA is an iterative process of specifying the building components for prefabrication and onsite installation, which involves the assessment of design options with decision variables such as cost, availability of materials, ease of manufacture and assembly. The current gap of DFMA implementation in the construction industry is the lack of information for decision-making and the fact that suppliers often contribute too little during the early-stage design [16].

The ideal case and purpose of this study entail the integration of suppliers' databases and information sources during early-stage design consideration for the adoption of offsite construction [5]. The argument here is that the information required for the assessment of design options should come from the suppliers of such prefabricated products, which brings up the question, how can the disjointed databases of suppliers be integrated using a big data framework for the assessment of design options through DFMA for offsite construction? This study aims to answer this question by proposing a Big Data Design Options Repository (Big-DOR) that: (i) enables the assessment of building design options through 3D BIM object classification (ii) provides access to suppliers-based information for prefabricated products through a big data framework (iii) supports optimal DFMA through BIM-based big data integration. In this study, we presented a background on the main components, including BIM, DFMA and big data, which will facilitate easy adoption of offsite construction. Abandah et al. [17] reported an argument that the most significant growth in construction productivity will be realised from the implementation of automated offsite activities that are facilitated by BIM. Offsite construction is preferable to traditional construction due to improved quality, more stable working conditions, standardised materials and processes, good health and safety, lower cost and reduced labour [18,19, 20]. The proposed Big-DOR system is expected to help in increasing the adoption of offsite construction by enabling the optimal selection of prefabricated materials and appointment of suppliers. Furthermore, in this study, we developed and tested a framework that details the system architecture and the critical components of a Big Data Design Options Repository (Big-DOR).

2 Background

This study approaches the duo problem of "low adoption of offsite construction" and "poor usage of big data" in construction through the integration of big data with other vital aspects of offsite construction such as BIM and DFMA for informed decision-making and optimisation [4, 5]. On the one hand, DFMA is considered as an approach that facilitates optimisation of offsite construction from the design phase and can be achieved more efficiently through BIM adoption [12, 21, 22]. On the other hand, BIM is an important technology that has demonstrated remarkable positive impacts and benefits on construction activities but continues to be limited by lack of adequate data during design considerations [17].

The changing markets have pushed the construction industry to gradually start adopting manufacturing approaches such as offsite construction [23, 24]. The adoption of offsite construction comes with benefits such as faster project delivery, greater consistency and quality, lower costs, lesser sites disruptions, and increased jobs stability for workers [25]. However, the first five barriers to the adoption of offsite construction include the enormous capital cost, the difficulty of achieving economy of scale, the complex interfacing between systems, the nature of planning systems and the inability to freeze designs early-on. Liu et al. [26] also identified some possible disadvantages of offsite prefabrication. They include: (1) the need for components installation expertise to guarantee structural integrity; (2) transportation and hoisting cost of large-scale prefabricated components; (3) the low flexibility of responding to change in construction demand, and; (4) the need for large-scale mechanical equipment.

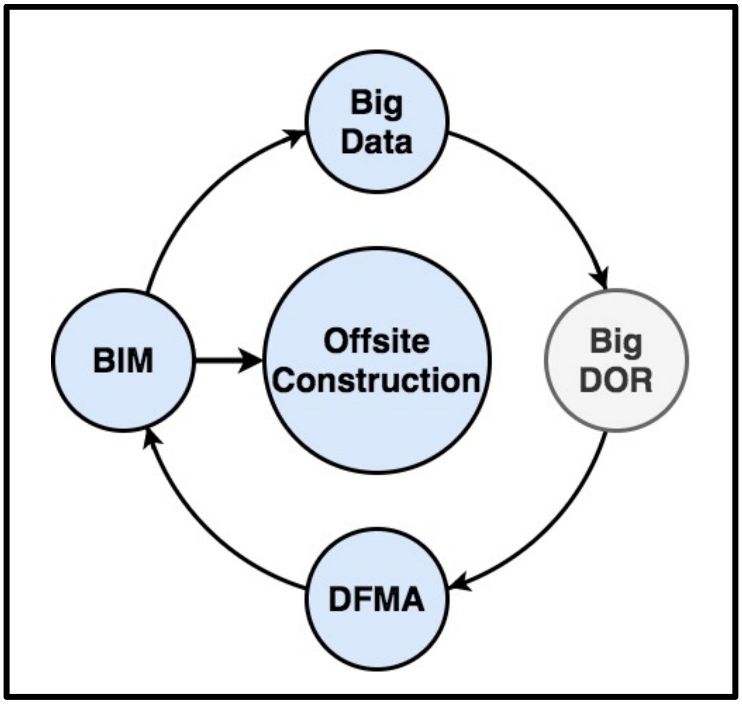

Figure 1: *Aspects of offsite construction in relation to Big-DOR*

In Figure 1, it is clear that BIM has a direct impact on improving the adoption of offsite construction by enabling the simulation of the entire offsite construction project in a virtual environment, and facilitating the automation of some processes of construction [8, 27]. BIM has been proven over the years to mitigate some of the barriers to the adoption of offsite construction, and it offers even more benefits such as better designs, faster delivery processes, better quality, lifecycle data, better team management, minimisation of costs and reduction of design changes due to unforeseen site conditions [28, 29]. However contrary to the case of traditional construction, BIM implementation alone is not enough to tackle most of the critical barriers to the adoption of offsite construction such as lack of certainty at the early design stage and the difficulty of achieving economy of scale [30, 26]. It is common to find the integration of DFMA and BIM in attempts to achieve better planning for offsite construction, DFMA helps to achieve better economy of scale, reduced order lead time and increased feasibility for products maintenance and component replacement [31]. DFMA also enables concurrent engineering, Just-In-Time (JIT) supply, waste minimisation and cleaner work environments [32].

The implementation of DFMA through BIM for supporting offsite construction is negatively affected by the lack of access to necessary information or data for assessing design options [16]. Existing platforms such as BIMobjects, NBS library and Revit City allow the upload of BIM objects/manufacturers' PIM for design integration [17]. As expected, this is beginning to encourage faster adoption of prefabrication as it allows manufacturers' products to get specified in BIM. However, in the case of assessing or comparing the available choices of prefab products for the adoption of offsite construction, it becomes incredibly tedious and almost impossible for a designer to download all potential products.

Considering the vast number of BIM design options, a big data framework is required to provide the necessary information required to enable a DFMA-based assessment [6]. The proposed Big-DOR system will mitigate the barriers of high capital costs, lack of certainty of cost and delivery time by allowing unlimited data flow between suppliers and designers. The proposed Big-DOR system will also be the missing link between big data and DFMA, and provide access for the necessary information to support DFMA. The Big-DOR system will rely on a big data framework acquiring, processing, analysing and applying data from existing disjointed databases of prefab suppliers to provide the necessary information required for assessing DFMA design options. The data sourced by the Big-DOR systems fits the definition of big data in terms of volume, velocity, variety and veracity. Therefore, a big data engineering approach will enable access to existing distributed databases. This section provides a review of extant literature in the domain of offsite construction optimisation from the perspectives of BIM, DFMA and big data.

2.1 BIM and Offsite Construction

With the argument thus far, evidence from literature further supports the assertion that offsite construction offers advantages such as better quality, higher whole-life value, lower costs, higher productivity and speedy delivery of construction projects [33, 34, 35]. However, the adoption of offsite construction comes with some barriers and constraints such as high initial costs, longer lead times due to pre-planning, unfavourable past experiences of collapse of the 1960s, lack of knowledge of the benefits, lack of codes and standards and poor integration of supply chain [36, 37, 38].

Abanda et al. [17] reviewed the literature on how BIM can enhance the benefits and also mitigate the barriers of offsite construction. While traditional construction often involves high wastage of materials during onsite processing as compared with offsite construction, BIM can enable a collaborative and yet remote design for offsite construction [39]. Through BIM adoption for offsite construction, inefficient and unnecessary onsite activities can be replaced by virtual BIM coordination for development and testing of building components at remote factories [40]. Offsite construction improves productivity by enabling concurrent production, which can be enhanced by BIM-enabled collaboration among stakeholders to effectively manage cost, fast-track the delivery of projects, avoid clashes, and eliminate wastes [8, 41]. A future opportunity identified by Kim et al. [42], entails the use of cloud BIM-based data exchange for the management of activities across multiple stakeholders in dispersed workstations.

BIM integration will further revolutionise the design process for such construction in the areas of generating automated detailed shop drawings for prefab components from 3D models as against the traditional approach of drawing sections and views from 2D plans [17]. The present-day challenge is to enable the integration of BIM for the coordination of supply chain activities to integrate the decision of suppliers and identify the existing interdependencies to minimise the total material management cost [43]. With the potential of offsite construction to improve the economic, environmental and social sustainability of the construction industry, it is essential to integrate BIM to achieve these potentials [44]. Summarily, BIM-enabled offsite construction is essential for collaboration, compliance checking, knowledge sharing, clash detection, and design optimisation.

2.2 Offsite Construction and DFMA Optimisation

In the adoption of offsite construction, the concept of DFMA is essential for evaluating the building design to improve the process of manufacturing, handling and onsite assembly [12]. The benefits of adopting DFMA are evident from its mandatory implementation on Singapore government land development projects, which has driven the number of offsite construction projects from less than 10 in 2013 to about 60 in 2018 [13]. The adoption of DFMA in construction will drive the desired goal for standardised construction processes, increased use of prefabricated components and ultimately, the adoption of offsite construction [45]. However, the adoption of DFMA in the construction industry has not been encouraging with about only 7% of construction projects in the UK using offsite construction approaches [6]. Gao et al. [13] identified a number of factors that affect the uptake of offsite construction, they include: project-specific factors like site constraints, transportation considerations, BIM and DFMA adoption. Goulding et al. [46] considered offsite construction as a complex process, which requires the integration of DFMA into the design. Gbadamosi et al. [5] also identified the "complexity of offsite construction" and the "wide variety of data formats in the construction industry" as significant motivations for the integration of DFMA in the adoption of offsite construction.

In the construction industry, DFMA involves the development of suitable designs for a chosen construction method to ensure optimal use of resources. There are many possible objectives for DFMA optimisation, which must be considered during design [16]. The primary objectives include cost, schedule, and quality while other relevant objectives include standardisation, part minimisation, preassembly engineering, installation review, sustainability, health and safety, and quality management [47, 48]. Although the adoption of DFMA for offsite construction optimisation is still nascent in the construction industry, there are some literature that explored the adoption of DFMA for offsite construction optimisation. Martinez et al. [49] adopted the principles of DFMA, lean manufacturing, and expert knowledge to develop a flexible field factory, which ensures flexible and mobile manufacture and assembly of precast components. The principles of DFMA have been adopted as the basis of a suitability assessment criteria for a standardised bridge construction using precast components [50]. Yuan et al. [21] integrated the principles of DFMA for the parametric design of prefabricated components in offsite construction. Gbadamosi et al. [5] also combined the principles of DFMA with lean construction for developing a BIM-based optimiser for onsite assembly of prefabricated components. With evidence from literature, parametric modelling is an essential aspect of adopting DFMA principles for offsite construction.

2.3 BIM and DFMA

BIM is a real opportunity in the AECO industry for enabling efficient construction planning through parametric modelling and information sharing [29]. BIM has enabled the capability of construction stakeholders such as clients, designers and facility managers to collect, store and reuse project information [51]. The benefits of BIM in creating an efficient working approach among construction professionals have been proven by the wide adoption of 3D BIM by architects and engineers for design visualisation and evaluation of design options [52]. Construction planners and quantity surveyors have also adopted 4D and 5D BIM for construction activities scheduling and project cost estimating respectively.

