Analysis of Critical Features and Evaluation of BIM Software: Towards a Plugin for Construction Waste Minimisation

Abstract

The overall aim of this study is to investigate the potential of Building Information Modelling (BIM) for construction waste minimisation. We evaluated leading BIM design software products and concluded that none of them currently supports construction waste minimisation. This motivates the development of a plugin for predicting and minimizing construction waste. After rigorous literature review and conducting four focused group interviews (FGIs), we have identified a list of 12 imperative BIM factors that should be harnessed for predicting and designing out construction waste. These factors are categorised into four layers, namely "BIM-core-layer", "BIM-auxiliary-layer", "waste-management-criteria", and "application-layer". Further, a process to carry out BIM-enabled Building Waste performance Analysis (BWA) is proposed. We have also investigated usage of big data technologies in the context of waste minimisation. We highlight that big data technologies are inherently suitable for BIM due to their support of storing and processing large datasets. In particular, the use of graph based representation, analysis, and visualisation can be employed for advancing the state of the art in BIM technology for construction waste minimisation.

Keywords – BIM, Construction Waste Prediction and Minimisation, Design out Waste, Waste Prevention, Big Data Analytics, NoSQL Systems

Paper Type – Review paper

1 Introduction

With huge material intake, construction industry produces large proportions of waste yearly in the United Kingdom (UK) [1]. The main problems that arise from construction waste include landfill depletion, carbon and greenhouse gas emission, huge wastage of energy and raw materials, and increased project cost [2, 3, 4, 5]. The economic and environmental benefits of construction waste minimisation are well understood. Unfortunately, existing initiatives either undertaken by the UK government or the Architecture, Engineering, and Construction (AEC) industry, are largely ineffective [2, 4, 6, 5] due to the ‘end-of-the-pipe’ treatment philosophy, which is a strategy whereby construction waste is considered only after it has been generated [3]. In contrast, a more promising approach, supported by the idea of design out waste research, is waste *prevention* [2, 4, 5].

Building Information Modelling (BIM) is revolutionizing the AEC industry and is becoming the de-facto standard to manage all of the activities of the AEC industry [7]. The superior BIM modelling philosophy enables stakeholders to identify design, construction, and operation related problems prior to its physical construction [8, 9, 10, 9]. While BIM has been highlighted to offer greater opportunities for construction waste minimisation [5, 11, 12], none of the existing BIM software products surprisingly offer any waste prediction and minimisation functionality. Considering the UK government’s BIM strategy of adopting collaborative 3D BIM by 2016 [13], and the importance of designing out waste, there are clearly unprecedented opportunities to employ BIM in plugin development for waste prediction and minimisation at early design stage.

Existing waste minimisation tools such as SMARTWaste™, SWMP, NetWaste, DoWT-B, SmartStart™, SmartAudit™, etc. are used to produce design guides and checklists that are not helpful for designers and contractors to predict and reduce waste at design stage [14, 5, 1]. Also, these tools can only be used after the bill of quantities has been produced, thereby making it too late for designers to incorporate relevant waste minimisation strategies. Additionally, these tools are not interoperable with existing BIM software but are used in isolation, therefore making it unsuitable for designers to minimise waste at early design stages [15, 5].

Based on the aforementioned reasons, this study aims to identify critical BIM features that could be harnessed to implement construction waste minimisation at early design stage. These critical BIM features are categorised into four layers: BIM core layer, BIM auxiliary layer, waste management criteria, and application layer. These critical features also provide a basis for evaluating existing BIM software products and devising a BIM-enabled building waste performance analysis (BWA) process. Further, some technological solutions including big data analytics, NoSQL systems, and semantic technologies have also been proposed to complement BIM, which are deemed useful for developing construction waste minimisation plugin.

More specifically, our research objectives are:

a) *Identification of the critical features of BIM and ICT based technology solutions for construction waste prediction and minimisation.*
b) *Evaluation of BIM software based on the identified critical features to assess their capabilities for plugin development.*

The main stream of knowledge behind this study involves a thorough review of extant literature on BIM software products and Focused Group Interviews (FGIs) to identify critical BIM features. Transcripts of FGIs were used to confirm and validate these criteria using thematic analysis. This study contributes to effective waste management by identifying critical BIM features along with identification of big data solutions that could be tailored to implement robust waste minimisation plugin. Our research contributions include *(i)* an evaluation of leading BIM software products on the basis of their support of critical BIM features, *(ii)* identification of 12 imperative BIM factors that should be harnessed to tackle construction waste, and *(iii)* devising a BIM-enabled construction waste performance analysis (BWA) process, and *(iv)* the study of the implication of using big data technologies for plugin development. This study contains general insights for stakeholders involved in construction waste management. In particular, we offer insights and guidelines for software engineers interested in developing similar kinds of tools for construction waste simulation by leveraging BIM and big data technologies.

Section 2 briefly introduces BIM software products. In Section 3, the research methodology underpinning this study is explained. Section 4 deliberates our layered approach to explain critical BIM features. Section 5 deliberates BIM-enabled building waste performance analysis (BWA) process. Section 6 highlights big data technologies and their promise to solve certain challenges while developing waste simulation tool. Section 7 concludes the paper and gives brief outlook to future research directions.

2 Literature Review: The BIM Design Software Products

In this section, BIM design software products are discussed. While there are a large number of BIM design software products in the market, five leading BIM design products have been chosen, namely Autodesk Revit, Bentley MicroStation, Graphisoft ArchiCAD, Vectorworks, and Digital Project for the purpose of this review. This is because a review of literature has revealed that prevailing purpose-built simulation software, developed for waste, thermal and energy analysis, are mostly based on the platforms offered by one of the selected BIM design software products [14, 16, 17, 4, 18]. This choice is further endorsed by the participants of FGIs who agreed that these BIM design software products are the most popular design tools in UK construction industry and that they use one of these products in majority of their daily design-related activities. Other purpose-built BIM based software, developed for complementing designer's activities such as model checking, 4D, and 5D, are not considered since they are domain-specific and are not designed to cover almost every activity happening at the early design stage; an aspect which this work is focused on. In this section, we provide a brief sketch of the history, key functionalities and limitations (where applicable) of these products.

2.1 Autodesk Revit

Revit, which was introduced by Autodesk in 2002 [19], is the most popular BIM design software among architects, engineers, designers, and contractors. The three key sub-systems of Revit are Revit Architecture, Revit Structural, and Revit MEP, which can be used to design different types of buildings, construct building components in 3D, and annotate components with 2D drafting elements. This information is stored into a centralised database to aid information sharing and collaboration among stakeholders. The centralised database supports concurrent operations on a single building model while maintaining the model's consistency. In particular, Revit offers an intuitive user-friendly interface that enables easy access to user options and manipulations of building models. Revit also provides a large number of in-built building objects that are categorized into "Revit Families". In addition, Revit supports a wide range of building performance simulations, which include energy analysis, environment impact analysis, site planning and analysis, quantity take-off and cost estimation, construction planning and monitoring, etc. All these have encouraged the wide adoption of Revit in the construction industry.

A key limitation of Revit is its in-memory management system that heavily relies on computers' main memory. This significantly slows down building modelling, rendering, and simulation when the project file grows beyond 300MB [16].

