

# Computational Building Information Modelling for construction waste management: moving from rhetoric to reality

## Abstract

There is a lively debate on the application of Building Information Modelling (BIM) to construction waste management (CWM). BIM can be utilised as a less expensive, virtual, graphical, and computational environment to enable designers to ponder different design options, or contractors to evaluate different construction schemes, both with a view to minimizing construction waste generation. However, although the debate too often treats BIM as a cure-all silver bullet, without some major hurdles being adequately addressed, the applications of BIM will remain rhetorical. This paper aims to demystify BIM by proposing its computational application to CWM. Based on a critical literature review, a prototypical framework of a computational BIM for CWM is delineated, within which the prerequisites of ‘information readiness’ and ‘computational algorithms’ are highlighted. Then, the paper details the required information and how it can be organised in a standalone database or encapsulated in existing BIM. Referring to the historical development of the similar database in the field of BIM-based cost management, this process could be tortuous but unavoidable. The paper also explores computational BIM algorithms that can manipulate the information to provide decision-making information for CWM, such as low-waste design or construction options. Although the framework has been substantially developed as a result of this study, it is not to be taken as an immediately applicable solution but rather as a shared footing based on which future development of computational BIM for CWM will proceed in a more efficient and effective fashion.

**Keywords:** Building Information Modelling (BIM); Construction waste management (CWM); Computational design

## 1. Introduction

While construction is a noble industry essential for materialising the built environment, which influences human health, economic activities and social behaviour, it also exerts grievous, adverse impacts on the natural environment in the form of resource depletion, greenhouse gas (GHG) emissions, noise, dust, and disposal of construction waste. Construction waste, sometimes called construction and demolition (C&D) waste, is defined as the surplus and damaged products and materials that arise from construction, renovation, and demolition activities (Roche and Hegarty, 2006). It often constitutes a prodigious portion of total municipal solid waste that contributes to degradation of the environment. For example, in the U.S., the estimated amount of building-related waste generated in 2003 was 170 million tons (USEPA, 2013). At present, the construction industry is responsible for about 32% of landfill waste and 25% of all used raw materials in the UK (Prism Environment, 2012). The European Commission (2013) reported that construction waste is responsible for 25-30% of all waste generated in the European Union. In Hong Kong, the solid waste ending up in landfills reached 14,311 ton per