Some studies have integrated the principles of DFMA with BIM because of the capability of BIM for object-based parametric modelling and integrated design information [5, 21, 53]. Abandah et al. [54] identified some drivers of BIM usage for integrating principles that improve construction efficiency. These drivers include: (1) existing BIM authoring and management software (e.g Revit, ArchiCAD, Navisworks, AutodestQTO, ConstructSim, Bentley, EnergyPlus); (2) existing data in BIM components libraries (e.g BIMObject, SmartBIM, NBS Library and Object depository) and; (3) robust interoperability standards (e.g syntactic, technical, semantic and organisational interoperability). Despite the existence of these drivers, BIM implementation is still mostly limited to parametric modelling, while the integration of DFMA is still below par due to the unavailability of adequate data and poorly harnessed big data.

2.4 Offsite construction and Big Data

So far, a significant gap in knowledge is the lack of efficient ways to seamlessly capture, store and utilise data for adopting offsite construction. Existing big data processing and storage techniques have been explored big data engineering techniques for improving construction operations. An example is the use of Map Reduce (MR) for optimal retrieval of BIM data (MR4B) [55]. A big data BIM platform in a distributed framework called BIMCloud have utilised big data storage systems such as Apache Cassandra [56]. Big data analytics techniques have also been adopted to optimise various aspects of construction [4]. Machine Learning (ML) techniques including rule-based approaches, artificial neural networks and case-based reasoning methods have been used in construction aspects such as automated compliance checking, construction document classification, optimal resource assignment and fault detection [57,58, 59, 60].

Although, some literature exists on the integration of DFMA with BIM for offsite construction, however, there remains no research that has developed any real-world application of big data-driven DFMA integration with BIM to enhance the adoption of offsite construction [5]. The lack of comprehensive data to assess the various DFMA options as well as the cost and time implications of adopting alternative designs remains a significant barrier to the adoption of offsite construction [61]. An exhaustive rationale for the integration of big data to drive the adoption of offsite construction is considered from the perspectives of BIM adoption and the changing data trends due to offsite implementation. Bilal et al. [4] noted that construction data is voluminous, heterogeneous and dynamic and if properly harnessed, can be used to optimise construction operations.

2.4.1 Big data for BIM-based DFMA

At the design stage for offsite construction, DFMA increases data requirements for product simplification, process planning, costing, scheduling, and optimisation [62]. Furthermore, DFMA can also generate voluminous data for production analysis, logistics planning, and assembly sequencing. Also, DFMA requires the integration of important information such as resource capabilities, key performance indicators and so on. Summarily, big data application is required for BIM-based DFMA design to ensure that the design of components is in congruence with manufacturer capabilities and can be mass-produced with competitive pricing, economy of scale and efficient logistics.

Another aspect of BIM-based big data requirement for DFMA is structural considerations where factors such as the weight of materials, structural strength, hoisting and lifting requirements and the requirement for temporary support will be considered when developing the detailed design. Big data application is also required to enable the structural analysis of a federated BIM model as well as the structural-effect analysis of individual components of the model. The design of prefabricated components, modules or units should include the considerations of their position, orientation, and accessibility for installation and maintenance. Likewise, there is a higher requirement for big data and information, which is attributable to the level of adoption of offsite construction. Li et al. [63] highlighted a hierarchical classification of prefabrication products, which includes: (i) construction materials such as concrete and glass; (ii) components such as staircase and partition wall; (iii) modules such as bathroom pod and building façade, and volumetric units.

Table 1 shows a description of various levels of Offsite Construction Adoption (OCA) and some corresponding BIM information requirement.

Table 1: *3D BIM Information Requirement for Existing Design Options for Offsite Construction*

ID	Existing Options	Description	BIM information requirement
OCA-0	Traditional construction	Involves the delivery of materials to site and construction activities mainly done on-site.	Shape, dimension, layout, material, quantity
OCA-1	Prefabricated components	Involves the prefabrication and installation of basic components such as staircase sections, partition wall, etc.	Shape, material, dimension, component specification, weight, volume, connection specification
OCA-2	Prefabricated modules	Involves the combined prefabrication of associated components (modules) such as 'wall section with fitted door and window' and the onsite installation	Shape, size, structure loads, weight, volume, material, the specification for coupling and decomposition
OCA-3	Prefabricated volumetric units	Involves the prefabrication volumetric units with some preinstalled components but requires some onsite finishes as well as installation.	Shape, dimension, weight, volume, material, the specification for coupling and decomposition, relationship between whole and parts, relationship between parent and child products
OCA-4	Prefabricated prefinished volumetric units (PPVC)	Involves the prefabrication and pre-finishing of volumetric units which only require onsite installation	Shape, dimension, weight, volume, material, the specification for coupling and decomposition, relationship between whole and parts, relationship between parent and child products, key constraints

It is important to consider the flexibility to assess these offsite construction options based on factors such as the client's existing capabilities, the feasibility of adopting new methods, resource availability, project requirements, cost performance, schedule performance and whole-life value. A major limitation of the flexibility of adopting these options is the rigidity of 3D BIM models, which are often constrained to a specific OCA level. Usually, 3D models are prerequisites to work items scheduling (4D) and costing (5D), which makes it presumably impractical to compare the 3D models of various OCA levels based on schedule and cost efficiency while in the process of 3D design [54].

It is also important to consider the practicality of adopting offsite construction approaches by traditional construction companies. Adopting offsite construction could have negative short-term effects on the profit margin considering their peculiarities such as existing resources and processes [7]. Therefore, the need for an optimisation approach through DFMA for adopting offsite construction is hinged on the ability to assess various manufacturing options and the flexibility of transitioning from conventional approaches without the traditional construction companies having to suddenly and completely discard its existing resources and processes [2, 6].

3 The Proposed Big Data Design Options Repository (Big-DOR)

The benefits of BIM implementation have been mainly focused on traditional methods of construction while BIM implementation for offsite construction optimisation is still deficient. This is due to the lack of semantic connection between BIM information requirement for offsite construction and the big data sources of such information [17, 21, 62, 64]. In this study, the following are the challenges: (i) enabling offsite construction options- evaluation through BIM-model components categorisation; (ii) identifying big data sources in offsite construction for assessing DFMA options; (iii) designing a DFMA options repository for application of big data in offsite construction and; (iv) integration of DFMA options repository with BIM. This section presents a framework to solve these challenges through the following: (a) design rationale (b) system architecture and (c) the technical features of the main components, which include, big data mediation schema, Big Data Design Options Repository, BIM model integration, option-based object classifier and user interface.

3.1 Design Rationale

The most crucial focus of this study is to enable the optimisation of offsite construction choices using big data and BIM-based DFMA options classification. The Big-DOR is designed to bridge the gap between the existing BIM authoring tools and big data sources in offsite construction sources. This gap still exists because the currently available BIM objects are domain-specific and have been tailored to suit existing methods of construction rather than offsite construction. This gap is further widened because the accuracy of cost estimation of BIM models is also dependent on the model, and this makes it difficult to compare the cost of two BIM model options without designing both options. The DFMA option-based 3D object classifier is designed to bridge this gap by using various features and relationships of various DFMA options available. Furthermore, there are various sources of big data from offsite construction stakeholders who use domain-specific database schemas, which cannot be easily integrated with the existing schemas in the construction industry. To maximise the usage of available big data both within and outside the construction industry, big data schema mediation component is integrated with the Big-DOR to ensure usability and scalability of the system. The following are the objectives of this study, (i) develop BIM model 3D object classifier using geometric features and DFMA option component relationships, (ii) develop a big data schema mediation system using peer-to-peer schema integration structure, (iii) integrate big data from offsite construction sources using relational database management system and (iv) develop an application user interface for big data input, management, and visualisation.

3.2 System Architecture

The conceptual architecture of a Big-DOR system for big data integration in offsite construction using BIM-based DFMA is shown in Figure 1. The system will facilitate the usage of big data for optimising the DFMA using essential factors such as cost, productivity, and constraints. The Big-DOR system includes four main components within a four-layered big data architecture. They include:

1. Big-Data Storage Layer: This layer includes two big data sources including offsite construction suppliers, and BIM users;
2. Big-Data Processing Layer: This layer holds the DFMA options repository, which uses big data mediation schema to coordinate peer-to-peer database integration;
3. Big-Data Analytics Layer: This layer will contain the DFMA option-based 3D object classifier, which uses DFMA features and relationships to classify 3D BIM objects to various design options and support optimal decision making;
4. Big-Data Application Layer: This layer integrates the user interface with a BIM authoring tool to enable the assessment of BIM design models.

Full-scale development of the Big-DOR system will integrate big data from the various autonomous and heterogenous sources for optimising designs. The critical components of the system architecture are described subsequently.

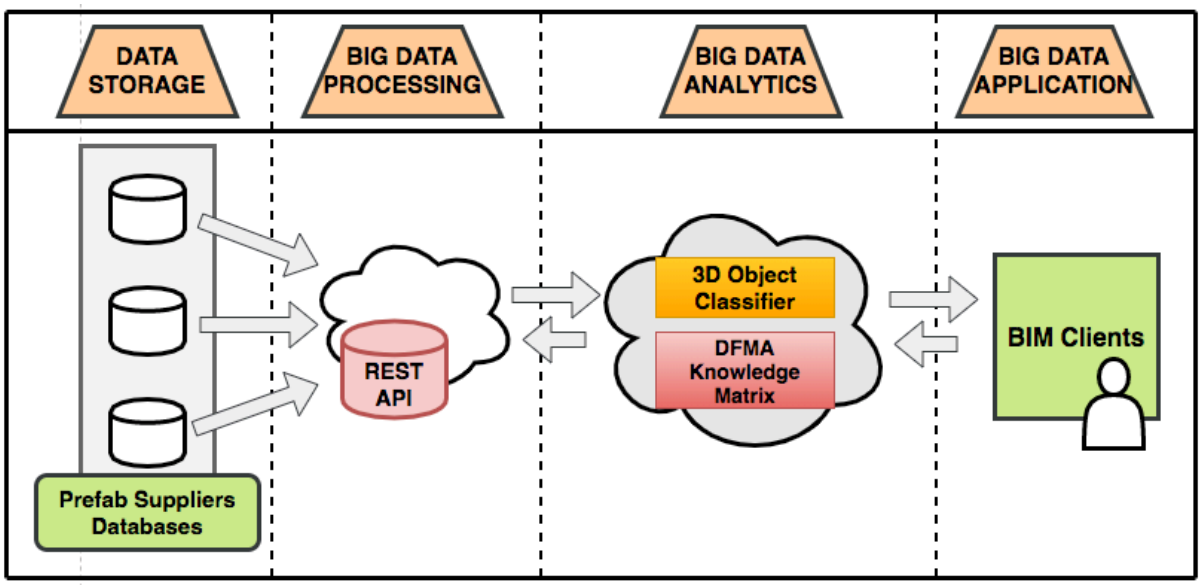

Figure 2: *System Architecture for Big-DOR*

The proposed Big-DOR system is a web application that has the backend big data platform running on the Amazon Web Services (AWS) for cloud storage on S3 bucket and supplier's database query logic on lambda. Existing Rest APIs for getting suppliers' products information was considered for this study including NBS library (https://toolkit.thenbs.com/articles/for-software-developers). The proposed Big-DOR system will integrate existing big data platforms to enable access to suppliers' product information for design options assessment by BIM clients. The current proposed system architecture is for a standalone web app, but in the future, the Big-DOR will be integrated into BIM authoring tools to enhance the ease of use.