2.2 Bentley MicroStation

Bentley Systems offers products for architecture, engineering, infrastructure, and construction. Bentley Systems developed MicroStation that is a file-based system where all actions are immediately written on files hence resulting in less memory overhead [20]. The key sub-systems of MicroStation include Bentley Architecture, Bentley Building Mechanical Systems, Bentley Building Electrical Systems, Bentley InRoads, Bentley Map, and Bentley MXROAD. The users can produce drawings, enable 2D detailing and annotate 3D surface. The MicroStation is multi-platform and provides server capabilities. The user interface of MicroStation is relatively complex and supports advanced features like drag-over operator hints, small cursor, and customized menus. With sophisticated drawing capabilities, designer can view even weights of lines along with text. It supports large number of built-in building objects that can be customized easily.

Since MicroStation has wide range of extensions to simulate almost every aspect of AEC performances; however, these extensions are often partially integrated [16].

2.3 Graphisoft ArchiCAD

Graphisoft initially developed ArchiCAD and introduced it to the market in 1980s [21]. Later in 2007, Nemetschek acquired the company, which is famous for civil engineering applications. ArchiCAD is an architectural BIM application that offers comprehensive design suite for architects, designers and planners with sophisticated support for 2D drawings, 3D modelling, design renderings and visualisations. The user interface of product is relatively easy and intuitive. Different programs are organized in context sensitive menus. A broad range of built-in parametric objects is available. It provides interoperability with large number of applications using Geometric Description Language (GDL), ODBC, and Industry Foundation Classes (IFC). It integrates seamlessly with Bentley BIM server to enable effective collaboration.

It is also an in-memory system like Revit and often incurs scaling problems for larger projects [16] which could be overcome by using DELTA Server extension.

2.4 Vectorworks

This product was initially developed in 1985 by Diehl Graphisoft and is later acquired by Nemetschek who named it Vectorworks. It is CAD software that offers comprehensive tools for the designers and architects [22]. This product targets small firms and provides a variety of tools including Architect, Designer, Landmark, Spotlight, Machine design, and Renderworks. The user-interface across tools is highly integrated, offering customizable menus with rich functionality. Drawing capabilities can associate annotations with model and offers partial bi-directional associativity. It provides wide range of customizable built-in objects. It also offers data exchange with structural, mechanical, energy, environmental, and visualisation applications using Open Database Connectivity (ODBC), API, and IFC.

The key limitations include restricted BIM functionality and lack of Globally Unique Identifier (GUID) or version information with objects [16].

2.5 Digital Project

Digital Project (DP) is developed by Gehry Technologies. It is BIM based CAD software and is file-based scalable system. It offers applications for architecture, engineering, construction, and manufacturing. The key sub-systems include Architectural and Structural, Imagine & Shape, Project Engineering Optimizer, Project Manager, and MEP System Routing [23]. DP has complex user interface that requires adequate knowledge for effectively using its features. The subsystems are consistent and customizable. It offers tools to integrate manufactured product design and has a vibrant support for fabrication. It also supports concurrent users through Apache Subversion (SVN) version control manager. DP offers good interface for importing and exporting object's data in Extensible Markup Language (XML) and spreadsheets. It also provides a powerful API for .NET developers to extend its core functionalities.

However, it has limited support for IFC and other data exchange formats and has limited built-in objects for building design. Drawing capabilities are also not remarkable for architectural purposes relative to other BIM software products [16].

3 Research Methodology

To prepare a comprehensive list of critical BIM features, we thoroughly reviewed the extant literature on waste management, design-out waste, BIM, and BIM software products. These critical factors were validated further by carrying out a qualitative study involving FGIs with professionals from top UK construction companies. Details are discussed in the following sections.

3.1 Literature Search Methods and Inclusion Criteria

Literature on construction waste management in general and construction waste minimisation, design out waste, and BIM in particular was broadly surveyed. Online databases of journals including Waste Management, Automation in Construction, Construction Engineering and Management, Resources, Conversation and Recycling, and Construction Management and Economics, to name a few, have been considered from the year 1995 to 2014. Furthermore, recent reviews of research and books on construction waste minimisation were also taken into consideration [24, 25, 26, 27]. Keywords comprising the search queries include: "construction waste", "construction waste management", "construction waste minimisation", "design strategies for construction waste minimisation", "designing out construction waste", "construction waste design spectrums and principles", "BIM critical features", "BIM for waste minimisation", "potential of BIM for waste minimisation in design stage", "big data in construction", "big data for construction waste minimisation", and "BIM based big data analytics for construction waste minimisation". Overall, 200 publications were selected. Active research groups where the issue of waste minimisation has been investigated were also identified. While our literature search is not exhaustive (not all publications have been incorporated due to the great breadth of published literature), we believe that our literature search has captured a representative balanced sample of the related research.

Studies where the application of BIM is primarily investigated to resolve construction related challenges were included. Studies that were not focused on waste minimisation in design stage were excluded. This reduced the number of published articles to 115. Each of these 115 publications was further scrutinized for their relevance by reading their abstract, introduction, and conclusions. Eventually, 91 publications were selected, for review in this study. These publications were further classified into three distinct categories of interest, which include: *(i)* Construction waste minimisation in design stage, *(ii)* BIM, and *(iii)* Application of ICT techniques like big data, visual analytics, semantic technologies, and decision support systems in construction waste prediction and minimisation.

It has been noticed that although literature has recently highlighted the importance of using BIM for construction waste minimisation [6, 5], existing BIM solutions do not incorporate waste minimisation functionality. This has motivated our study in which we explore the various technical aspects of critical BIM features for plugin development. We contributed to the literature by identifying twelve (12) critical BIM features for construction waste prediction and minimisation, out of which ten (10) features—"Object Parametric Modelling", "Design", "Visualisation", "Data", "Holistic", "Lifecycle", "Interoperability", "Technology", "Cost Benefit Analysis", and "Plugin Support"—came from literature review.

3.2 Focused Group Interviews (FGIs)

To validate critical factors, and the need to understand multiple viewpoints of dealing with construction waste, FGIs were used to bring-together real-life experience of industry practitioners. The choice of FGIs was made as compared to individual interviews with participants, since it allows participants to express their own experiences as well as respond to the views expressed by others. Thus, FGIs enabled group thinking and promote shared beliefs with deeper insights and broad range of perspectives on the issue of waste minimisation in a short period of time. In addition, the validity and applicability of critical BIM features is also authenticated before they were used to develop a holistic BIM framework for waste prediction and minimisation. The perception and expectation of industry practitioners was also better understood. In order to maintain openness and ensure contributions of all participants the FGIs were proactively supervised by the research team.

Four FGIs were conducted with a total of 24 participants from the sustainability, lean, design, and supply chain engagement teams. The participants were selected based on their responsibilities relevant to waste generation and for adopting best practices for waste management.