1 day (tpd) in 2013, of which 25% was from construction activities (HKEPD, 2015), whereas, in  
2 Japan, construction contributes 20% of the total solid waste generated by all industries (MoE,  
3 2014). It is a common practice for construction waste to be used for landfill. However, landfill  
4 of waste leads to extensive amounts of air, water, and soil pollution due to production of CO<sub>2</sub>  
5 and methane from anaerobic degradation of the waste. It also brings tremendous pressure to  
6 valuable landfill space, particularly in compact urban spaces such as those in Hong Kong,  
7 Singapore, and Japan. Researchers and practitioners of the industry have endeavoured to manage  
8 construction waste by devising policy, engineering, economical, and managerial approaches.  
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12 During the process of devising such approaches to construction waste management (CWM),  
13 Building Information Modelling (BIM) has been increasingly explored. According to the U.S.  
14 National BIM Standard (2007), BIM is “a digital representation of physical and functional  
15 characteristics of a facility and a shared knowledge resource for information about a facility  
16 forming a reliable basis for decisions during its life cycle” (p.149). Davies and Harty (2011)  
17 expounded that BIM is a term used to refer to a family of technologies and related practices used  
18 to represent and manage the information used for, and created by, the process of designing,  
19 constructing and operating buildings. With its 3D presentation and virtual reality simulation  
20 capability, BIM was introduced as a technical tool that can be applied to improve the  
21 construction industry in a number of areas, such as design quality enhancement, construction  
22 plan rehearsal and optimisation, and site management (CIFE, 2007; Kaner et al., 2008; [Li et al.,](#)  
23 [2009](#)). On the other hand, BIM has an indirect, yet probably more significant impact on projects  
24 by overcoming the many inherent problems in project organisations. For instance, with its  
25 information interoperability and 3D presentation, BIM can improve communication amongst  
26 parties (Fischer and Kunz, 2004). As a continuing digital platform, it can retain the information  
27 or knowledge (e.g. design rationale) to reduce discontinuity ([Li et al., 2009](#)). BIM can also be  
28 used to encourage integration and collaboration ([Taylor and Bernstein, 2009](#)), particularly when  
29 used in collaboration with the integrated project delivery model (AIA and AIA CC, 2007; Sive,  
30 2009). Partly owing to these potential benefits, BIM has been enthusiastically advocated as a  
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45 The UK's Construction 2025 Strategy states that “BIM has the potential to reduce construction  
46 waste during design and construction stages” (HM Government, 2013), and many professionals  
47 in the industry, such as architects, engineers and surveyors, take this a step further by  
48 considering BIM to be a silver bullet in the battle against construction waste. The rhetoric  
49 includes widely propagated potential benefits of BIM, such as clash detection and on-site  
50 coordination, with the assumption that they will automatically become a reality. This is  
51 indicative of the mystery surrounding BIM's application to CWM. Without demystifying the  
52 mystery, BIM will remain a fad. There are a number of academic studies using a normative  
53 approach to examine how BIM and CWM can be joined or juxtaposed (e.g. [Baldwin et al., 2009](#);  
54 [Porwal and Hewage, 2012](#); Cheng and Ma, 2013; Porwal, 2013; Liu et al., 2015). While these  
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1 studies are critiqued later in the paper, generally speaking they add to the rhetoric rather than  
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4 Drawing upon the experiences in both BIM and CWM research, this paper helps to move  
5 BIM-enabled CWM from rhetoric towards reality. It does so by stressing the importance of  
6 information in a BIM initiative and the need to develop a database that stores state-of-the-art  
7 waste generation levels of various design options and construction schemes. The argument is  
8 that with such a database of information in place, BIM can then be utilised as a virtual  
9 computational environment within which designers and contractors can manipulate different  
10 design and construction options with a view to minimizing construction waste.  
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16 In order to deal with the topic in a clear and logical manner, the paper is divided into four main  
17 sections subsequent to this first introductory section. Section 2 is a critical assessment of the  
18 existing studies on the application of BIM to CWM, while section 3 delineates the prototypical  
19 framework of computational BIM for CWM and highlights the framework's two essential  
20 prerequisites of information readiness and computational algorithms to manipulate the  
21 information for decision-making. Section 4 details the required information by suggesting the  
22 development of two databases, namely, the 'Design Options - Waste Generation' database and  
23 the 'Construction Schemes - Waste Generation' database. Section 5 explores how BIM can be  
24 developed into a computational environment that will allow different design options and  
25 construction schemes to have their waste generation levels calculated instantaneously. Although  
26 the framework has been elaborated to a large extent, it has not been fully developed as a solution  
27 that can help implement BIM for CWM immediately. The intention is rather that the framework  
28 should provide a promising direction in which future studies on BIM for CWM can proceed  
29 more effectively and efficiently.  
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## 39 **2. Literature review**