3.3 Big Data Sources

Big data is generated in various phases of construction such as design, scheduling, costing, resources planning, logistics, construction, and facilities management, and occurs in various formats such as DWG (short for drawing), DXF (drawing exchange format), DGN (short for design), RVT (short for Revit), ifcXML (Industry Foundation Classes XML), ifcOWL (Industry Foundation ClassesOWL), DOC/XLS/PPT (Microsoft format), RM/MPG (video format), and JPEG (image format). There are two primary sources of big data input into the Big-DOR system, they include:

1. **BIM Authoring Tools:** These tools are usually used by designers to add building information, which typically includes data about thousands of BIM objects with variants in terms of materials, shapes and sizes. These objects are created, modified and reused within BIM authoring tools where they can be classified during "quantity take-off" and used for cost estimation [65]. The quantity take-off of objects from BIM models requires accurate object classification into "work packages" or "prefabricated components" in offsite construction to enable synergy with data from other sources such as unit cost and production constraints of prefabricated products [66].
2. **Suppliers' Product Information Modelling (PIM) Tools:** Existing manufacturers information platforms such as 'NBS library' and 'BIMObject' hosts above 1 million users with millions of BIM

object variants from various manufacturers. These platforms are designed to improve access to suppliers' product specification for BIM design integration. The challenge is to enable the comparative assessments of the vast number of prefab PIMs (or DFMA components) by multiple suppliers for BIM design optimisation. There are multiple objectives and project phases to consider during design optimisation, which makes design optimisation tedious, however, a major objective of the Big-DOR system is to map BIM objects to DFMA design options with relevant information obtained from suppliers/manufacturers data sources using a big data framework [67].

3.4 DFMA Option-based 3D Object Classifier

The function of this module, the DFMA option-based object classifier is to utilise a comprehensive DFMA knowledge system for classifying BIM objects into DFMA components according to the DFMA design options. Although, some object classification systems such as SeeBIM, have used a rule-based approach to integrate domain experts' knowledge for object classification [68]. Rule-based inference approaches have limited practical use for object classification in complicated design optimisation for offsite construction because it can be error-prone, the validity of rules can be challenging and, equally stringent rules can be conflicting [65]. The proposed approach of representing DFMA knowledge for the BIM object classification module is the use of a "Matrix System" to store the features and relationships, which will then be used for matching BIM objects with DFMA components. The workflow for continuously compiling a comprehensive DFMA knowledge matrix for classifying BIM objects into DFMA components is shown in Figure 3. It is important to note that a DFMA component can be formed either by aggregating or segregating BIM objects depending on the DFMA option. Also, DFMA components are defined in the comprehensive knowledge matrix using the features and relationship of its constituent objects.

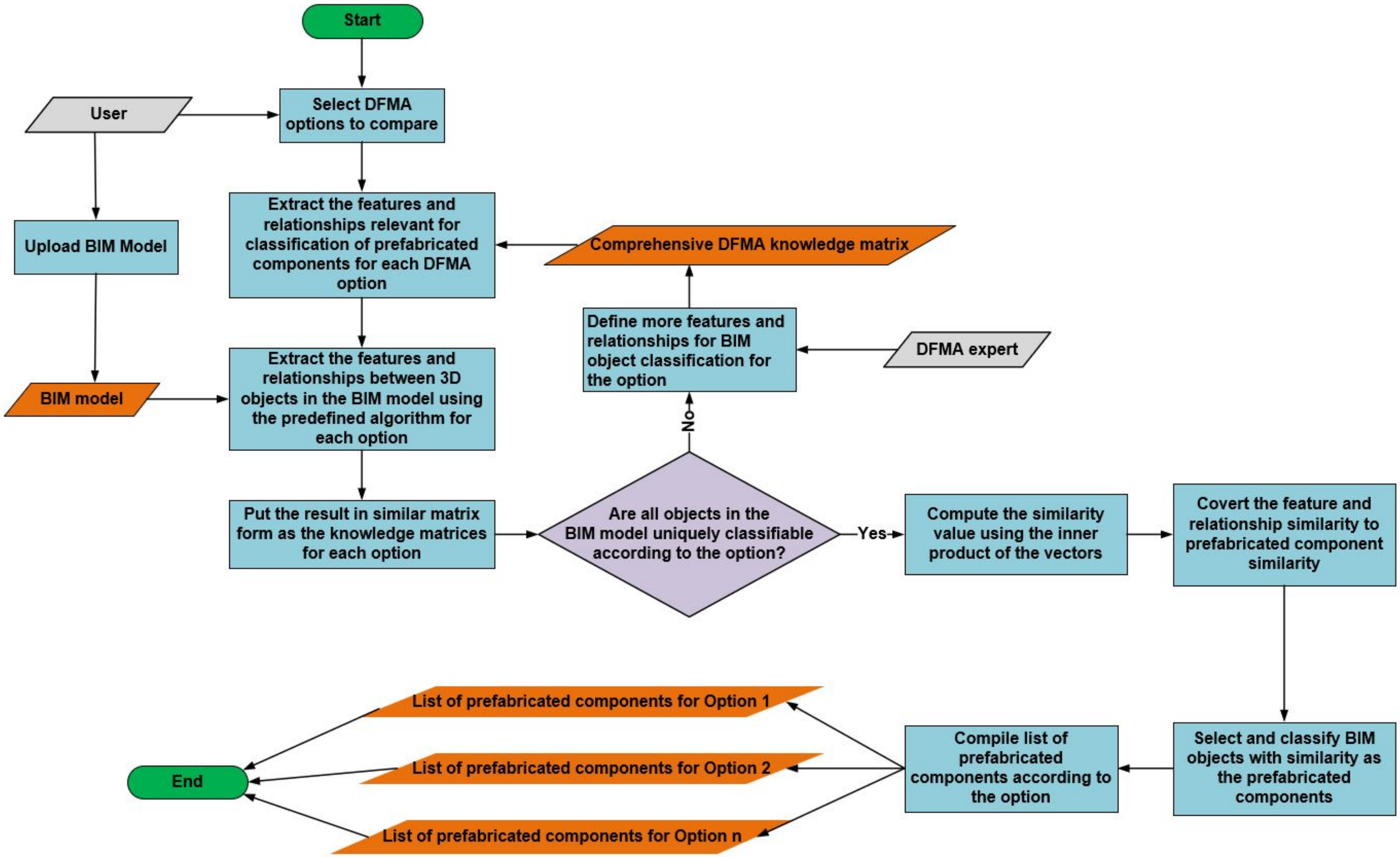

Figure 3: *Workflow for a continuous compilation of DFMA knowledge matrix for BIM object classification*

Relevant features for BIM objects classification include shape, size, orientation, location, material, weight volume an so on, while objects relationship includes level, grid, proximity, orthogonality and parallelism and so on [69, 68, 65]. The compiled list of DFMA components for each design option is then computed using the algorithm shown in Figure 4.

```
Algorithm
Input: 3D BIM Model (ψ) and DFMA Strategies Repository (ϕ)
Output: Optimal 5D BIM Model (ψ*)
index Parameters (Vkx)

get components ci from ψ
get design options Rj from ϕ
        for each
        group ci by Rj ∀ work items for Rj = Wn,j
                get Wn,j
                for Wn,j do:
                                                  ⎧  Kx.c  if Kx = cost index
                        get design KPIs Kx =      ⎨ Kx.d if Tpf = duration index
                                                  ⎩ Kx.k if Kx = constraint index
                        for each k in KPIs do:
                                get values (V) for Vkx
                                compute Kx
 optim.type='ABC'
 v' = optim.solve(V)
 m' = m* v'
 return m'
end
```

Figure 4: *Object Classification Algorithm*

The comprehensive knowledge base of DFMA components can be organised in matrix format using the possible relationships between the constituent object types. In Table 2, a sample knowledge matrix where the values "-1", "0" and "1" are assigned for relationships that "never exist", "may exist" and "always exist" respectively between object types for a DFMA component. The sample knowledge matrix consists of three object types X1, X2 and X3, and four relations.

Table 2: *An example of DFMA knowledge matrix*

	Relation 1	Relation 2	Relation 3	Relation 4
X_1, X_1	0	1	1	1
X_1, X_2	1	-1	-1	0
X_1, X_3	-1	0	0	0
X_2, X_1	1	0	1	1
X_2, X_2	0	-1	1	-1
X_2, X_3	1	1	0	0
X_3, X_1	1	1	0	-1
X_3, X_2	0	0	1	-1
X_3, X_3	1	0	0	1

Given a 3D BIM model with two objects B1 and B2, a BIM model fact matrix of the relationship between the objects can be organised in the same matrix format as the sample DFMA knowledge matrix shown in

Table 2. While X1, X2, and X3 are object types in the knowledge matrix, B1 and B2 are actual objects in the BIM model. Therefore, there are no such pairs as [B1, B1] as we have [X1, X1]. Also, there is no such value as "0" in the fact matrix because the objects either have a relationship "1" or not "-1". An example of a BIM model fact matrix is shown in Table 3.

The similarity between the objects in the 3D BIM model and the object types of the DFMA components in the comprehensive knowledge matrix can be found by computing the inner product of the vectors in each row of the knowledge matrix and fact matrix.

Table 3: *A sample BIM model fact matrix.*

	Relation 1	Relation 2	Relation 3	Relation 4
B1, B2	-1	1	1	1
B2, B1	1	-1	-1	1

Let K(a, b) be the four-dimensional vector of each row in the knowledge matrix, where a, b Î [1, 2, 3, 4], and F(x, y) be the four-dimensional vector of each row in the factual matrix, where x, y Î [1, 2], a ¹ b. The similarity values S(a, b)(x, y) of the 3D BIM objects and DFMA component object types are computed using equation 1, below.

$$\mathrm{S(a,b)(x,y)} = \frac{\boldsymbol{K}(a,b)\cdot\boldsymbol{F}(x,y)}{|\boldsymbol{K}(a,b)|\ |\boldsymbol{F}(x,y)|} \quad (1)$$

A semantic path can now be established between the objects that exist in any BIM model and the object types that make up the prefabricated components for DFMA options in the knowledge matrix. The object classifier can then output a list of prefabricated components that exist in a BIM model according to the DFMA option for comparative assessment.

3.5 Big Data Design Options Repository

The primary function of the Big Data Design Options Repository is the facilitation of schema mediation for semantic big data sharing between various data models such as the industry foundation classes extensible markup language (ifcXML) and functionalities of the Big-DOR is to hold (i) the comprehensive knowledge matrix for classifying BIM ifcObjects into prefabrication products (ii) offsite construction peers mapping (iii) catalogue of standardised prefabrication products and; (iv) algorithm for semantic schema matching and mapping. Figure 5 shows the peer-to-peer data integration for the Big-DOR. It illustrates a peer-to-peer big-data integration system that enables offsite construction practitioners to access data for assessing various options for DFMA.