Table 1: The Details of Participants, their background and experience in FGIs

S.No.	Team	Expectations/ Themes	Participants	Experience in BIM (Years)	Experience in AEC (Year)	Firm Type	Background	Role
1	Design	– Design factors that contribute to waste. – BIM role in design activities – Critical BIM design related features	6	8	12	Consultant	Civil Eng.	BIM Manager
2				15	20	Consultant	Structures	Structural Designer
3				12	15	Consultant	Civil Eng.	BIM Director
4				7	10	Consultant	Architecture	Senior Designer
5				12	15	Consultant	Architecture	Technical Manager
6				10	15	Consultant	Architecture	BIM/CAD Technician
7	Sustainability	– Current waste management strategies – Waste monitoring, quantification, segregation tools & approaches	6	10	15	Contractor	Accountant	Waste Manager
8				8	12	Consultant	Architecture	Senior Designer
9				5	10	Consultant	Civil Eng.	BIM Manager
10				3	12	Contractor	Env. Eng.	Waste & Recyc. Mgr.
11				10	15	Consultant	Civil Eng.	Sustainability Director
12				7	12	Consultant	Civil Eng.	Manager Lean Const.
13	Lean	– Lean thinking techniques and practices – Role of design and BIM in waste minimisation	6	-	5	Consultant	Project Mgmt	Project Mgr. BIM
14				6	10	Contractor	Civil Eng.	BIM/CAD Technician
15				7	7	Consultant	Civil Eng.	Site Manager
16				8	12	Consultant	Env. Eng.	Waste & Recyc. Mgr.
17				7	12	Contractor	Civil Eng.	Waste Manager
18				12	15	Consultant	Civil Eng.	BIM Director
19	Supply Chain Engagement	– Suppliers factors that contribute to waste – Role of BIM for contractors and suppliers	6	5	2	Contractor	Accounting	Site Manager
20				4	10	Contractor	Business	Supplier
21				2	15	Contractor	Civil Eng.	Site Engineer
22				6	10	Contractor	Business	Principal Contractor
23				15	20	Contractor	Architecture	Senior Designer
24				3	9	Contractor	Env. Eng.	Waste Manager

The discussions were focused on how teams have employed tools in mitigating construction waste in different projects and how can BIM software products influence the dilemma of construction waste. Open discussions were encouraged. Interactions were recorded and later compared with notes taken to ensure necessary information was captured. The details of FGIs are show in Table 1.

Transcripts were segmented for thematic analysis to compile a comprehensive list of critical BIM factors. Coding scheme was structured in a way to identify various waste management and technical related issues associated with plugin development and usage. The critical factors that were identified from literature were also confirmed by FGIs. Additionally two critical factors were identified besides those acknowledged by literature, such as “Bi-directional Associativity” and “Intelligent Modelling”. For the sake of this study, a thematic analysis—that is an exploratory qualitative data analysis approach—was employed [28].

An exhaustive comparison of all transcript segments is carried out to examine structure and relationships among themes. The process began with familiarization with data by reading transcripts several times in search of meanings, reoccurring patterns and repeating issues. Similarities and patterns among the codes were also identified for categorising the data. Finally, thematic map was generated to provide an accurate representation of the transcripts.

4 Critical Features of the BIM Software Products for Construction Waste Minimisation

This section deliberates critical features of BIM that could be harnessed to implement waste prediction and minimisation in building projects. The discussion often tends to emphasize technical aspects of critical features, leading to detailed specifications for plugins (software) development [29]. The discussions are started with transcript segments taken from FGIs. Furthermore, the leading BIM software products (discussed earlier in section 2) are evaluated to investigate the extent to which they support these critical features. These findings are summarized in Table 2.

This evaluation will provide basis for selecting appropriate BIM software for future plugin development. This study has identified 12 critical BIM features. To better explain the concept, a layered approach is adopted as illustrated in Figure 1. The various layers, where critical factors, were grouped are listed below:

1) BIM Core Features Layer
2) BIM Auxiliary Features Layer
3) Waste Management Criteria Layer
4) Application Layer

These layers, and the features they encompass, are explained in greater depth in the subsequent sections.

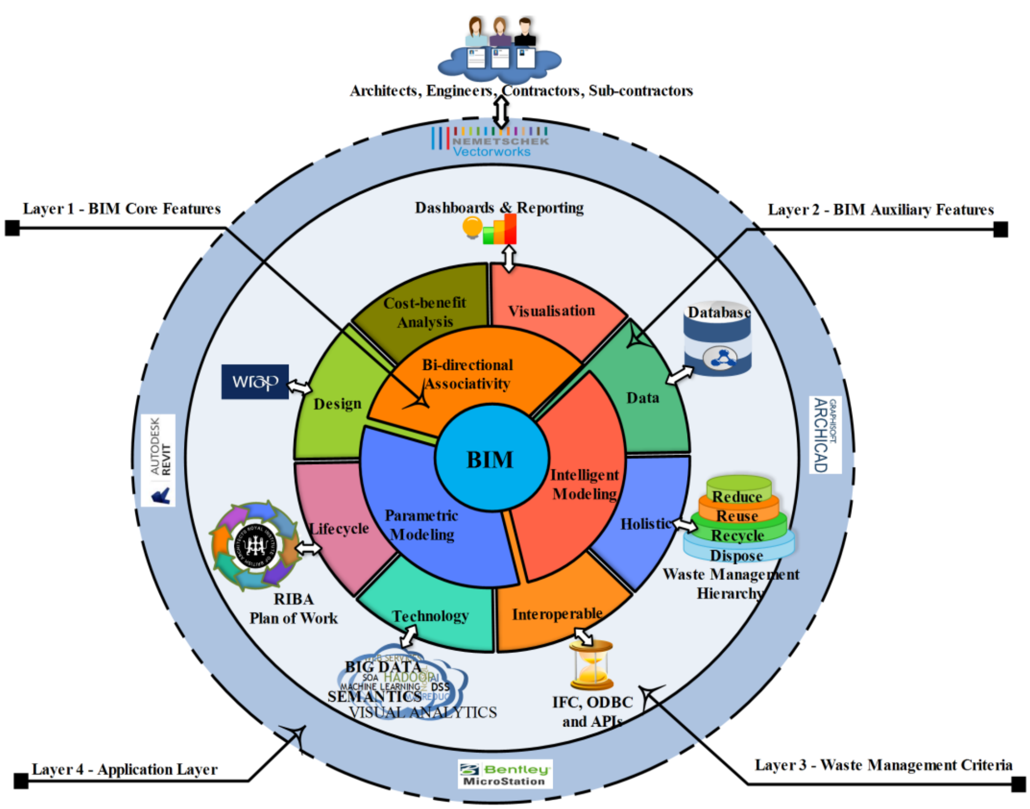

Figure 1: Critical Features of BIM for Construction Waste Prediction and Minimisation

4.1 Layer 1 – BIM Core Features Layer

This layer comprises three BIM features, which are fundamental requirements for any software to become BIM compliant [16]. These features also provide the basis for computational building model.

4.1.1 Object Parametric Modelling

"The definition of waste changes with context e.g. waste from perspective of virgin materials used into construction process is different from the rest. This context driven information could be better modelled through object parametric modelling of BIM."

Building model is comprised of software objects that reflect behaviours and attributes of real-world materials, assemblies, and equipment. To imitate design intent, these objects are assigned geometric and non-geometric data in building model. Parametric modelling is specialized methodology to capture design intent in building model using parameters and rules [16, 30]. This novel representation ensures that design intent is always preserved in response to user or contextual change (Betting, 2001; Jonathan; 2001).