40 There is a limited but growing body of literature exploring how BIM can be implemented for  
41 CWM. Porwal and Hewage (2012) conducted a BIM-enabled analysis to minimize the waste  
42 rate of structural reinforcement. They did so by selecting BIM as the hub for communicating  
43 project information among various design teams (e.g. architectural, structural, mechanical) and  
44 then using an optimization algorithm to minimize reinforcement waste. Cheng and Ma (2013)  
45 developed a BIM-based system for demolition and renovation waste estimation, and waste  
46 disposal planning. While their research illustrated the importance of information to make BIM  
47 truly useful for CWM, it did not articulate the key information required to develop a convincing  
48 algorithm to perform the estimation based on the information. Research from Loughborough  
49 University advocated 'designing out' construction waste ([Osmani et al. 2008](#); [Baldwin et al.,  
50 2009](#)). Their works were espoused by a Generic Process Model for the detailed design process  
51 and a technique known as the Design Structure matrix (DSM), which is developed in-house and  
52 promoted as a major decision-support system by the school. In their recent work, BIM was  
53 proposed as a potential design decision-making tool to support effective CWM (Liu et al., 2015).  
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1 Whilst the above studies have not convincingly linked BIM and CWM, they have at least  
2 identified the sources of construction waste generation as a starting point. In CWM literature,  
3 many researchers have focused on on-site waste management by viewing it as the stage where  
4 waste is actually generated. On-site operations such as construction methods, materials handling  
5 skills/practices ([Shen et al., 2004](#)), housing keeping ([Trigunarsyah et al., 2006](#)), on-site sorting  
6 ([Yuan et al., 2013](#)), and off-site sorting ([Lu and Yuan, 2012](#)), have all had a significant impact on  
7 waste generation, although a certain level of waste generation is perceived as unavoidable ([Teo  
8 and Loosemore, 2001](#)). As construction adopts a contracting/sub-contracting system, researchers  
9 have extended CWM to the downstream construction supply chain by managing sub-contractors,  
10 advocating green procurement ([Ofori, 2000](#)), or extending producer responsibilities ([Acree and  
11 Horvath, 2003](#)). Those advocating 'design out' construction waste ascertain that designers have a  
12 decisive role in helping waste reduction, although survey results have shown that this has only  
13 been sporadically practised (e.g. [Yuan, 2013](#); [Wang et al., 2014a](#)). Minimization of construction  
14 waste is still secondary to the traditional project objectives of time, cost, and quality. The  
15 UK-based WRAP (Waste & Resources Action Programme) (2007), conducted a comprehensive  
16 study to identify five key principles that design teams can use to reduce construction waste,  
17 which were cited by Liu et al. (2015) as: (a) Design for reuse and recovery; (b) Design for  
18 off-site construction; (c) Design for materials optimisation; (d) Design for waste efficient  
19 procurement; and (e) Design for deconstruction and flexibility. The measures outlined in  
20 WRAP's (2007) report are guided by the '3Rs' principle of 'reduce, reuse, and recycle' and by  
21 classifying waste management strategies according to their desirability ([Peng et al., 1997](#)). As a  
22 result of the foregoing research, it has become clear that decisions made at both the design and  
23 construction stages have an impact on construction waste generation.  
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37 So what can BIM offer to minimize construction waste generation? In simple terms, BIM is a  
38 digital representation of physical and functional characteristics of a facility that aims to facilitate  
39 the exchange and interoperability of information ([Eastman et al., 2008](#)). BIM is a "richer  
40 repository" ([Eastman, 1999](#)) than a set of drawings or static CAD files, since it has the ability to  
41 store different types of information and contains both geometric and non-geometric information  
42 about the project ([Pratt, 2004](#)). Geometric information includes size, volume, shape and spatial  
43 relationships, while non-geometric information includes the type of individual construction  
44 component, specifications of material, construction schedule, and cost. [Schlueter and Thesseling  
45 \(2009\)](#) claimed that BIM information should include geometric, semantic and topological  
46 information. Geometric information directly relates to the building form in three dimensions;  
47 semantic information describes the properties of components, i.e., more advanced rule and  
48 function information; and topological information captures the dependencies of components.  
49 Without all the available information, BIM cannot do anything meaningful. The level of  
50 development (LOD) and specification defined by BIMForum (2013) not only stresses the  
51 importance of information in BIM but also goes further to specify which development level of  
52 the information, ranging from 100 to 400, corresponds to BIM functionalities, e.g. for quick  
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1 demonstration, or for fabrication, assembly, and installation. The momentum that BIM has  
2 gained can be better understood by Flanagan and Lu's (2008) philosophical contention that  
3 managing a construction project involves using available information and knowledge to make an  
4 array of decisions across processes including architecture, engineering, construction, and  
5 operation. The main objective of information management is to support decision-making by  
6 ensuring that accurate information is always available at the right time in the right format to the  
7 right person to allow making informed decisions ([Chen et al., 2015](#)). If properly devised, BIM is  
8 a useful platform that can provide this decision-support information.  
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12 Assuming that all the information needed is ready, what makes BIM a useful decision-making  
13 tool for construction waste management? BIM can provide a less expensive, virtual, graphical,  
14 and computational environment to ponder various design options and construction schemes,  
15 which have a decisive impact on construction waste minimization; this is computational design  
16 thinking. Owing to construction projects' heavy physical resource engagement, and their one-off,  
17 irreversible nature, it is too expensive if not entirely impossible to try different design and  
18 construction schemes before a project is actually built. This leads to two major problems. First,  
19 design errors arising from the design stage cannot be effectively identified in advance ([Li et al.,](#)  
20 [2009](#)), which could cause substantial disruption or loss, including construction waste, when the  
21 errors are discovered. Second, different construction schemes cannot be tried and rehearsed in  
22 advance ([Li et al., 2009](#)) and are developed at the planning stage where there is a heavy reliance  
23 on rules of thumb and experience. A not-well-thought-out construction scheme may cause  
24 problems in the delivery of a project, including not be able to achieve minimal construction  
25 waste generation. However, BIM can provide the virtual environment to undertake these works.  
26 With all the detailed 3D models of building available in the BIM component library ([Huang et](#)  
27 [al., 2007](#)), it is possible to create a 3D presentation of a construction project rapidly and  
28 affordably. The virtual environment allows designers to ponder different options conveniently  
29 with the changes of presentations, functionalities, quantities, or in this case, waste generation  
30 being computed instantaneously and presented graphically in the form of a dashboard.  
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36 Nevertheless, as the digital representation of a physical facility, BIM itself cannot manipulate  
37 information to allow informed decision-making for CWM; it relies on algorithms tailor-made for  
38 this purpose. This was captured in Porwal's (2013) work by articulating that construction waste  
39 generation can be determined by both design and construction stages, and by developing a  
40 system dynamics (SD) model to estimate waste generation in relation to different design and  
41 construction combinations. Although the authors of this paper agree with exploring  
42 computational BIM for CWM, they think that the SD model should be curtailed owing to its  
43 black-box nature and the mixing of responsibilities between design and construction, and that  
44 algorithms are the way to go.  
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58 To summarize, there is a growing body of literature exploring how BIM can be used to minimize  
59 construction waste. However, there are several mysteries surrounding BIM that need to be  
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demystified before it can be really implemented for CWM. BIM can provide a less expensive, virtual, and computational environment to ponder various design options and construction schemes, with a view to minimizing waste before it is actually generated on site. Nevertheless, computational BIM will remain as a fad without two essential prerequisites in play, namely, information readiness, and computational algorithms to manipulate the information.