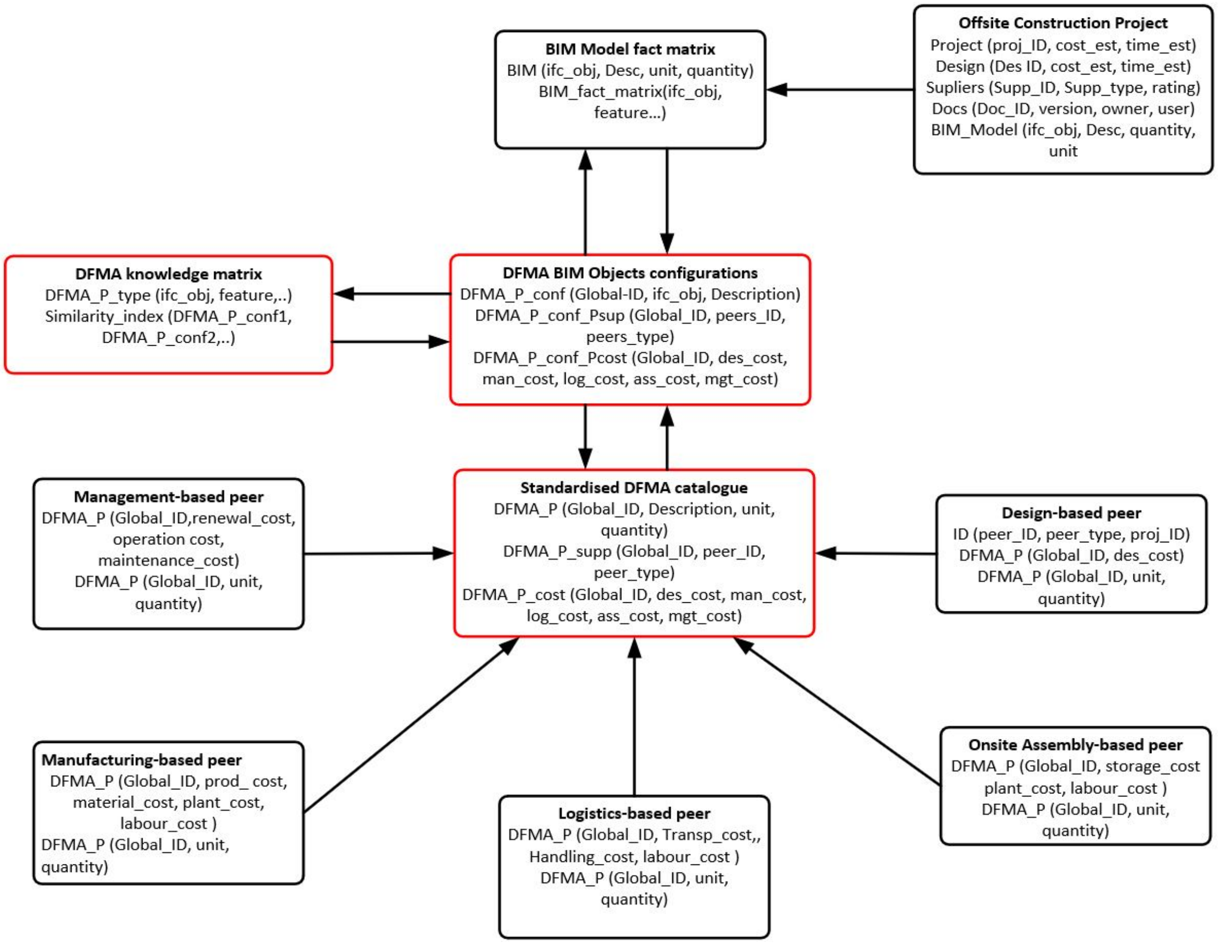

***Figure 5:** Peer big data integration setting for Big-DOR*

To enable big-data integration for offsite construction optimisation through the Big-DOR, it is essential to reconcile the heterogeneity of the big-data storage and schema of offsite construction peers. Given the vast number of Potential Offsite Construction peers POCi {POC1, …, POCn} and a set of Peer Schemas SOCj {SOC1, …, SOCm}, unlimited access to data from a set of stored relations Tbdi at each offsite construction peer POCi, will be enabled to support the combinatorial optimisation of a set of objects Cifci in BIM models for identifying opportunities for optimal integration of prefabrication in designs. The standardised DFMA catalogue will enable the query routing for assessing the data in the stored relation DOCP, of the offsite construction peers. An example of the storage description of the standardised DFMA catalogue (SDC) is:

```
SDC: DFMA_P_cost(G_ID, des_cost..) ⊆ Design-Based peer: DFMA_P (G_ID, des_cost..)
                                   ⊆ Manufacture-B peer: DFMA_P (G_ID, Prod_cost..)
                                   ⊆ Onsite_A-B peer: DFMA_P (G_ID, Storage_cost..)
                                   ⊆ Logistics-B peer: DFMA_P (G_ID, Transp_cost..)
                                   ⊆ Management-B peer: DFMA_P (G_ID, renewal_cost..)
```

The standardised DFMA catalogue (SDC) also stores information about registered peers and allows user-input to enable comparative assessment of peers based on past performance of the participating peers.

```
SDC: DFMA_P_cost (G_ID, des_cost..) ⊆ D-B peer: ID (Peer_ID, Peer_type, Location, Experience)
```

4 Case study

The proposed framework was applied to assess the DFMA strategies of a block of five-offices. The total floor area of the office block is 1200 ft2 (111.48m2). The model was developed in Autodesk Revit and exported in FBX format to the proposed Big-DOR application. Important information for enabling automatic BIM objects classification was specified using Revit functionalities, as shown in Figure 6.

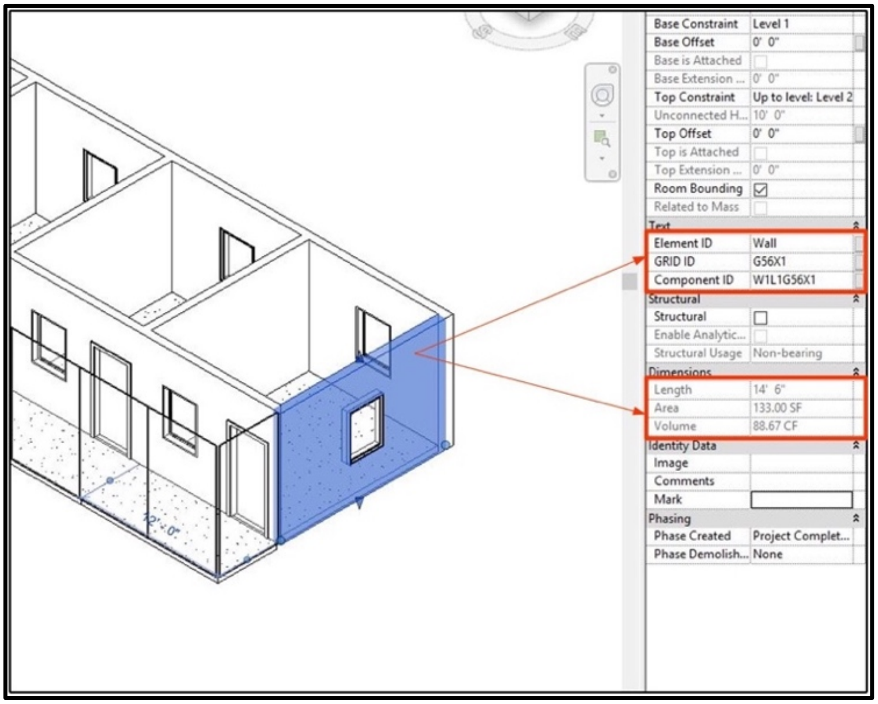

Figure 6: *Specification of BIM Object Classification Features and Relationships in a Revit Environment*

The purpose of this illustrative case study is to demonstrated the functionality of the Big-DOR system for the optimisation of offsite delivery method and the selection of offsite suppliers. This section presents the development of a decision optimisation algorithm that compares the suppliers’ price quotation with the estimated whole-life value of the available methods. The FBX format of the BIM model was uploaded to the Big-DOR prototype and big data storage and analytics was implemented using Amazon Web Services (AWS) including Amazon S3 and Amazon Lambda. Figures 7 and 8 show the application user interface and the cloud service interface for the proposed Big-DOR system. A description of the illustrative case study is subsequently presented.

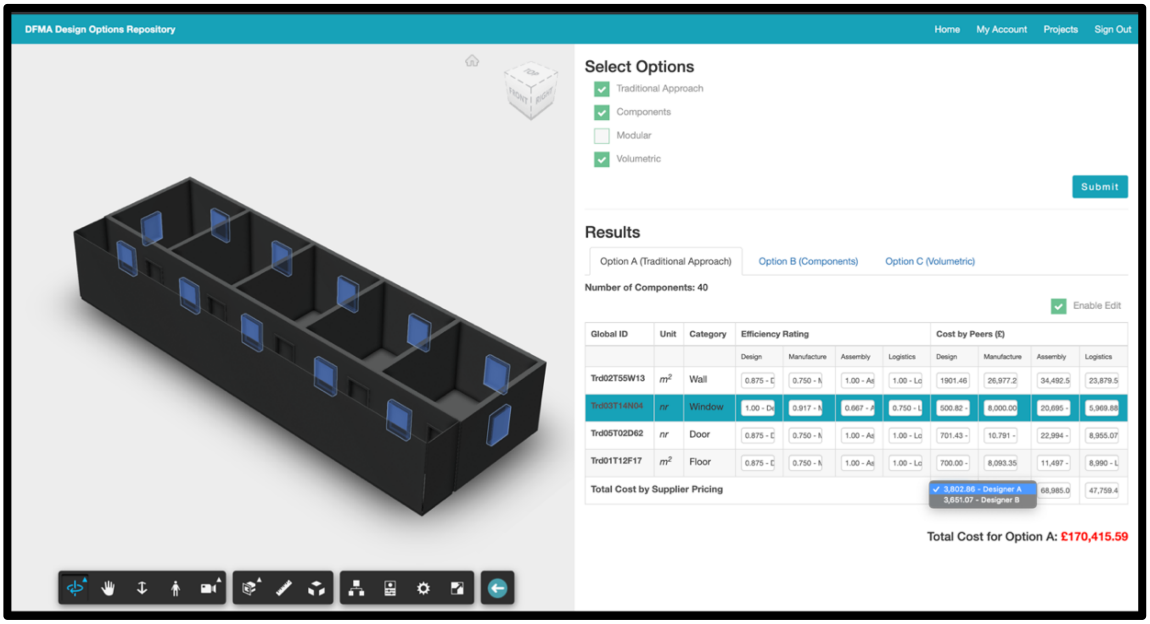

Figure 7: Prototype Big-DOR Application

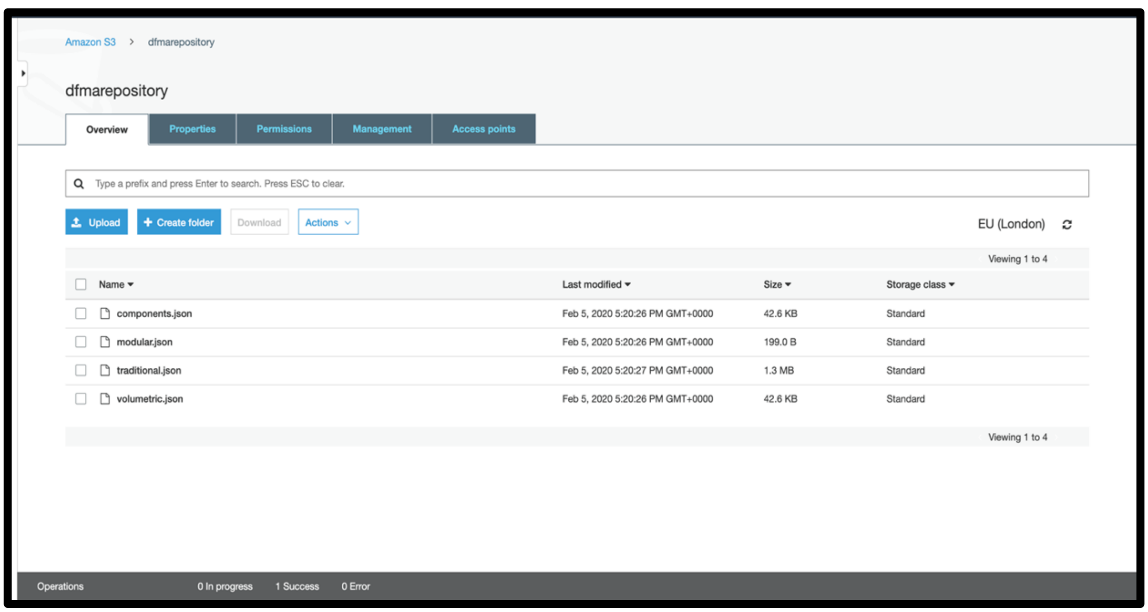

Figure 8: Cloud Storage of Classified BIM Objects on Amazon S3 in json Format

4.1 Optimisation algorithm

A typical offsite construction project consists of five phases viz design, manufacture, logistics/handling, assembly, and facility management. The design phase entails critical evaluation of DFMA choices with a vast number of decision variables for offsite construction choices. An overview of some critical design consideration has been explained for the proposed framework. For this case study, the following four objectives were set for comparing the DFMA strategies: (i) cost; (ii) duration; (iii) ease of implementation (iv) whole-life value.