The domain knowledge related to design, procurement, and construction is indispensable for the construction waste prediction and minimisation. The parametric modelling of BIM may be augmented to entrench waste-specific domain knowledge in building objects since it is considered as a suitable tool to embed domain knowledge in the building objects [31]. Likewise, waste estimation involves calculating the waste at different levels of aggregation (like wall, room, floor, and building). One of the characteristics of parametric modelling is its built-in capability for aggregation of quantities [16] and can therefore be tailored to implement the levels of aggregation in construction waste estimation. Moreover, construction waste minimisation encourages excluding the building objects that are likely to generate more waste thereupon the object feasibility based constraint specifications of parametric modelling which guides when certain changes violate the feasibility of given object [16], could be extended to implement eliminating objects that generate beyond a threshold of construction waste.

Since object parametric modelling is a core feature, almost every BIM software product supports this feature to varying extent. To attain this feature in plugin for construction waste prediction and minimisation, APIs provided by these products would be utilized.

4.1.2 Bi-directional Associativity

"The bi-directional associativity would certainly go with the solution to propagate the impact of any materials or design related change for instant feedback."

The building components, views, and annotations are key elements of building model[1]. Changing one of these elements may cause modifications to either of the building elements. Some of examples of such changes include stretching wall or placing new components in model. Accurately assessing and then applying the impact of these changes in building model is conceived to be laborious and non-trivial task. As such, bi-directional associativity complements object parametric modelling by calculating the impact of design changes and then propagating these changes automatically to the relevant parts of the building model accurately in real-time [16, 30]. Internally, the network of building elements and their relationships is maintained which is used to resolve changes later.

Different construction techniques, construction materials, and design alternatives affect the amounts of construction waste in the building model. Existing solutions of construction waste minimisation are unable to turn up this effect instantly at the design stage to check the suitability of technique, material, and design alternative. A sophisticated change management mechanism is needed that enables designers to foresee the impact of these changes instantly and to choose suitable options that are likely to generate less waste. In this context, the bi-directional associativity is relevant and can be customized to incorporate sophisticated change management functionality.

The BIM software products offering object parametric modelling also support bi-directional associativity, as these features complement each other. The APIs provided by

[1] Building components include walls, roofs, doors, windows, and floors; Views include schedules and sheets; Annotations include text notes, dimensions, and spot elevations.

these products could be also be utilized to implement this feature into waste prediction and minimisation plugin.

4.1.3 Intelligent Modelling

"Keeping in view the underlying complexity of waste minimisation, we need to exploit BIM capabilities, particularly, the intelligent modelling, for embedding waste related data into the building model."

Although geometric data is essential for graphically representing building objects but there is large number of supplementary data including dimensions, quantities, relative locations, schedules, or specifications that is required for different analytical and evaluation purposes. The ability to attach supplementary data once with building objects and extract it repeatedly for different analytical and reporting purposes is called intelligent modelling [16, 30].

Technically, geometries or properties are used to link data to building objects. As design convention and best practice, small fraction of purely geometric data goes to geometries while the rest of data is better modelled through object properties either as textual values or as links to external sources. Linking objects to a wide array of external sources enhances semantic capabilities of building objects, therefore making objects richer containers of information. Examples include linking an object to own schedule or attaching an object to its specifications.

The construction process deals with large number of construction materials. These materials possess several auxiliary characteristics that are vital to accurately predict and minimise construction waste. A key implementation milestone includes accurately storing

Table 2: The Capabilities of BIM Software Products to Support Critical Features of Waste Prediction and Minimisation

Critical BIM Features & BWA Process	BIM Design Software Products	Autodesk Revit	Bentley Microstation	Graphisoft ArchiCAD	Vectorworks	Digital Project	Focused Group Interviews (FGIs)	References
1.	**Layer 1 – BIM Core Features Layer**							
1.1	Object Parametric Modelling	√	√	√	√	√	**1, 3**	[16, 30, 31]
1.2	Bi-directional Associativity	√	√	√	√	√	**1, 3**	[16, 30]
1.3	Intelligent Modelling	√	√	√	√	√	**2, 3,4**	[16, 30]
2.	**Layer 2&3 – BIM Auxiliary Features & Waste Management Criteria Layers**							
2.1	Design	√	√	√	√	√	**1, 2, 3, 4**	[32, 6, 3, 4, 2, 15]
2.2	Visualisation	√	√	√	√	√	**1, 3, 4**	[16, 33, 34, 35]
2.3	Data	√	√	√	√	√	**2, 4**	[36, 37, 38, 39]
2.4	Holistic	√	√	√	√	√	**1, 4**	[26, 40, 4, 5]
2.5	Lifecycle	√	√	√	√	√	**2, 3, 4**	[16, 5, 26, 40, 4, 41, 26, 42, 18, 43]
2.6	Interoperability	√	√	√	√	√	**1, 2, 3**	[35, 16]
2.7	Technology Centric	√	√	√	√	√	**2, 3, 4**	[44, 45, 46, 47, 48, 49, 33, 50, 51]
2.8	Cost Benefit Analysis	×	×	×	×	×	**3, 4**	[52, 53, 16]
3.	**Layer 4 – Application Layer**							
3.1	Plugin Support	√	√	√	√	√	**1, 2, 3**	[16, 5]
4.	**BIM based Building Waste Performance Analysis (BWA) Process**							
3.1	Building Model Analysis	×	×	×	×	×	**1, 2, 4**	[54, 55, 56, 57]
3.2	Waste Prediction	×	×	×	×	×	**2, 3, 4**	[25, 40, 58, 59, 60, 61, 62, 63, 64]
3.3	Waste Visualisation	×	×	×	×	×	**1, 3, 4**	[65, 66, 67, 68, 69]
3.4	Waste Minimisation	×	×	×	×	×	**1, 3**	[16, 4, 6]

this high volume of multifarious data with building objects in materials database and then efficiently querying it during the process. The role of intelligent modelling comes in play that could be democratized to implement proportion of materials database using objects properties. This will achieve the significant fraction of implementation. Just as in the case of parametric modelling, this feature could be achieved, for the development of construction waste prediction and minimisation plugin, by importing the relevant APIs provided by BIM software products.

4.2 Layer 2&3 – BIM Auxiliary Features and Waste Management Criteria Layers

This section discusses two layers. Layer 2 contains auxiliary BIM features, which could be extended to augment core features of BIM software products. As such, these auxiliary features on layer 2 could be exploited to support waste management at design stages using corresponding waste management criteria on layer 3. These proposed criteria define extensions that shall be considered for effective waste prediction and minimisation.

4.2.1 Design

"Most of the construction and demolition (C&D) waste is due to design changes, lack of dimensional coordination, and standardization of materials."

The process of waste minimisation requires trying out different design alternatives and choosing the ones with lesser waste output. Design changes proposed in response at later stage of the project tends to cause rework and ultimately leads to material and time wastage [32]. Hence, any attempt to minimize waste in the later construction stages becomes costlier, ineffective, and impractical [6]. This is the key reason behind the failure of existing efforts to tackle construction waste because they are mostly based on the remedial measures after waste is generated and are designed to work in later stage of the construction project [3]. As such, design stage, in contrast to construction stage, has greater potential to accommodate design changes and embraces experimenting different design alternatives for waste efficiency [4].