### 3. The prototypical framework

Fig. 1 illustrates the prototypical framework of computational BIM for CWM. It covers the design and construction stages, which play a decisive role in determining the generation of construction waste. It emphasizes that human beings (e.g. the designers and contractors in Fig. 1) are the decision-makers at the core, while BIM is a technology to facilitate the decision-making processes. Based on BIM, a designer ponders different design options, which are formed by various 3D parametric models stored in the BIM component library; a procedure similar to playing with Lego. In this case, the 3D models are linked to a particular database indicating state-of-the-art average waste generation levels if the models are adopted. For example, one can evaluate whether a bay window or a balcony should be designed by meeting various design criteria, such as cost, functions, energy consumption, and waste minimization.

<<Please insert Fig. 1 here>>

Likewise, in the BIM environment, a construction planner ponders different construction schemes, each of which is linked to the database indicating the most updated, average waste generation levels if that scheme is adopted. For example, the planner can evaluate whether timber or metal formwork should be selected, given the required criteria such as buildability, cost, time, quality standard, and waste minimization. In real design and construction practice, construction waste minimization will rarely be singled out but considered in conjunction with the criteria such as time, cost, quality, safety, sustainability, and so on. All these design and construction evaluations are undertaken in a virtual environment without engaging heavy and physical resources. All related design and construction documentations, including quantity take-offs, counts, and measurements, are automatically updated if any changes are made to the BIM design (Porwal, 2013). It is thus less costly to coordinate design and construction changes.

Currently, neither commercial BIM solutions nor academic studies have sufficiently extended BIM to perform CWM, despite widespread calls to do so. As previously argued, the application of BIM to CWM rely on two essential prerequisites, namely, information readiness and computational algorithms to manipulate the information for decision-making. The two components are highlighted in the conceptual framework and are elaborated upon in following sections.

### 4. The design options/construction schemes - waste generation database

Although there should be two separate databases indicating the average waste generation levels

1 caused by different design options or construction schemes, because of their similarities they are  
2 considered together here. For easy elaboration, they are called the DO-WG database (Design  
3 Options - Waste Generation) and CS-WG database (Construction Schemes – Waste Generation).  
4 A simple relational database as shown in Fig. 2 suffices. One column stores various design  
5 components such as doors, windows, and floors; another stores their average waste generation  
6 levels that have been proportioned to the components’ geometric properties, such as size,  
7 volume, or shape; and a third optional column can be used to provide a graphical 3D prototype  
8 of the design component.  
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16 The databases can be standalone. This form will help focus on the commitment to develop the  
17 databases. The burdensome task of exhaustively listing the myriad of building components and  
18 organizing them in a hierarchical structure can be conducted with the maturity of BIM ontology,  
19 which has defined structure and acts as a shared vocabulary that formally describes all BIM  
20 terms in an unambiguous manner ([Lee and Jeong, 2012](#)). For example, the component ontology  
21 provides the description of components and their decomposition, while the relationship ontology  
22 defines the geometrical relationship between two or more components. Furthermore, as BIM  
23 ontology can be interpreted in a consistent way and is expansible, it facilitates acquiring and  
24 sharing information in BIM ([Succar, 2009](#)) and can respond to the increasing requirements of  
25 BIM users. The databases can also be linked to the BIM component library or the building  
26 information model itself by using record linkage (Dunn, 1946), a term used by statisticians,  
27 epidemiologists, and historians, among others, to describe the process of joining records from  
28 one data source to another that describe the same entity. Fig. 3 illustrates how these databases  
29 are linked together.  
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42 The databases can also be merged into the existing BIM component library. Fig. 4 is a sample of  
43 the existing BIM component library from Autodesk Revit. The main area is the 3D graphical  
44 presentation of the facility, formed by various components. The grids on the left-hand side is the  
45 dashboard for both geometric and non-geometric information of the BIM components, as can be  
46 seen in any model created by Autodesk Revit. What is different is the additional columns called  
47 ‘design waste generation level’, ‘construction waste generation level’, ‘design waste amount’,  
48 and ‘construction waste amount’, all of which can be perceived as new properties that can be  
49 encapsulated in the components. Similar to material specifications, construction schedule, and  
50 costs, the columns become the non-geometric information of the component, which could be  
51 further expanded by adding other properties such as energy. Actually, a building information  
52 model, regardless of its 3D presentation and information richness, can be perceived as a  
53 relational database *per se* from the perspective of computer database experts ([Wang et al., 2013](#);  
54 [Liu et al., 2015b](#)). Some information is initially contained in the model, while others are  
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continuously generated and imported to the model throughout the project life cycle. Through a certain mapping approach, information from an external source, such as a MS Excel file or MS Access, can be linked to the entire project or a specific component ([Xie et al., 2011](#); [Wang et al., 2014b](#); Kang and Hong, 2015).