Table 4: Set of variables for proposed DFMA optimisation

	Notation for a set of variables	Set of variables	Notation for variables	Variables	Value range (Z)
Design	$\beta_{PF,Di}$	Design delivery efficiency factor	ER_D	Designer DFMA expertise rating for	[0-2]
			EL_D	Designer DFMA experience level	[0-4]
	ϕ_{PF}^{Di}	Design constraints factor	C_D	Design complexity	[0-4]
			DD_{WI}	Work item detailing difficulty	[0-4]
	K_{Di}^{WI}	Design unit cost for work item (i)	µD	Average unit cost for work item design	
Manufacture	$\beta_{PF,Mi}$	Production efficiency factor	EX_M	Manufacturing process experience for work item	[0-4]
			EM_M	Experience of material use in production	[0-4]
			S_{PM}	Part standardisation rating	[0-2]
	ϕ_{PF}^{Mi}	Production constraints factor	SR_M	Set up requirement	[0-2]
			FP	Fragility of parts	[0-2]
	K_{Mi}^{WI}	Offsite production unit cost for work item (i)	µM	Average unit cost for work item production	Value
Logistics	$\beta_{PF,Li}$	Handling efficiency factor	EH_L	Handler's expertise level for work item logistics	[0-2]
			ER_L	Handler's experience rating for work item	[0-4]
			HD	Handling difficulty	[0-2]
	$K_{\boldsymbol{Mi}}^{WI}$	Logistics unit cost for work item (i)	µL	Average unit cost for work item logistics	Value
Assembly	$\beta_{PF,Ai}$	Assembly efficiency factor	EI_A	Installation process experience	[0-4]
			ER_A	Assembler's expertise rating	[0-2]
			TC_A	Type of connection used	[0-4]
	ϕ_{PF}^{Ai}	Assembly constraints factor	SA_A	Site accessibility	[0-2]
			ST_A	Site storage allowance	[0-2]
	K_{Di}^{WI}	Assembly unit cost for work item (i)	µA	Average unit cost for assembling work item	Value
Operation	λ_{PF}	Useful life efficiency	M_O	Maintainability of work item	[0-4]
			RM_O	Removability of work item	[0-4]
			RU_O	Reusability of work item	[0-4]
	Q_{WI}	Quantity of work item			Value

Let OCAi represent a DFMA strategy such that $0 \leq OCAi \leq 1$ ($\forall$ i $\in$ Z+), then the objective function Z is expressed as;

$$Z = \max\,[\beta_{PF}, (1-\phi_{PF}), \lambda_{PF}] \tag{1}$$

Where, β_{PF} = delivery efficiency factor, ϕ_{PF} = delivery constraints factor, λ_{PF} = useful life efficiency factor. These three factors are then used to determine the Total Factored Cost (TFC) for work items "WIi" for each of the design options and is expressed as;

$$\mathrm{TFC} = \sum_{1}^{n} \frac{1}{\lambda_{PFi}} \left(\frac{\phi_{PF}^{Di}}{\beta_{PF,Di}} \bullet K_{Di}^{WI} + \frac{\phi_{PF}^{Mi}}{\beta_{PF,Mi}} \bullet K_{Mi}^{WI} + \frac{\phi_{PF}^{Li}}{\beta_{PF,Li}} \bullet K_{Li}^{WI} + \frac{\phi_{PF}^{Ai}}{\beta_{PF,Ai}} \bullet K_{Ai}^{WI} \right) \tag{2}$$

There are 13 sets of decision categories, which contain 29 decision variables for selecting a DFMA strategy using datasets from BIM components and offsite construction stakeholder's external database. The three sets of decision variables for the design category viz: (i) design delivery efficiency factor "$\beta_{PF,Di}$"; (ii) design constraints factor "ϕ_{PF}^{Di}"; and (iii) design unit cost for work items "K_{Di}^{WI}" are expressed in Equation 3, 4 and 5 as;

$$\beta_{PF,Di} = 0.25\ ER_D + 0.125\ EL_D \quad (3)$$

$$\phi_{PF}^{Di} = 0.125\ C_D + 0.125\ DD_{WI} \quad (4)$$

$$K_{Di}^{WI} = Q_{WI} * \mu D \quad (5)$$

The three sets of variables for the manufacturing category including: (i) production efficiency factor "$\beta_{PF,Mi}$"; (ii) production constraints factor "ϕ_{PF}^{Mi}", and; (iii) manufacture unit cost for work item "K_{Mi}^{WI}" are expressed in Equation 6, 7 and 8.

$$\beta_{PF,Mi} = \frac{1}{3}(0.25\ EX_M + 0.25\ EM_M + 0.5S_{PM}) \quad (6)$$

$$\phi_{PF}^{Mi} = (0.25SR_M + 0.25FP) \quad (7)$$

$$K_{Mi}^{WI} = Q_{WI} * \mu M \quad (8)$$

The three sets of variables for the logistics category, which include handling efficiency factor "$\beta_{PF,Li}$", logistics constraints factor "ϕ_{PF}^{Li}" and logistics unit cost for work item (i) "K_{Li}^{WI}" are expressed in Equation 9, 10 and 11.

$$\beta_{PF,Li} = 0.25\ EH_L + 0.125\ ER_L \quad (9)$$

$$\phi_{PF}^{Li} = \frac{1}{2}(HD) \quad (10)$$

$$K_{Li}^{WI} = Q_{WI} * \mu L \quad (11)$$

In the assembly category, the sets of variables for assessing DFMA options including: (i) assembly efficiency factor "$\beta_{PF,Li}$"; (ii) logistics constraints factor "ϕ_{PF}^{Li}", and; (iii) logistics unit cost for work item "K_{Li}^{WI}" are expressed in Equation 9, 10 and 11.

$$\beta_{PF,Ai} = \frac{1}{3}(0.25\ EI_A + 0.5\ ER_A + 0.25TC_A) \quad (12)$$

$$\phi_{PF}^{Ai} = (0.25SA_A + 0.25ST_A) \quad (13)$$

$$K_{Ai}^{WI} = Q_{WI} * \mu A \quad (14)$$

Finally, the set of variables related to whole-life value of the work items i.e., useful life efficiency "λ_{PF}" is expressed as;

$$\lambda_{PF} = \frac{1}{3}(0.25\ M_O + 0.25\ RM_O + 0.25\ RU_O) \quad (15)$$

4.2 Assessment of BIM-Model for Offsite Approach

Three construction methods viz traditional construction, prefabricated components, and volumetric construction were identified as the options for assessing the construction method for the BIM model. Tables 5 – 7 show the three options of BIM object classification for offsite construction. One of the options reflects the traditional approach of quantity take-off to enable the comparison of offsite construction with traditional construction. Table 5 shows the quantity take-off for the tradition approach option.

Table 5: *Object Classification for DFMA Option-A (Traditional Construction)*

Global ID	Categories	Description	Unit	Quantity	Number of BIM objects
Trd02T55W13	Wall	Basic wall	m^2	222.96	16
Trd03T14N04	Window	Fixed window (36" x 48")	nr	12	12
Trd05T02D62	Door	Single-flush wooden door (36" x 84")	nr	5	5
Trd01T12F17	Floor	Concrete slab (6")	m^2	111.48	10
					43

Table 6 shows the second option, which is the use of standardised prefabricated components. The components type is stored in the Big-DOR repository with a global Id among offsite construction peers and can be accessed and reused for BIM model design.

Table 6: *Object Classification DFMA Option-B (Components Prefabrication)*

Global_ID	Categories	Description	Unit	Quantity	Number of BIM objects
CompX15T346B	Façade component Type 346B	Wall panel (8") with Single-flush wooden door (36" x 84") and Fixed window (36" x 48")	Nr	5	15
CompX15T357C	Façade component Type 357C	Wall panel (8") with Fixed window (36" x 48")	Nr	5	10
CompX15T357F	Façade component Type 357F	Wall panel (8") with Fixed window (36" x 48")	Nr	2	4
CompX15T338D	Façade component Type 338D	Wall panel (8")	Nr	4	4
CompF32T267E	Concrete precast floor slab Type 267E	Concrete precast floor slab (6")	Nr	5	5
CompF32T267B	Concrete precast floor slab Type 267B	Concrete precast floor slab (6")	Nr	5	5
					43

Table 7 shows the third construction option, which is another approach to offsite construction and involves the offsite prefabrication of volumetric modules rather than components. The standardised modules are stored in the repository and can be reused.

Table 7: *Object Classification DFMA Option-C (Volumetric construction)*

Global_ID	Categories	Description	Unit	Quantity	Number of BIM objects
ModX89T12D	Volumetric module G12	Prefabricated prefinished volumetric concrete unit	GFA (m2)	22.3	10
ModX73T16K	Volumetric module G23	Prefabricated prefinished volumetric concrete unit	GFA (m2)	22.3	8
ModX73T16K	Volumetric module G34	Prefabricated prefinished volumetric concrete unit	GFA (m2)	22.3	8
ModX73T16K	Volumetric module G45	Prefabricated prefinished volumetric concrete unit	GFA (m2)	22.3	8
ModX89T12E	Volumetric module G56	Prefabricated prefinished volumetric concrete unit	GFA (m2)	22.3	9
					43

4.3 Offsite Construction Options Quotation

After identifying the candidate-products for the offsite construction options, conjunctive queries can now be made to get unit costs for the candidate-products for the BIM model. Table 8 shows a sample of the query response report for a BIM model assessment for method selection and suppliers' selection. The unit costs are split into design cost, manufacture cost, logistics cost and assembly cost [71]. The various unit costs are laid out according to the offsite construction phases as well as the query response from the respective databases of offsite construction peers or suppliers.