To truly achieve construction waste minimisation, the tools and techniques should aim to prevent construction waste [3, 4] because it is the most anticipated waste management approach [2]. Since waste minimisation at design stage is likely to promote the idea of waste prevention, it is highly desirable [5]. Furthermore, it is also realised that design decisions correlates the amounts of construction waste generated [4]. Moreover, to be more precise, inappropriate design decisions inculcate almost 33% of construction waste [70]. In short, design stage is ideal to implement waste prediction and minimisation functionality. It also sets the stage for zero waste particularly for 'design-induced' waste management, which would be a major breakthrough (if achieved) for the construction industry. However, keeping in view complexities underlying construction process, achieving waste minimisation at design stage is non-trivial and has myriads inherent intricacies that need to be explored for effective construction waste minimisation [15].

To implement waste minimisation in the design stage, Waste and Resource Action Plan (WRAP) has identified following five design principles (see Figure 2) that need to be considered for resource efficiency:

1) **Design for re-use and recovery:** This design principle encourages reuse of structural elements and building materials repeatedly as-is (re-use) or as new products (recycle).
2) **Design for resource optimisation:** Under this design principle, those aspects of the design are investigated that can result in less consumption of materials, water, and energy during construction and operations of building.
3) **Design for off-site construction:** This design principle advocates modularity in the design and encourages considering volumetric properties of elements to support prefabrication of structures, components, and panels.
4) **Design for resource efficient procurement:** This design principle ensures resource efficient procurement methods are chosen, specification of materials is simplified, the materials are selected that are likely to generate less waste, and procurement routes are properly optimized.
5) **Design for the future:** This design principle considers specifying building materials and structural elements that are flexible, de-constructible and durable. They require

less maintenance efforts and can be easily dismantled, reused, and recycled during demolition.

The current BIM software products mostly support design related activities [43, 71], hence could be improved to support activities relating to construction waste prediction and minimisation.

4.2.2 Visualisation

"To ensure effective collaboration, waste should be visualised such that all the participant can not only see and understand it but can also react to the situation by changing design strategies and materials selection."

Visualisation combines interactive visual techniques for data analysis with human background knowledge, intuition, and creativity to discover latent trends in support of effective decision-making [72, 34]. In the context of construction, essential aspects of the building model are visualized, better understood for potential issues, and right decisions are taken to resolve them prior to any fieldwork [16, 35].

Although visualisation is relevant throughout lifecycle of building, it is of immense importance to waste prediction and minimisation. It could be helpful in the following ways. *1)* It provides true enabling environment to experiment design changes for waste efficiency; *2)* the materials could be better labelled with associated waste potential which enables designers to intuitively choose appropriate materials with lesser waste output without undergoing complex optimizations for materials selection; *3)* using visual inspections, designers can also identify building elements that are likely to yield more waste hence can be discarded or replaced with alternative waste efficient elements; *4)* lastly, it sets the stage

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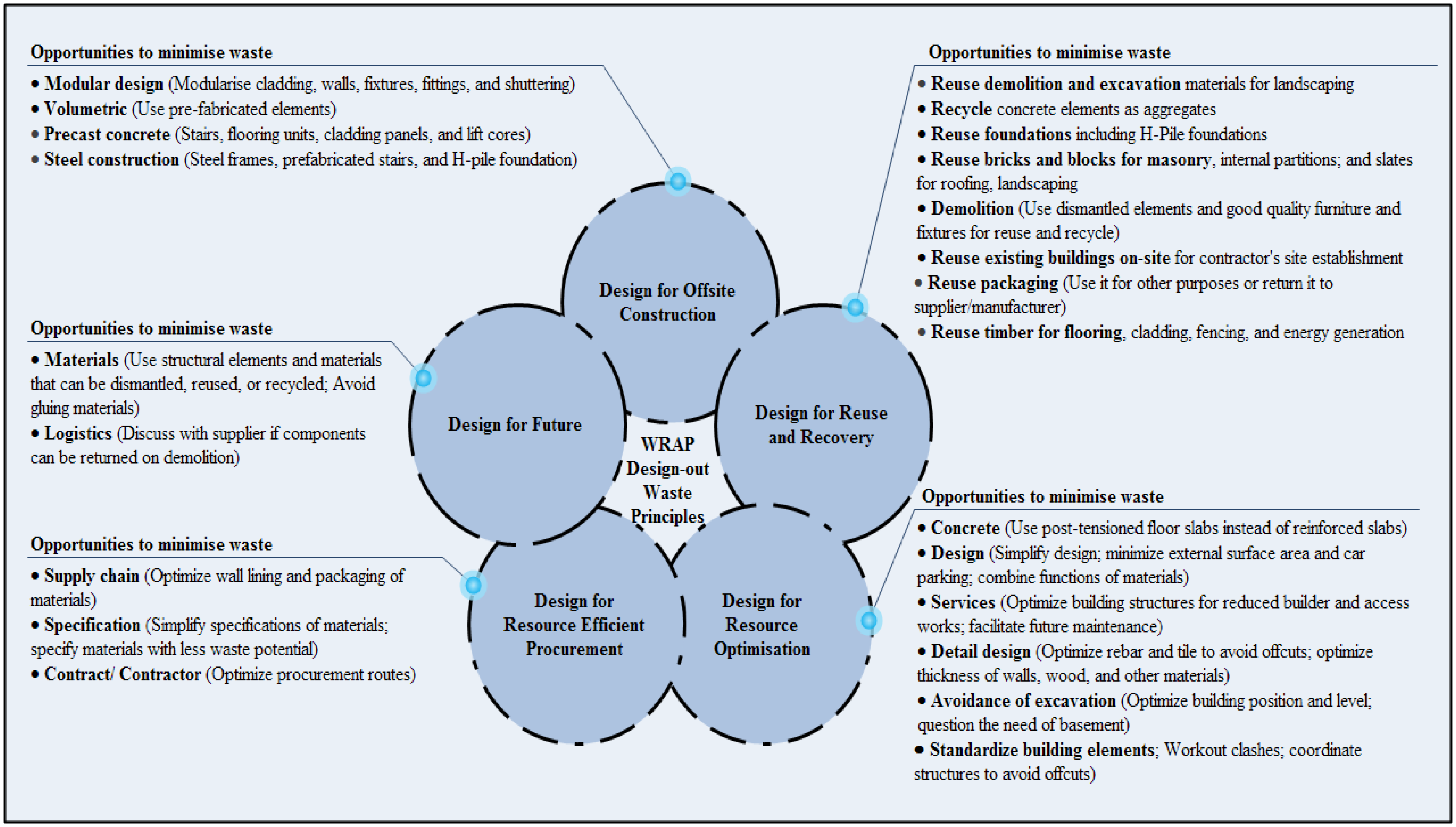

434 **Figure 2: WRAP Design Principles to Minimise Construction Waste**

for design optimisation where multiple designs are merged together and best waste efficient design strategies and building elements are combined to produce superior design that tends to generate minimum construction waste. The BIM software products offer visualisation to varying extent, mostly in the form of photo-renderings, animations, walkthroughs, and shaded 3D views of building design. These capabilities could be further harnessed to accurately visualize construction waste such that designers do not only see waste as 'object' attached to building elements but could also respond to it by changing design strategies, materials, and construction methods.