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## 5. The computational BIM

With the information in place, computational BIM algorithms are required to manipulate the information in the BIM and provide decision-making information for CWM, such as low waste design options and construction schemes. The flowchart for developing the computational BIM for measuring waste generation at the design or construction stage is illustrated in Fig. 5. Prior to a detailed description, it should be noted that there are two typical modes for BIM of a construction project. One is that the model is developed by the designer at the design stage and is then shared with the contractor for construction planning, while the other is that the contractor develops the model on his own. As the computation of waste generation under these two modes follows a similar logic, for simplification this study only considers the situation where the designer and contractor develop their own separate building information model.

<<Please insert Fig. 5 here>>

### 5.1 Measuring waste generation at the design stage

The first step is to develop the building information model. Unlike traditional methods that use lines, points, and arcs to draw the building components, a designer directly uses 3D digital objects to create the model in commercial BIM software (e.g. Autodesk Revit and ArchiCAD). Each of the objects, regardless of being provided by BIM software, developed by the designer himself/herself, or exported from a third-part library, has various parameters such as length, area, thickness, volume, offset, level, and slope. The parameters have initial values, which can be modified and changed. For example, the designer selects a window with an initial size of 1000mm\*500mm from the component library, but can then easily adjust both width and height if the window does not fit the design requirements.

Before moving forward to the second step, one important issue is to check and revise the name and type of the object, which lays the foundation for mapping the component with its waste generation level. Application program interface (API) is used to build the connection between BIM and Design Options - Waste Generation (DO-WG) databases. Depending on the BIM software used, the connection can be programmed in different languages. After the connection is developed, the waste generation level of each component in the BIM model is automatically acquired by matching the component in the model with the database (See Fig. 6).

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1 The third step is to calculate the amount of waste and present the results. BIM can automatically  
2 measure the quantity of each component. Depending on the type of the building object, the  
3 quantity can be presented by area, volume, or piece. Together with the waste generation level,  
4 the waste generation of one object can be denoted as Equation [1]:  
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$$7 \quad W_{Di} = Q_{Di} \times L_{Di} \quad [1]$$

8 Where  $W_{Di}$  is the waste generation of the component  $i$  under the current design option,  $Q_{Di}$  is  
9 the quantity of the component  $i$ , and  $L_{Di}$  is the waste generation level stored in the DO-WG  
10 database.  
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12 The total waste  $W_D$  can then be denoted as Equation [2]:  
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$$14 \quad W_D = \sum_1^n W_{Di} \quad [2]$$

15 Finally, the designer can review the waste generation in BIM software, and find which  
16 component in a certain design option causes a large amount of waste (shown in Fig. 7). Based on  
17 the waste generation and other criteria, the designer will decide whether the original design  
18 should be improved. If the design is modified, the above steps will be repeated to calculate the  
19 latest waste generation. The whole process can be swiftly reiterated in the BIM environment  
20 without involving a large amount of resources.  
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### 32 **5.2 Measuring waste generation at the construction stage**

33 Similarly to evaluating waste generation at the design stage, the waste generation at the  
34 construction stage is measured following the four steps: (1) Developing the BIM model for  
35 construction works; (2) Linking the model and the Construction Schemes - Waste Generation  
36 (CS-WG) database; (3) Calculating the amount of waste; and (4) Reviewing the results. In  
37 reality, contractors often need to reconsider or even optimize the design from a buildability  
38 perspective. In this case, waste generation, amongst other criteria such as time, cost, and quality,  
39 is taken into consideration. Mathematically, the waste generation of a certain construction  
40 scheme can be shown as Equation [3]:  
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$$45 \quad W_{Ci} = Q_{Ci} \times L_{Ci} \quad [3]$$

46 Where  $W_{Ci}$  is the waste generation of the construction scheme of component  $i$ ,  $Q_{Ci}$  is the  
47 quantity of the component  $i$  using the construction scheme and  $L_{Ci}$  is the waste generation level  
48 stored in the CS-WG database.  
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51 The total waste  $W_C$  can then be denoted as Equation [4]:  
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$$53 \quad W_C = \sum_1^n W_{Ci} \quad [4]$$

54 In addition, if the construction schedule is integrated with the model, the waste generation along  
55 with the construction process will be illustrated in a BIM environment. Such direct illustration  
56 has two benefits: firstly, the constructor can have a clear understanding of the amount of waste  
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generated in each construction work, which will be one of the criteria for analyzing whether the current scheme is appropriate; secondly, site managers can use it as a baseline to timely arrange transportation for construction waste delivery, thereby helping to maintain a clean and organized site.