Table 8: *Unit cost quotation by offsite construction peers for work items for each option*

Global_ID	Unit	Design Unit Cost by Peers		Manufacture Unit Cost by Peers		Logistics Unit Cost by Peers		Assembly Unit Cost by Peers	
		Designer-A	Designer-B	Manufacturer-A	Manufacturer-B	Logistics-A	Logistics-B	Assembler-A	Assembler-B
Option-A									
Trd02T55W13	m^2	£6.50	£3.70	£55.00	£65.00	£32.50	£27.50	£145.00	£150.60
Trd03T14N04	nr	£97.00	£127.00	£2,140.00	£2,120.00	£414.00	£395.00	£950.00	£930.50
Trd05T02D62	nr	£93.00	£115.50	£750.00	£820.00	£175.00	£182.00	£670.00	£655.00
Trd01T12F17	m^2	£6.50	£4.50	£110.00	£115.00	£311.00	£320.50	£196.50	£155.00
Option-B									
CompX15T346B	nr	£155.00	£120.00	£2,750.00	£2,420.00	£675.00	£642.00	£1,355.00	£2,725.00
CompX15T357C	nr	£140.00	£155.00	£2,500.00	£2,560.00	£650.00	£656.00	£1,550.00	£2,560.00
CompX15T357F	nr	£196.00	£114.50	£2,600.00	£2,400.00	£660.00	£640.00	£1,600.00	£2,500.00
CompX15T338D	nr	£192.00	£125.00	£2,700.00	£2,500.00	£670.00	£650.00	£1,475.00	£2,675.00
CompF32T267E	nr	£140.00	£110.00	£3,150.00	£4,950.00	£915.00	£895.00	£1,560.50	£2,785.50
CompF32T267B	nr	£150.00	£130.00	£5,250.00	£5,150.00	£725.00	£715.00	£1,550.50	£2,250.50
Option-C									
ModX89T12D	GFA	£145.00	£165.45	£850.00	£625.50	£220.00	£270.00	£149.00	£124.00
ModX73T16K	GFA	£140.00	£160.45	£850.00	£625.50	£220.00	£270.00	£149.00	£124.00

ModX73T16K	GFA	£145.00	£160.45	£850.00	£625.50	£220.00	£270.00	£149.00	£124.00
ModX73T16K	GFA	£145.00	£160.45	£850.00	£625.50	£220.00	£270.00	£149.00	£124.00
ModX89T12E	GFA	£150.00	£165.45	£850.00	£625.50	£220.00	£270.00	£149.00	£124.00

Other relevant information for assessing the proposed options include the user-based rating of the participating offsite construction suppliers, the evaluation of the prefabricated products for potential constraints and evaluation of factory and site conditions.

4.4 Offsite Construction Suppliers Assessment

The optimisation algorithm integrates a supplier competency assessment, which extends suppliers assessment beyond quantitative parameters such as unit cost and distance to project site, and allows users to compare various peers or suppliers based on experience and expertise. The offsite construction peers' ratings according to their experience and expertise for the three options are shown in Table 9. In practice, the rating will be determined through established relationships with the OC peers or through a predetermined evaluation matrix.

Table 9: *User-based Ratings of OC Suppliers based on Expertise and Experience*

Offsite Construction Suppliers	Option A (Traditional)		Option B (Prefab Components)		Option C (Modular)	
	Experience [0-4]	Expertise [0-2]	Experience [0-4]	Expertise [0-2]	Experience [0-4]	Expertise [0-2]
Designer X	3	2	3	1	2	1
Designer Y	4	2	4	2	1	2
Manufacturer X	1	0	3	2	4	2
Manufacturer Y	2	1	4	2	2	1
Logistics X	4	2	3	1	3	1
Logistics Y	2	2	4	2	3	2
Assembler X	4	2	3	2	3	1
Assembler Y	2	1	4	2	3	2

4.5 Offsite Construction Products Assessment

Offsite construction products were assessed in terms of the workability at various phases of offsite construction delivery. Such assessment would be user-based as most construction companies have a rating system for the ease of use for various construction elements. In practice, the Big-DOR will automatically calculate the respective ratings for offsite prefabricated products based on performance records obtained from offsite construction peers and suppliers. Table 10 shows a sample of a rating system for offsite construction products. These ratings were used in calculating the efficiency and constraints factors for the various options.

The repository-based assessment of work items or prefabricated products for various offsite construction strategies is essential for understanding and comparing the potential constraints for delivering the BIM design using the various options [72]. Inefficiencies can be mitigated by factors such as the expertise and experience possessed by the various offsite construction peers, as shown in Table 9, the user-based rating for offsite construction peers was integrated with the repository-based prefabricated products ratings to determine the efficiency penalty factors and the constraints penalty factors.

Table 10: *Repository-based Rating for Work Items for the OC Options*

	Categories	Design complexity [0-4]	Detailing difficulty [0-4]	Standard parts [0-2]	Setup requirement [0-2]	Fragility of parts [0-2]	Handling difficulty [0-2]	Type of connection [0-4]	Site access requirement [0-2]	Site storage requirement [0-2]	Maintainability [0-4]	Removability [0-4]	Reusability [0-4]
Option-A													
Trd02T55W13	Wall	0	1	2	1	0	2	4	1	3	3	0	0
Trd03T14N04	Window	1	1	2	1	1	1	1	0	2	3	1	1
Trd05T02D62	Door	0	1	2	1	1	1	3	0	2	3	1	3
Trd01T12F17	Floor	0	1	2	1	0	2	4	1	3	3	0	0
Option-B													
CompX15T346B	Façade component Type 346B	2	2	2	2	1	2	3	1	1	3	2	3
CompX15T357C	Façade component Type 357C	2	2	2	2	1	2	3	1	1	3	2	3
CompX15T357F	Façade component Type 357F	2	2	2	2	1	2	3	1	1	3	2	3
CompX15T338D	Façade component Type 338D	2	2	2	2	1	2	3	1	1	3	2	3
CompF32T267E	Precast floor slab Type 267E	1	1	2	1	0	1	3	1	1	3	2	3
CompF32T267B	Precast floor slab Type 267B	1	1	2	1	0	1	3	1	1	3	2	3
Option-C													
ModX89T12D	Volumetric module G12	3	2	1	2	2	2	1	2	0	3	3	3
ModX73T16K	Volumetric module G23	3	2	1	2	2	2	1	2	0	3	3	3
ModX73T16K	Volumetric module G34	3	2	1	2	2	2	1	2	0	3	3	3
ModX73T16K	Volumetric module G45	3	2	1	2	2	2	1	2	0	3	3	3
ModX89T12E	Volumetric module G56	3	2	1	2	2	2	1	2	0	3	3	3

Table 11: *Efficiency and Constraints Factors for the Peers for each DFMA Option*

Global_ID	Designer A		Designer B		Manufacturer A		Manufacturer B		Logistics A		Logistics B		Assembler A		Assembler A		
	Design delivery efficiency factor	Design constraints factor	Design delivery efficiency factor	Design constraints factor	Production efficiency factor	Production constraints factor	Production efficiency factor	Production constraints factor	Handling the efficiency factor	Logistics constraints factor	Handling the efficiency factor	Logistics constraints factor	Assembly Efficiency Factor	Assembly Constraints Factor	Assembly Efficiency Factor	Assembly Constraints Factor	Useful Life Efficiency Factor
Option-A																	
Trd02T55W13	0.875	0.125	1.000	0.125	0.750	0.250	0.917	0.250	1.000	2.000	0.750	2.000	1.000	1.000	0.667	1.000	0.250
Trd03T14N04	0.875	0.250	1.000	0.250	0.583	0.500	0.750	0.500	1.000	0.500	0.750	0.500	0.750	0.500	0.417	0.500	0.417
Trd05T02D62	0.875	0.125	1.000	0.125	0.583	0.500	0.750	0.500	1.000	0.500	0.750	0.500	0.917	0.500	0.583	0.500	0.583
Trd01T12F17	0.875	0.125	1.000	0.125	0.750	0.250	0.917	0.250	1.000	2.000	0.750	2.000	1.000	1.000	0.667	1.000	0.250
Option-B																	
CompX15T346B	0.625	0.500	1.000	0.500	0.750	0.750	0.833	0.750	0.625	1.000	1.000	1.000	0.917	0.500	0.583	0.500	0.667
CompX15T357C	0.625	0.500	1.000	0.500	0.750	0.750	0.833	0.750	0.625	1.000	1.000	1.000	0.917	0.500	0.583	0.500	0.667
CompX15T357F	0.625	0.500	1.000	0.500	0.750	0.750	0.833	0.750	0.625	1.000	1.000	1.000	0.917	0.500	0.583	0.500	0.667
CompX15T338D	0.625	0.500	1.000	0.500	0.750	0.750	0.833	0.750	0.625	1.000	1.000	1.000	0.917	0.500	0.583	0.500	0.667
CompF32T267E	0.625	0.250	1.000	0.250	0.750	0.250	0.833	0.250	0.625	0.500	1.000	0.500	0.917	0.500	0.583	0.500	0.667
CompF32T267B	0.625	0.250	1.000	0.250	0.750	0.250	0.833	0.250	0.625	0.500	1.000	0.500	0.917	0.500	0.583	0.500	0.667
Option-C																	
ModX89T12D	0.500	0.625	0.625	0.625	0.667	1.000	0.417	1.000	0.625	1.000	0.875	1.000	0.750	0.500	0.333	0.500	0.750
ModX73T16K	0.500	0.625	0.625	0.625	0.667	1.000	0.417	1.000	0.625	1.000	0.875	1.000	0.750	0.500	0.417	0.500	0.750
ModX73T16K	0.500	0.625	0.625	0.625	0.667	1.000	0.417	1.000	0.625	1.000	0.875	1.000	0.750	0.500	0.417	0.500	0.750
ModX73T16K	0.500	0.625	0.625	0.625	0.667	1.000	0.417	1.000	0.625	1.000	0.875	1.000	0.750	0.500	0.417	0.500	0.750
ModX89T12E	0.500	0.625	0.625	0.625	0.667	1.000	0.417	1.000	0.625	1.000	0.875	1.000	0.750	0.500	0.417	0.500	0.750

5 Results and Discussion

This study involved the combination of suppliers' ratings of experience and expertise with the constraints involved in delivering various methods of offsite construction. As per Mahamadu et al. [73], expertise and experience are important factors in demonstrating competence for BIM qualification during suppliers' selection. The optimisation of offsite construction involves the estimation of the potential value accruable from exploiting opportunities and mitigating risks [16]. In figure 6, the comparative rating of the potential offsite construction peers is shown. The rating is based on the existing record of the suppliers based on their levels of experience and competencies in relation to the delivery of various methods of offsite construction. The consideration of these ratings in the optimisation algorithm will enable us to demonstrate the consideration of value during the selection of DFMA options and the suppliers.

Through the assessment rating, the optimisation algorithm was used to estimate the cost implications of the supplier's level of expertise and experience on the delivery of the DFMA options. It was found that an approach to quantitatively assess the experience and performance of the offsite construction peers and supply chain is essential for understanding offsite maturity and developing delivery strategies for DFMA.

In Figure 6, the scores of the potential peers are shown for the respective DFMA options. It means that peers can be assessed and monitored in terms of the performance growth for various offsite delivery strategies. For example, the detailed design unit cost quoted by designer-Y (£165.45) for option C modules was higher than designer-X (£145.00). However, the level of expertise of designer-X for Option C is also higher than designer-Y. The scale for the experience [0-4] range includes not-experienced (0), slightly-experienced (1), moderately-experienced (2), experienced (3), highly-experienced (4). While the scale for the expertise [0-2] includes non-expert (0), average (1), and expert (2).