4.2.3 Data

"Although, waste minimisation is a complex issue; however, if what causes waste is known, then, they could be factored into waste management tools; to achieve this, the tool shall certainly consider multifarious data sources"

The equation of construction waste estimation cannot be confined to just aggregating volumetric data of building model, but certainly it should consider exhaustive list of multi-dimensional criteria to accurately estimate construction waste. However, it is unlikely that a single BIM database contains all relevant data required to predict and minimise construction waste [37]. As such, access to number of diverse data sources pertaining to design, procurement, and construction is essential. In addition to this, supporting domain knowledge is integral to understanding context of data and to enable semantic reasoning for analysing and estimating construction waste precisely [36]. Therefore, the issue of construction waste prediction and minimisation is conceived as data driven and knowledge intensive in nature.

The capabilities of existing BIM software products could be uncovered by utilising their underlying database of building information [38]. Majority of the design related data is readily available and can be queried for different analytical and evaluation purposes. However, special extensions are required in this regard. Particularly, not a single BIM software product offers comprehensive materials database containing all the properties required for the process. Furthermore, hardly would any BIM software product store the design, construction, and procurement related domain knowledge [39]. Since detailed data and appropriate domain knowledge is at the crux of this process, this therefore calls for the extension of the databases of existing BIM software products to capture additional data and relevant knowledge pertaining to design, procurement, and construction.

4.2.4 Holistic and Lifecycle

"While discussing the definition of waste, it is highlighted that definition changes with context e.g. waste from the perspective of virgin materials used into construction process is different from the rest. It arises throughout the lifecycle of building in different forms."

Construction waste is influenced by large number of factors spanning throughout the lifecycle of construction project [5]. Existing waste estimation models are unitary in the sense that they often consider volumetric information to estimate construction waste [26, 40, 4]. More holistic criteria has to be considered, including:

1) Waste management hierarchy–a generic waste management framework that offers set of logical strategies to deal with construction waste [2]. This initially proposes adopting preventive measures to reduce construction waste and then recommends appropriate measures to reuse, recycle, and eventually as last resort landfill construction waste [41].

2) WRAP design principles–as discussed earlier in Figure 2, also offers a number of opportunities to minimise waste at design stage. To simplify this, a comprehensive computational model of waste estimation is needed that considers all factors leading to construction waste.

Furthermore, different construction phases are interrelated and activities carried-out in one phase influence activities of other phases [26]. Since Royal Institute of British Architects (RIBA) Plan of Work proposes generic lifecycle for construction projects irrespective of project size, practices, and procurement routes [42], juxtaposition of waste management hierarchy with RIBA Plan of Work stages even brings interesting opportunities for construction waste minimisation. Additionally, roles of different participants of construction projects cannot be ignored. Their early involvement in design stage and providing them with appropriate tools to evaluate and give feedback on relevant aspects of the design could help to tackle this issue effectively.

Since BIM software products encourage integration of roles of all stakeholders in building project and support activities undertaken across the lifecycle of construction project [18, 43], they support holistic and lifecycle driven approach to plugins development for waste prediction and minimisation.

4.2.5 Interoperability

"The solution shall work with normal design tools currently prevailing in the industry but we are expecting more collaboration with supply chain."

As discussed above, construction projects involve multiple teams, which often use heterogeneous applications to carry-out different tasks. Exchanging data seamlessly among these applications is at the heart for successful project delivery [35]. Interoperability is the ability of software application to exchange data with heterogeneous software applications to streamline and/or automate workflows [16]. Since higher level of coordination and collaboration is conceived essential for successful project delivery, interoperability of the underlying software has pivotal role to achieve the greater coordination and collaboration.

In the context of construction waste prediction and minimisation, interoperability allows reading required data from different data sources (including design, procurement, and construction) for analysing and evaluating construction waste. After waste is quantified successfully, the waste related details are then exported back to the data sources where designers could visualize waste in their native tools for analytics and understand trends of how waste is arising in building design and how it could be better approached for minimisation.

BIM software products provide the three ways to achieve interoperability. Firstly, ODBC, as a standard API for accessing the DBMS of a software package. Secondly, set of programs in the form of API, that is used to develop plugin for BIM software products. Lastly, open data exchange standards, which are vendor-neutral data exchange formats and have industry-wide acceptance like IFC and gbXML. Table 3 summarizes interoperability of existing BIM software products.

4.2.6 Technology

"Only with the help of innovative and latest technologies, this complex issue of construction waste could be surpassed."

Technological advancement in ICT has affected all aspects of society and almost every industry. The following emerging technologies are of vital importance here since they are known to solve similar kind of problems prevailing construction waste prediction and minimisation.

Big data refers to data that is not conveniently processed by traditional database and data warehousing technology [73]. It often relates to the emerging frameworks for storing, processing, and analyzing such (voluminous, varied, and high-velocity) data, comprising diverse sources and representations, scalably and reliably using a cluster of commodity servers [45, 44]. One of the reasons for widespread adoption of big data is its capabilities for enabling analytics that includes exploratory and descriptive analytics. This helps to model and understand latent trends as well as predictive analytics, which are aimed at forecasting future events [46, 47].

Specifically the field of 'visual analytics' that came into being originally to solve hardest problems faced by government, business, and science but later realized to have broader applicability to solve generic IT related problems. It is hybrid approach that combines best of automated reasoning and visualisation [48, 49]. It brings intelligent automated algorithms and gigantic computational capabilities of contemporary computers together with human background knowledge and intuition to find good candidate solution with higher level of trust [51, 68, 50]. Visual analytics based systems empower analytical reasoning of analysts by maximising their abilities to perceive, understand, and reason about highly complex and dynamic data and situations [33, 74, 34, 75].

The requirement of a robust material database that has the potential to answer complex queries referring to the properties of materials, along with a comprehensive support for interactive visualisation is vital for enabling designers to proactively analyse and respond to construction waste in the early design stage. This calls for incorporating number of big data components to be employed during the development of this plug-in. We discuss the technological solution for waste management sketched here in brief in much more detail in section 5.

4.2.7 Cost/benefits Analysis

"It is always cheaper to reduce waste but currently we have no means to prove it."

Cost/benefits analysis is dominating factor, influencing adoption of software in industry [52, 53]. This factor could play an important role by changing the beliefs of stakeholders regarding waste prediction and minimisation in the following ways.

It is argued that there are situations when generating waste is conceived cheaper than avoiding waste e.g. standard-sized materials versus custom-sized materials. The custom-sized materials produce less construction waste but incur overhead cost of manufacturing whereas standard-sized materials are cheap but generate construction waste by off-cuts. Since cost of materials outweighs benefits of waste minimisation, companies prefer cheaper option of standard-sized materials and generate waste. Therefore, there exists pertinent relationship between commercial and sustainability. The belief that waste minimisation is costlier is mythical and this mind-set could be changed by putting efforts to bring together commercial, design, and procurement factors into BIM software for waste prediction and minimisation and it could be shown that waste minimisation is indeed always cheaper option in all the cases.