## 6. Discussion

The above sections introduced computational BIM for CWM, and detailed the two essential components, i.e., the BIM information readiness and the computational algorithms to manipulate the information. However, it is unlikely that computational BIM for CWM will become a reality any time soon. There is still a long way to go in its development, which can be better understood by comparing it to the historical development of BIM-based cost estimating. In the early days, BIM was mainstreamed to bring about a revolutionary impact on cost estimating in quantity surveying practices prevailing in Commonwealth countries. As a BIM model contains 3D objects with geometrical information, it is easy to capture the quantities of objects whose volumes and areas can be automatically and instantly extracted (Jiang, 2011; Kymmell, 2008) to form the basis of an accurate cost estimate after mapping them against the cost database. This is comparable to computational BIM for CWM, wherein the quantities are similar to the quantities of all the components (see Equations [1] and [3]) and the cost database is similar to the DO-WG or the CS-WG database. Wu et al. (2014) reviewed the BIM-based cost estimating in UK quantity surveying practice, and identified several key challenges in terms of information exchange, model quality, and UK standards. These key challenges can also be identified in the development of computational BIM for CWM.

In comparison with the DO-WG or the CS-WG database, the cost index database is more mature. In its simplest form, the cost index database, includes material types, labour, professional services, and their corresponding prices, which should reflect the locality and keep updated with market fluctuation. The complexity to develop the cost database is considerably high, but owing to efforts over the past decades from surveying firms such as Langdon & Seah and Rider Levett Bucknall enduringly collecting and publishing cost indexes in various economies, the cost index database nowadays is acceptable as a common baseline by clients, contractors, and consultants for estimating building costs. Researchers specialising in CWM have endeavored to investigate waste generation rates (WGRs), which can form an important part of the DO-WG or the CS-WG databases (See Fig. 2). A WGR can be calculated by dividing the waste in volume ( $m^3$ ) or quantity (tons) by either the amount of virgin materials purchased, or the amount required by the design, or per  $m^2$  of gross floor area (Formoso et al., 2002). Researchers have used diverse methods to collect the data for calculating WGRs: direct observation (Poon et al., 2001); questionnaire survey (McGregor et al., 1993); sorting and weighing the waste materials on-site (Bossink and Brouwers, 1996); collecting data through consultation with construction company employees (Treloar et al., 2003); and tape measurement and truck load records (Skoyles, 1976; Poon et al., 2004). A problem is that most of the studies had a relatively small sample or sampled relatively small sites due to the difficulties involved in conducting a full coverage survey over a

1 long period of time (Katz and Baum, 2011; [Lu et al., 2011](#)) and the reported WGRs are too  
2 divergent to be accepted with confidence. Recently, researchers have utilised big data in the  
3 hope of deriving more convergent WGRs (e.g. [Lu et al., 2015a](#); 2015b). In view of the  
4 development of BIM-based cost estimating and the advancement of CWM, it is not overly  
5 optimistic to expect that the DO-WG and the CS-WG databases will one day be fully developed,  
6 despite the laboriously slow process of collecting the necessary data.  
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10 The computational algorithms as shown in Equations [1] to [4] will not be free from criticisms  
11 for their linearity. It might be considered overly simplified to decompose a design into different  
12 options or a construction scheme into different trades to examine their unit construction waste  
13 generation. Construction waste generation is perhaps better understood by putting it in a system  
14 rather than by examining the individual components that form the system. In a sense, Porwal's  
15 (2013) system dynamics model backed by high order equations is better suited to capture waste  
16 generation in the design and construction stages as a whole. However, the model mixes the  
17 responsibilities of designers and contractors in CWM, which blurs the direct effects of changing  
18 design options or construction schemes on waste minimization. The intuitive suggestion is to  
19 examine the linear relationships between design options/construction schemes and their waste  
20 generation and make them more robust for developing computational BIM for CWM. Although  
21 the discussion has not provided an immediate solution to computational BIM for CWM, it has  
22 nevertheless demystified several typical confusions surrounding the issue.  
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## 31 **7. Conclusion**