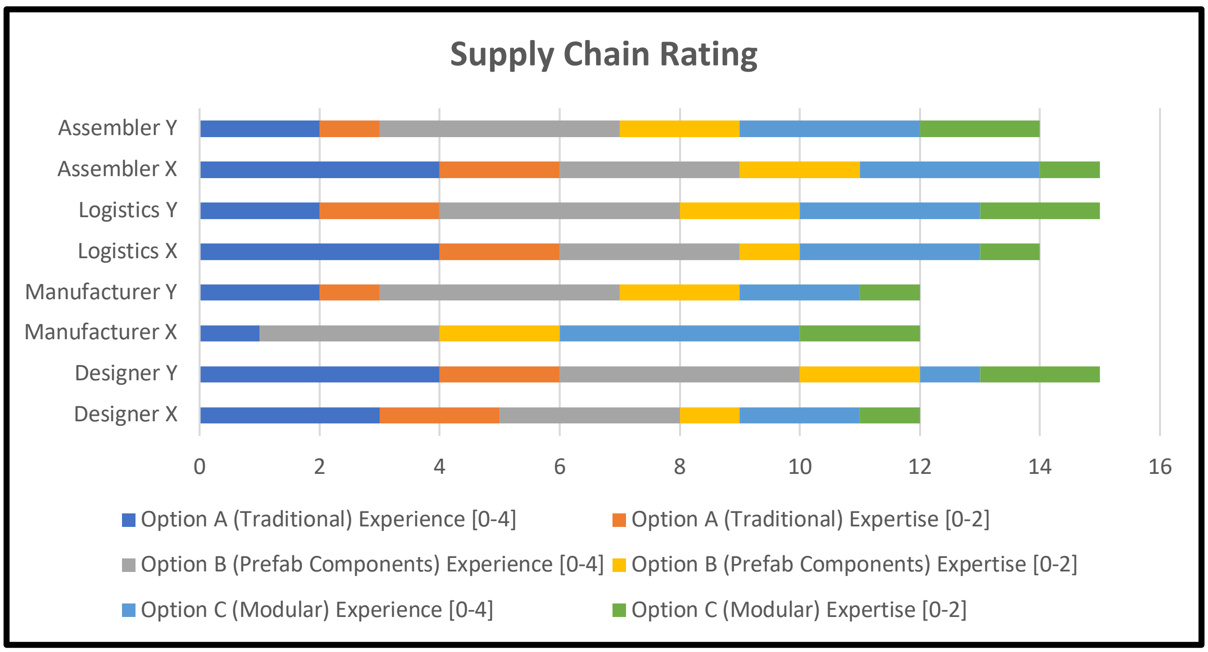

Figure 6: *Overview of peers' competencies for the considered DFMA Option*

5.1 Comparison of DFMA Options and Peers Using Total Cost

While considering the constraints of delivering the various DFMA options, the experience and expertise of the potential peers were also used to calculate the efficiency penalty factors for the options [5]. Consequently, the balance between the constraints and efficiency is a major determining factor for choosing the DFMA option and peers.

Table 12: *Total Costs for DFMA Options according to Peers Quotation*

DFMA Options	Designer-X	Designer-Y	Manufacturer-X	Manufacturer-Y	Logistics-X	Logistics-Y	Assembly-X	Assembly-Y
Option-A	£3,802.86	**£3,651.07**	**£53,955.60**	£56,852.60	£47,759.48	**£47,510.74**	£68,985.02	**£65,298.18**
Option-B	£4,085.00	**£3,304.00**	**£84,250.00**	£90,200.00	£18,825.00	**£18,420.00**	**£39,180.00**	£67,305.00
Option-C	**£16,167.50**	£18,113.18	£94,775.00	**£69,743.25**	**£24,530.00**	£30,105.00	£16,613.50	**£13,826.00**

A preliminary assessment of the optimal DFMA option as well as the peer's combination for delivering the option can be seen in Table 13. Option-C appears to be the best option with a grand total cost of £124,266.75 as compared to Option-A (£170,415.59) and Option-B (£145,154.00). Also, the best combination of peers for each DFMA option to achieve the lowest possible grand total cost also resulted in the combination of designer-X, manufacturer-Y, logistics-X and assembler-Y for the delivery of option-C.

Table 13: *Peers combination for Delivery for DFMA Options*

Option-A	Peer combination	Designer-Y	Manufacturer-X	Logistics-Y	Assembler-Y	
	Total cost	£3,651.07	£53,955.60	£47,510.74	£65,298.18	£170,415.59
Option-B	Peer combination	Designer-Y	Manufacturer-X	Logistics-Y	Assembler-X	
	Total cost	£3,304.00	£84,250.00	£18,420.00	£39,180.00	£145,154.00
Option-C	Peer combination	Designer-X	Manufacturer-Y	Logistics-X	Assembler-Y	
	Total cost	£16,167.50	£69,743.25	£24,530.00	£13,826.00	£124,266.75

A significant limitation of using the peer quoted cost for selecting the DFMA option, and peers' combination is that it fails to consider the efficiency and constraints penalty factors for delivering the DFMA options by the peers. The next section shows the implementation of the proposed optimisation algorithm to determine the total factored costs (TFC).

5.2 Selection of DFMA Options and Peers Using Total Factored Cost

Table 11 shows the efficiency and constraints penalty factors, which were applied to the total costs using equation 2, to determine the cost implication of the suppliers' performance as well as the constraints of delivering the DFMA options.

Table 14: *Total Factored Costs for DFMA Options according to Peers*

DFMA Options	Designer-X	Designer-Y	Manufacturer-X	Manufacturer-Y	Logistics-X	Logistics-Y	Assembly-X	Assembly-Y
Option-A	£2,154.47	**£1,813.12**	£91,863.58	**£75,200.32**	**£342,077.65**	£455,184.08	**£238,360.22**	£342,181.81
Option-B	£4,032.40	**£2,028.20**	£84,391.88	**£76,335.27**	£35,343.53	**£21,594.66**	**£32,062.78**	£86,552.31
Option-C	£26,948.53	**£24,153.32**	**£189,587.92**	£223,223.04	£52,335.90	**£45,878.87**	**£14,770.51**	£23,232.33

In comparison to table 13, table 15 shows the optimal combination of peers for delivering each DFMA option. It is shown that the best option, according to the TFC, is Option-B as against Option-C in Table 13. This shows the significant impact of suppliers benchmarking and constraints assessment for DFMA options in decision making. Also, useful life efficiency, which considers the maintainability, removability, and reusability components was a major determining factor. This is evident from the comparison of the total cost for option-A (£170,415.59) and the total factored cost for option-A (£657,451.31). The optimal peers' combination for the best option, Option-B is to select designer-Y, manufacturer-Y, logistics-Y and assembler-Y.

In the history of construction, cost and time overrun have been persistent among other contributors to low productivity in construction [7]. The most common approach for generating construction cost estimates has been flawed over the years due to inaccuracies and the lack of consideration of essential factors such as expertise and experience of the process [2]. Figure 7 shows the comparison of the quoted costs by the suppliers with the factored cost obtained from the optimisation algorithm, which considered opportunities and constraints that influence project costs. This shows a huge potential impact for the Big-DOR system in improving construction practices through early supplier involvement; pricing rather than cost estimating; open-source data and standard specification, and; manufacturing-based construction [14].

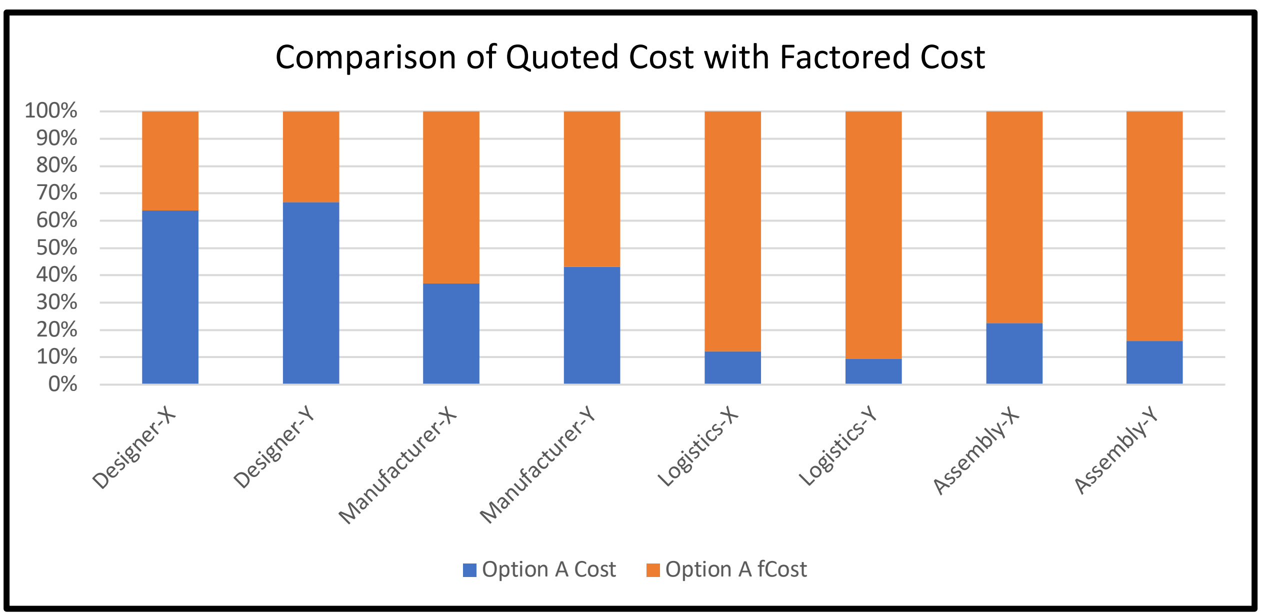

Figure 7: *Comparison of Quoted Costs with Factored Costs*

The level of potential variation in cost can be assumed from the comparison of the quoted cost and the factored cost. For example, the logistics cost for X can vary with up to 900% over the quoted cost due to the level of experience and difficulty in handling such materials for the given method of construction.

Table 15: *Optimised Peers Combination for Delivery of DFMA Options*

Option-A	Peer combination	Designer-Y	Manufacturer-Y	Logistics-X	Assembler-X	
	Total cost	£1,813.12	£75,200.32	£342,077.65	£238,360.22	£657,451.31
Option-B	Peer combination	Designer-Y	Manufacturer-Y	Logistics-Y	Assembler-X	
	Total cost	£2,028.20	£76,335.27	£21,594.66	£32,062.78	£132,020.91
Option-C	Peer combination	Designer-Y	Manufacturer-X	Logistics-Y	Assembler-X	
	Total cost	£24,153.32	£189,587.92	£45,878.87	£14,770.51	£274,390.62

Over the last 20 years, the construction industry has only improved in productivity by 1%, which is far less than the manufacturing industry that has increased its productivity by 1.7 times the construction industry. Many stakeholders have proffered potential solutions for the improvement of productivity in the construction industry. Some of the recommendations for productivity improvement include the adoption of digital technologies in construction, adoption of offsite construction approaches and implementation of big data-driven technologies for decision support, optimisation, and benchmarking.