Since BIM supports cost-estimation functionality at early design stage [16, 76], this tool will leverage on it to estimate the cost/benefits of every design related change made by the designers.

4.3 Application Layer

"This whole functionality would be available as single software plug-in, integrated and run through native design BIM software products."

This layer represents BIM based plug-in for construction waste prediction and minimisation. Programs supported by plug-in will be written using Software Development Kits (SDK) of BIM software products. The purpose of plug-in development is to extend functionality of existing BIM software products for construction waste prediction and minimisation. This plug-in can be seamlessly integrated with the menu system of underlying BIM software products using standard access points and methods supported by these platforms. Users will interact with plug-in in their native designing tools.

Table 3: The Capabilities of BIM Software Products to Support Interoperability

BIM Products / Project Data	Autodesk Revit	MicroStation	ArchiCAD	Vectorworks	Digital Project
File Extension	*.rvt	*.dng	*.pln	*.vmx	*.CATProduct
Application Programming Interface (API)	Revit Open .NET API	MDL API	Geometric Description Language (GDL)	API + Vectorscript scripting language	VB based .NET API
Open Standards					
– Architectural Model	IFC, RVT, DWG, DGN, PLN, NWD	IFC, DNG, DWG	IFC, DWG, DGN	IFC	IFC, DWG
– Structural Model	IFC, CIS/2	IFC, CIS/2	IFC	IFC	IFC, CIS/2
– CAD Data	DXF, DWG	DWG, DXF	DWG, DXF	DWG, DXF	DWG, DXF
– GIS Data	SHP, KMZ, WFS, GML	SHP, KMZ, WFS, GML	SHP, KMZ, WFS	SHP, KMZ, WFS	-
– Civil Engineering	LandXML, DWG, DGN	LandXML, DWG	LandXML, DWG	DWG	DWG
– Cost Estimating	XLSX, ODBC	ODBC	ODBC	ODBC	ODBC
– Visualisation Model	FBX, SKP, NWD	SKP, Rhino	MOV, SKP, WMF	SKP	-
– COBie Data	IFC, XLSX	IFC	IFC	IFC	-
– Scheduling Data	P3, MPP	P3, MPP	P3, MPP	MPP	P3
– Energy Analysis	IFC, gbXML	IFC, gbXML	IFC, gbXML	IFC, gbXML	IFC, gbXML
– Site Imagery	JPG, PNG	PNG	PNG, JPG, BMP, TIFF	BMP, JPG, PNG	GIF, PNG, TIFF

5 BIM-enabled Building Waste Performance Analysis (BWA)

The term Building waste performance analysis (BWA) is coined here to capture the whole process of employing the BIM for predicting and designing out construction waste. The BWA is mainly comprised of four key steps namely, *(i)* building model analysis, *(ii)* waste prediction, *(iii)* waste visualization, and *(iv)* waste minimisation. Transcripts of the FGIs are used to develop the phases of the BWA, which are given at the beginning of these phases. The BWA process is illustrated in the Figure 3 as shown below.

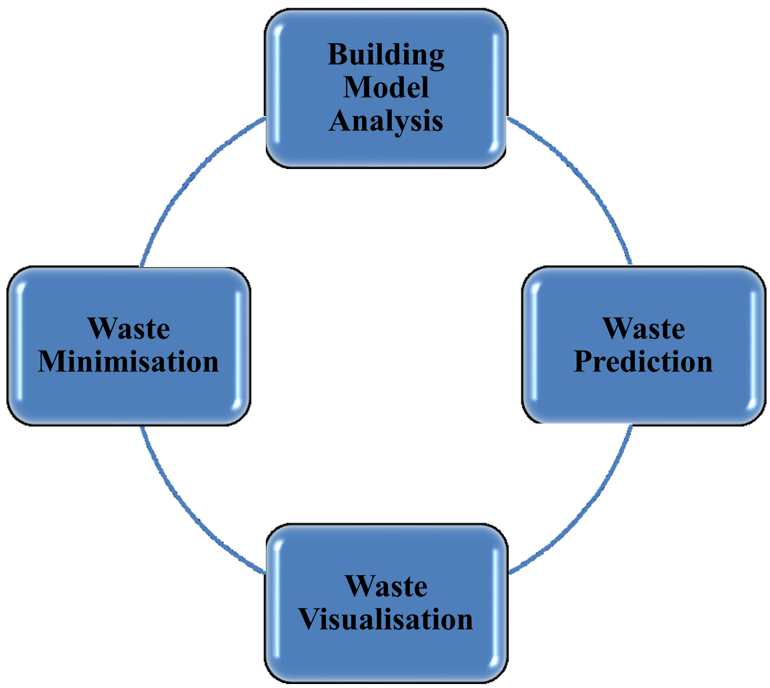

Figure 3: BIM based Building Waste Performance Analysis (BWA) Process

5.1 Building Model Analysis

"The process shall be design centric and shall begin with decomposing the building model to its smallest granularity of building elements"

The BWA process will begin with building model analysis, which involves reading a variety of data about building design, procurement, and construction. During this phase, the elementary building elements/components (such as Walls, Doors, Windows, Roofs, etc.) will be identified along with the details about materials being specified and construction strategies being employed for building these elements (like standard masonry wall with stretcher bond type). This data is fundamental for accurately predicting the waste potential of building design at the fine-grained level. Accordingly, large number of data sources may be queried during this phase to extract the relevant data. These data sources may be intrinsically heterogeneous in terms of underling format, schema, and contents [55, 56]. Common examples of format-related heterogeneities include data stored in flat files, relational, web pages, XML, and JavaScript Object Notation (JSON). This requires highly generic wrappers to sort out these heterogeneities while importing the relevant data [77, 56, 54]. The queried data will be further transformed using global terms by applying series of transformation functions and rules, including selections, projections, joining, transposing, pivoting, aggregations, translating codes, and encoding values [56]. Finally, the transformed data will be stored persistently into staging tables to support the computations for predicting and designing out construction waste [57, 56].

5.2 Waste Prediction

"And then estimating the amounts of construction waste for every building element by applying modern heuristics based techniques to generate more accurate waste forecast."

Waste prediction provides basis for understanding causes, types and quantities of construction waste arising from the building models [25]. During this phase, building elements will be evaluated for the amounts of construction waste they tend to generate. Accordingly, robust waste prediction models will be employed. Existing waste prediction models estimate the construction waste based on Materials Waste Rates (MWR) [60, 61, 62, 78, 79, 40] and waste generation indexes [58, 24, 59]. The techniques underlying these models are mainly based on the percentage of waste to material procured and the Gross Floor Area (GFA) of the building respectively. However, there are more factors contributing to construction waste generation asides material quantity and GFA [25, 60].

A robust waste prediction model will be developed which will consider every building elements and construction strategies for their contribution of construction waste.

Consequently, a comprehensive waste forecast will be generated after examining every aspect of the building model. Prediction system will be developed, mainly comprised of two integral components such as reasoning system and accurate database querying system [63, 64]. In this phase, the reasoning system will be specifically used to carry out the computational workload underpinning predicting and designing out construction waste. State of the art techniques and algorithms will be utilised to develop reasoning systems particularly big data analytics as discussed in Siegel (2013). More details about the relevance of big data analytics for this development is discussed later in Section 5.