32 Exploration of BIM has too often assumed it to be a silver bullet that can fix anything, including  
33 CWM. While it is true that BIM can provide a less expensive, virtual, graphical, and  
34 computational environment to enable decision-makers to evaluate different design options or  
35 construction schemes so as to manage construction waste more effectively, many issues remain  
36 to be demystified before BIM can be effectively used for CWM. This paper proposes a  
37 computational BIM for CWM by firstly delineating a prototypical framework and then  
38 elaborating its two prerequisites, including information readiness and computational algorithms.  
39 Using a normative approach, the authors argue that the key information should be the average  
40 waste generation levels, i.e. waste generation rates (WGRs) associated with different design  
41 options or construction schemes. The key information can be organized in standalone databases  
42 but connected with a BIM, or be encapsulated in the existing BIM components to become their  
43 new properties; research into WGRs will help develop the key information. Referring to the  
44 historical development of the building cost index, the process will not be easy but it is a  
45 promising direction that cannot be avoided.  
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55 The computational algorithms developed in this study can automatically calculate the quantities  
56 of a design option/construction scheme for BIM, instantaneously mapping them to the WGRs  
57 database and estimating the potential amount of waste generated. Using some graphical  
58 presentation skills, such as pie chart and spider diagrams, results can be displayed graphically in  
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1 the form of a dashboard to support designers and contractors when making decisions in relation  
2 to CWM. The linearity of the algorithms may not entirely reflect the nature of construction  
3 waste generated by the decisions made at the design or construction stage, but the idea is to have  
4 straightforward algorithms so that designers and contractors will have a clear understanding of  
5 the impact of their decisions on construction waste generation, and their responsibilities will not  
6 be mixed up or shifted to each other.  
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10 The paper is deliberately presented in an exploratory and discursive way, and the computational  
11 BIM for CWM is proposed in a normative rather than a positive fashion. Based on the authors'  
12 many years of research experiences in both fields, the aim is not to provide an immediate  
13 solution to computational BIM for CWM but rather to demystify the typical confusions  
14 surrounding this issue. Future studies are recommended to further develop the  
15 design/construction - waste generation level by embracing advancements in information  
16 technology and CWM. It is hoped that through the study presented in this paper, development of  
17 computational BIM for CWM will proceed more efficiently and effectively.  
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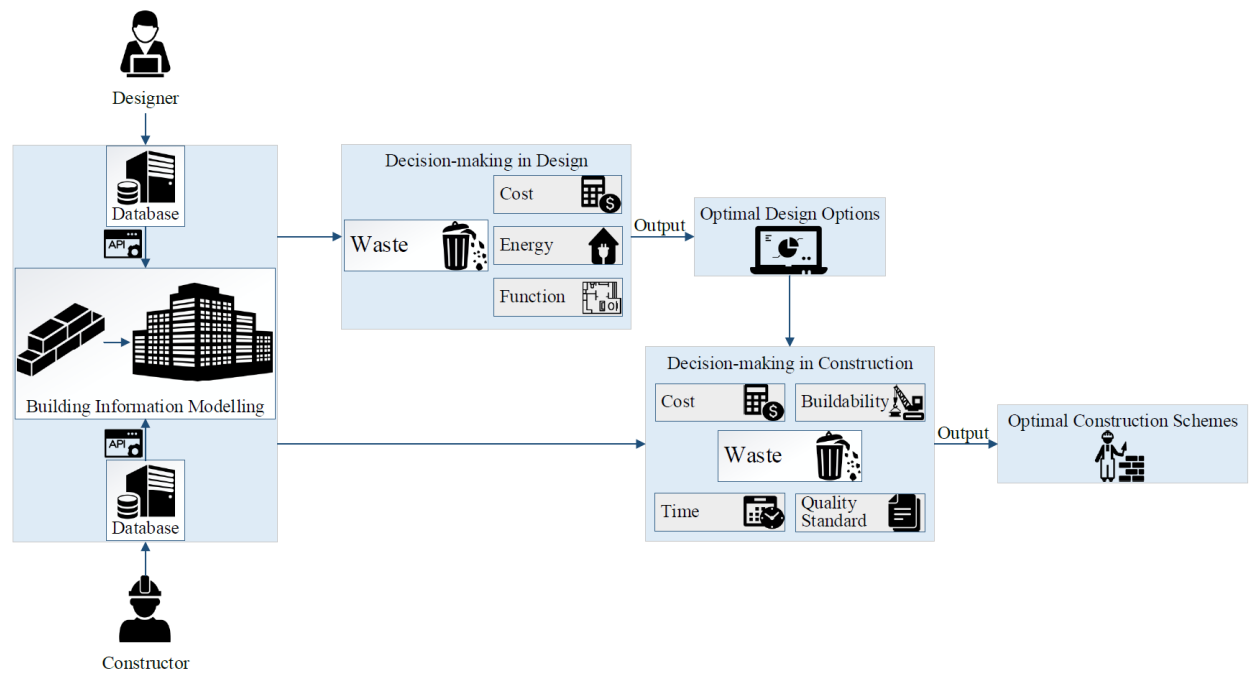