5.3 Validation of the Proposed Big-DOR System

The proposed Big-DOR prototype was evaluated and validated through two focus group surveys and discussion with experts in the construction industry. Two focus group discussions were held with a total number of twelve participants. The participants were selected using expert sampling method with predetermined selection criteria of a minimum of 2 years' experience in the construction industry and knowledge of at least one of the following: BIM; DFMA; Big data, and; offsite construction. Table 16 shows the details of the focus group participants. The focus group participants comprised of 2 senior architects, 4 senior structural engineers, 2 Quantity Surveyors (QS), 2 prefab suppliers, 1 construction manager and 1 innovation director. Most of the participants (50%) had between 2 to 4 years of experience while 16.6% had between 5 to 9 years, 16.6% had between 10 to 14 years, and 16.6% had over 15 years of experience. All of the participants had knowledge of offsite construction, however, only 50% of them had pre-existing knowledge of DFMA. 83.3% of the focus group participants had prior knowledge of BIM while 66.6% had knowledge of big data application in the construction industry.

Table 16: *Background of Focus Group Respondents*

		Frequency	Percentage (%)
Job description	Architect	2	16.6
	Structural Engineer	4	33.3
	Quantity Surveyor	2	16.6
	Construction Manager	1	8.3

	Prefab Supplier	2	16.6
	Construction Innovation Director	1	8.3
Years of Experience	2 – 4 years	6	50.0
	5 – 9 years	2	16.6
	10 -14 years	2	16.6
	Over 15 years	2	16.6
Expertise	BIM	10	83.3
	DFMA	6	50.0
	Big data	8	66.6
	Offsite construction	12	100.0

The focus group event involved three main steps, viz: (i) demonstration of the Big-DOR prototype; (ii) questionnaire evaluation of the prototype by focus group respondents, and; (iii) discussion about the merits, limitations and areas of improvement of the Big-DOR prototype. The participants were asked to evaluate the Big-DOR prototype based on three main criteria viz: applicability; ease of adoption and commercial acceptability. Table 17 shows the average rating of the proposed system as evaluated by the participants using a Likert scale of (1-5), with 1 being the lowest and 5 being the highest.

Table 17: *Average Rating of the Proposed System based on Validation Factors*

Factors	Question	Average Score (5)	Standard Deviation
Applicability	How applicable is the proposed Big-DOR system to your current line of business?	3.67	1.15
Ease of Adoption	In your opinion, how easy will it be for you to adopt the proposed system for your current operations?	2.75	0.62
Commercial Acceptability	How would you rate the commercial acceptability of the proposed system?	3.75	1.06

Figure 7 shows the evaluation summary of the proposed system by job description of the respondents. The participants were further asked to discuss about the proposed system in line with the pre-established validation factors. The outcome of the focus group discussion is presented below.

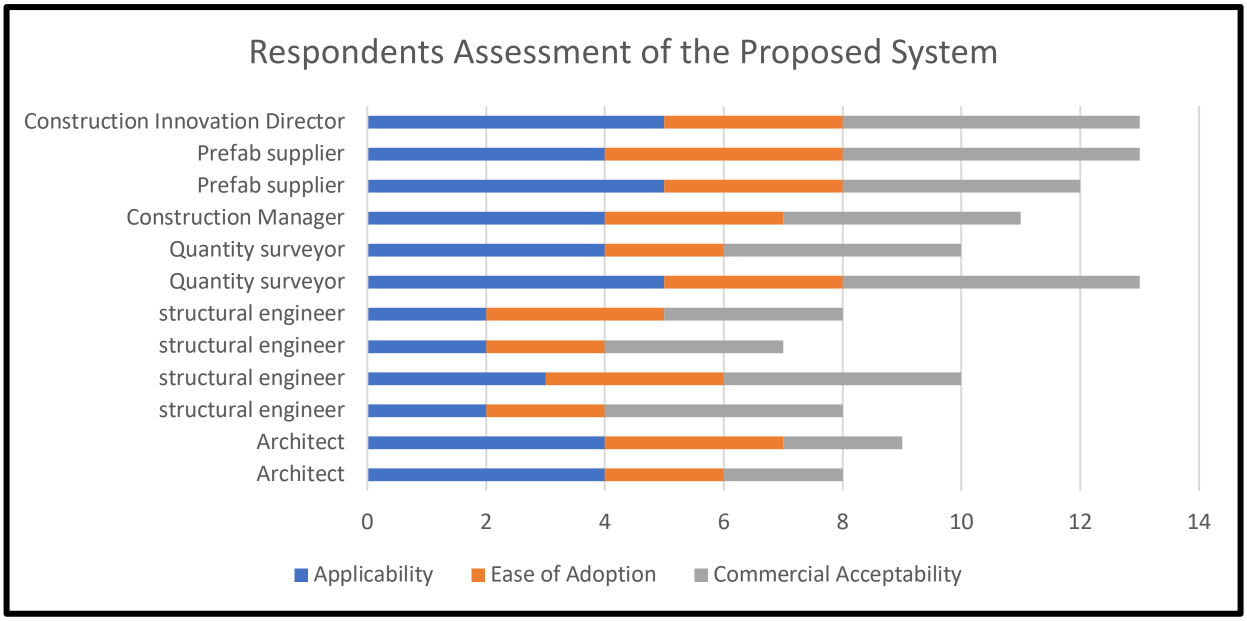

Figure 7: *Summary of Evaluation Results of the Proposed Big-DOR System*

5.3.1 Applicability

The expert participants discussed the practicability of adopting the proposed Big-DOR system as part of the building design process. Two main demerits of the proposed Big-DOR system for the design process that were identified including high design cost and increased design tasks. A structural designer opined that "it is difficult to assess various opportunities offered by suppliers rather we have a specific go-to libraries where we get products that we are familiar with" FG-1. It is clear that the success criteria considered by the designers is mainly focused on design schedule, design budget, technical and functional specification [74]. However, from the perspective of the investment organisation, factors such as profitability, new product line, technological capability and new market opportunities are very important [17]. The experts attributed the merits of the proposed Big-DOR system to the clients' market assessment and cost estimation process. A QS confirmed the practicability of the system, saying "it would be interesting to pass on to the client and contractor a list of suppliers with alternative products with cost and lead time information" FG-1. It was resolved that despite the potential increase in design cost, which arise from comparing alternatives, there is huge potential for significant decrease in cost of construction and an improvement in the efficiency of successful delivery process of offsite construction [74].

5.3.2 Ease of Adoption

The focus group experts discussed about the potential most beneficial user groups for the proposed Big-DOR system. The identified beneficial users include architects, suppliers, project managers, schedulers, cost estimators and clients. A structural engineer suggested that the proposed system would be really embraced by project planners due to the capability to pull important information about prefab object's costs and lead times, he opined that "this is an important plug for 5D BIM" FG-1. While considering the readiness of prefab suppliers to use the proposed Big-DOR system, the prefab contractors considered the "increased visibility" of their products to be a major driver. Theoretically, the increased visibility of prefab products to potential clients/designers will translate to more sales and profitability for the suppliers. The experts further discussed the possibility of the proposed system to be used for a live web-based management of multiple stakeholders to deliver an offsite construction project [39]. While identifying the limitation of the proposed system to the easier adoption for repetitive buildings such as student housings and hospitals, an architect raised the question of the applicability of system for assessing design alternatives of prefab components by multiple suppliers for a BIM model for bespoke buildings. From the foregoing discussion, it is clear that the proposed system, although having its limitations, would enhance the design process for offsite construction by ensuring that functional requirements are met for both the individual prefab components and the whole integrated BIM model [21].

5.3.3 Commercial Acceptability

The expert participants resolved that the greatest commercial potential for the proposed Big-DOR system is to enable competitive bidding of prefab solutions for BIM models. An architect mentioned that "since the detailed specification of components would be coming from the prefab manufacturer, we just need to provide a wireframe BIM model and spatial requirement and then assess the prefab solutions offered by the suppliers" FG-2. The expert participants agreed that there is the need of intelligent information and knowledge management in the process of ensuring modular efficiency of prefab components as well as the integral performance of the components in the whole building system. While discussing the success of similar platforms that offer lesser functionalities, the experts argued that there is a huge potential for commercial adoption of the proposed Big-DOR system.

6 Implication for Practice

The practical implications of this study on various construction stakeholders and the construction industry are presented in this section. Firstly, with a view of transforming current practices, individuals in the construction industry such as construction managers and designers can adopt some of the aspects of the proposed framework to introduce the concepts of DFMA on their projects. For instance, a typical problem usually faced by designers in the construction industry is constant design changes according to changing methods of construction, which can be resolved by ensuring design flexibility. Also, construction managers with a transformational portfolio can leverage on Big-DOR to assess implementation choices during early-stage design. The illustrative case study demonstrated some critical information that should be considered in adopting the offsite construction approach.

The proposed framework is of immense importance to individuals seeking to propose new approaches as it provides adequate information for data integration and for identifying potential opportunities and barriers. From the perspectives of construction project teams seeking to adopt new methods of construction through integrated project delivery, an approach for collaborative delivery can be implemented through big data schema mediation in for a Win-Win optimisation strategy by understanding their complementary strengths and weaknesses in delivering offsite construction. Furthermore, there is a massive opportunity for construction process and product standardisation by identifying the variables that contribute most to the delivery cost and whole-life value.

This study has developed a framework that is capable of solving the age-long productivity challenge of the construction industry by providing a pathway to successful implementation. Consequently, construction organisations can now clearly identify the factors which contribute to offsite construction adoption, which will then inform the implementation policies such as equipment procurement, training and development, digital skills acquisition and so on. Summarily, adopting a big data approach is central to the implementation of offsite construction in the industry, and as such, there is a need for improved data acquisition, sharing and integration with purely manufacturing-based companies. Also, the availability and pervasiveness of quality big data are necessary for optimisation algorithms to maximise the benefits of offsite construction adoption.

7 Conclusion

This study targeted to address the productivity lapses of the construction industry through the adoption of manufacturing approaches from the perspective of big data-driven BIM-based DFMA. A framework for developing a Big Data Design Options Repository for big data integration in early-stage design consideration was proposed. A significant contribution to knowledge in this study is the development of an extensible Big Data Design Options Repository, which allows the optimisation of building design based on design and construction factors such as resource availability, the expertise level of partners, constraints and whole-life cost efficiency. The repository has a practical implication for construction companies that intend to adopt new approaches in gauging their existing capabilities and the feasibility of implementing new methods from the design stage. The Big-DOR is an essential link between project planning database and practical DFMA strategies as well as their cost implication.

The Illustrative case study used in demonstrating the functionality of the system revealed that offsite construction requires a multi-objective optimisation approach, which allows designers to achieve the best prescriptive options in design development. This study has successful integrated BIM, big data, DFMA and offsite construction in a single framework through the proposed Big-DOR system. The proposed system enables the early stage assessment of design alternatives for offsite construction by using big data from multiple suppliers' sources. The proposed Big-DOR system has a considerable potential to facilitate the adoption process of offsite construction, significantly improve the rate of adoption and expand the offsite construction market. Besides aiding in the selection of the most optimal choices and combination of design components, the proposed Big-DOR system also enable the selection of competent suppliers to deliver the optimal components.

A limitation of this study is the lack of adequate data sources because the offsite construction approach is still at its nascent stage in the UK construction industry. However, through this study, adequate data acquisition and BIM integration have been demonstrated to enhance the positive perspective of implementing offsite construction and adopting digital technologies [75]. Further research is recommended to ascertain the disposition of construction clients in adopting offsite construction through big data-driven digital technologies. In summary, the construction industry can benefit from adopting manufacturing approaches to attain similar productivity records with the manufacturing industry. Although, a significant barrier to adopting manufacturing approaches by construction clients include lack of adequate data to assess the manufacturing options. This study demystified the ambiguity between poor data practices and lack of offsite construction uptake and further established a growth cycle to enable continuous improvement between big data-driven approaches and offsite construction.

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