5.3 Waste Visualisation

"And then waste is displayed pictorially as 3D objects so that designers could understand the trend of how waste is arising from the given building design."

During this phase of the BWA, different elements of the waste forecast, generated during the previous step, will be mapped onto the visual components. Visual representation of construction waste will enable effective communication and stimulate the designers' engagement for employing waste efficient strategies. As such, interactive visual representation technologies will be used to enable the designers to investigate larger datasets at once for holistic decision-making [65, 66]. The aim of employing visualisation in this context is to carry out exploratory data mining in which experience of the designers will be integrated with the effective visualisation techniques for predicting and designing out construction waste [67, 68]. This phase will not only sort out the challenges of mapping and presenting highly dimensional data in an analysis-friendly visualisations but the wider issues of data uncertainties, incompleteness or misleading trends shall also be considered and tackled to minimize the degree of error in the overall process of the BWA [69].

5.4 Waste Minimisation

"Analysing the waste forecast using interactive visualisation tools and technologies can really assist designers to try out design changes and material selection to reduce construction waste."

Since the human brain is the best tool for identifying the latent trends in the information, this phase of the BWA will engage the designers to react to the waste arising from the building design using technology-driven visual data exploration techniques. This idea of visually representing construction waste will harness the designers' abilities of better understanding the building design from large number of dimensions. They will be provided with vibrant environment to change construction materials as well as the design strategies and check their influence on the generation of construction waste. The system will provide real time waste forecast based on the changes incurred in the design and the latest trends of construction waste will be disseminated instantly to either accept or reject the design changes. Moreover, this whole process of the BWA will be embedded into their native BIM software product as plugin to give them a realistic opportunity of predicting and designing out construction waste. As a result, the designers will come up with building designs, having better design strategies, material selection, and procurement routes. And, these modifications will be carried out in the building design unless an optimised and waste efficient building design is eventually produced.

6 The Promise of Big Data/ICT for Construction Waste Minimisation

Although, BIM sets an ideal stage for the development of powerful and innovative applications for AEC industry by providing additional layer of data, but the plugin for construction waste minimisation is highly data driven and requires access to large volumes of additional datasets pertaining to design, procurement, and construction. The collection, storage, processing, analysis, and interactions with such datasets impose special challenges that are beyond the capabilities of traditional hardware and software technologies including BIM.

Big data analytics is recently getting more momentum in analysing massive datasets to discover latent trends and insights for effective decision making, the analytical tools such as machine learning, statistics, time-series analysis, business intelligence, data warehousing, and data mining, along with specialized techniques for processing big data, could be profitably employed here for the development of plugin for construction waste prediction and minimisation. This area is largely an unchartered territory and the use of big data techniques in waste minimisation hold significant promise in creating more efficient waste management subsystems through the development and processing of data-driven insights.

In this section, we propose big data/ data analytics as a potential technological solution to the problem of managing the large datasets that are relevant for waste minimisation. Big data technologies are worth a special consideration here due to their relevance, since they can handle storage and processing of massive datasets by virtue of their 3V (Volume, Velocity, Variety) capabilities (Siegel, 2013). This dedicated section discusses the open research challenges that call for the application of big data technologies into the development of plugin for construction waste prediction and minimisation.

6.1 The issue of handling massive material database

The issue of waste management is to deal with large number of materials arising from the construction process [80]. Since every material has an associated waste output, accessing specific material details for waste efficient materials selection and optimization is highly desirable [3]. This calls for comprehensive material database containing material properties and allied domain knowledge. Owing to complexity and volume of large number of materials data, material database itself constitutes a huge data repository. Storage of the terabytes of material database would not only be insurmountable rather real-time processing, analysis and interaction with this data would be challenging. Literature has revealed the use of relational databases for storing building related data, but the limits are reached soon within the first few months of data storage and processing [17]. Similarly, time series databases are also explored in lieu of relational model to achieve high performance [81], but due to the specialized access pattern required to query material database has made these approaches ineffective. Some commercial solutions are also available for real-time energy data collection, storage, and analysis [82]. Recently, Internet of Things database is proposed which is designed specifically to store and process voluminous data pertaining to building automation and energy analysis [83].

6.2 The issue of graph based representation, analysis and visualisation

In this context, the datasets often come from different independent parties and applications, hence, resulting in a large number of schematic and semantic heterogeneities [54]. Reconciling heterogeneities for integration into a common and unified format is another open research challenge. Literature witnessed large body of research carried out on schema and ontology matching [84, 85]. With the advent of semantic web, ontologies are used for graph based data representations because capturing datasets as graphs (containing nodes and links) enables the application of graph theory based simulations and visualisation techniques. Ontology is formal description of concepts and relationships in a domain of interest [86]. Web Ontology Language (OWL) is popular language used for creating ontologies in Semantic Web, which has dominated rest of the ontology languages (SHOE [87], OIL [88], DAML+OIL [89]) due to its expressivity and better reasoning abilities [90]. Data in ontology is stored as Resource Description Framework (RDF) triples, comprising of subject, predicate, and object [91]. NoSQL (for "not only SQL") systems are getting prominent as emerging RDF triple stores [92], to persistently store and query RDF data in modern enterprise applications, complementing their relational counterpart [93, 94, 95]. Despite the fact that NoSQL systems are storing unstructured data in a highly efficient and flexible key-value format [96], the RDF triple store requires specialized features to store and process graph data, thereby a graph based data model is proposed [97] for efficiently traversing RDF data in NoSQL systems. Some of the examples of NoSQL databases include Oracle NoSQL [98], Apache Cassandra [99], Voldemort [100], and MongoDB [101].

Exploring these datasets to derive meaningful insights is another open research issue. Information visualisation techniques for small sized hierarchical datasets are studied in Cawthon and Vande (2007). A specialized technique of visualisation of large environmental datasets is proposed in Shneiderman (2008) and Wu, et al., (2009). Recently, a framework for visualisation of complex domains has been proposed in Bai, et al., (2009) that can handle complex spatio-temporal multi-dimensional data.

7 Conclusions

This paper discusses the potential of BIM and big data technologies for construction waste prediction and minimisation. We have identified and discussed 17 critical features of BIM that could be harnessed to implement the plugin for construction waste prediction and minimisation. These critical BIM features are categorized into five layers: BIM core layer, BIM auxiliary layer, waste management criteria, waste processing cycle, and application layer. We have evaluated existing BIM software products for the support of these critical features. Although BIM is the de-facto standard in the AEC industry, it unfortunately has limited support for waste prediction and minimisation. This lack of functionality reveals a serious technological gap. To bridge this gap, efforts have been undertaken but they are not effective since these are not based on BIM, hence it can be concluded that BIM based implementation is a promising way forward to effectively and efficiently tackle issue of construction waste. We have also identified big data technologies as a real game changer that can potentially lead to the development of high performance and technology smart plugin for construction waste prediction and minimisation. The paper provides the basis for detailed technical specifications that would be useful during the implementation of waste prediction and minimisation plugin.

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