Fig. 1 The prototypical model of computational BIM for construction waste management





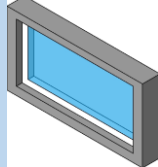
waste_generation		Design Component	Average Waste Generation Level	Size	3D Prototype
id INT(11)		1 Column_concrete	1.1	750*750mm	
design_component VARCHAR(45)		2 Door_metal	1.02	1900*1370mm	
average_waste_generation_level INT(11)		3 Door_wood	1.05	2100*750mm	
3d_prototype POLYGON		4 Door_glass	1.05	2400*850mm	
Indexes		5 Window_glass	1.05	1000*500mm	

Fig. 2 An illustration of the structure of the design options/construction schemes - waste generation databases

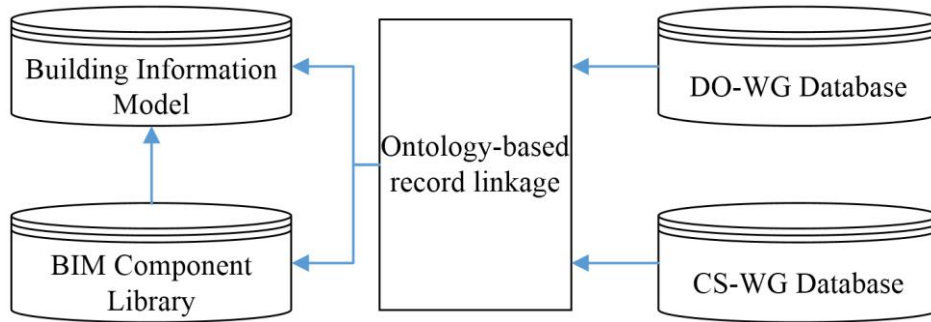


Fig. 3 The standalone design options/construction schemes - waste generation databases and their linkages to BIM component library

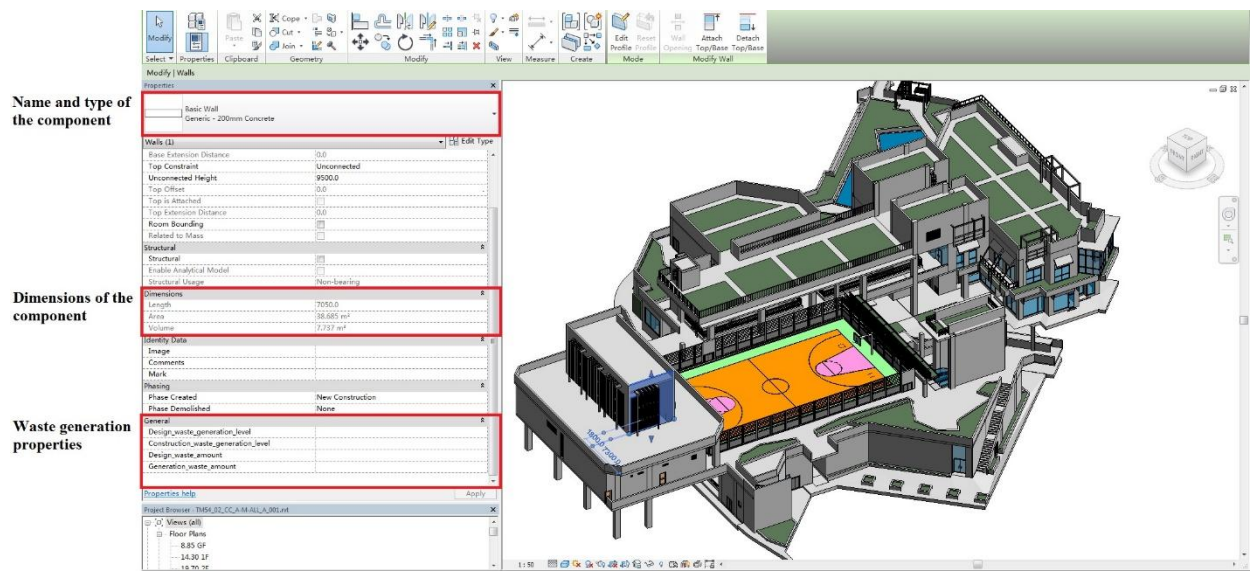


Fig. 4 A screen shot of computational BIM for construction waste management at the design stage

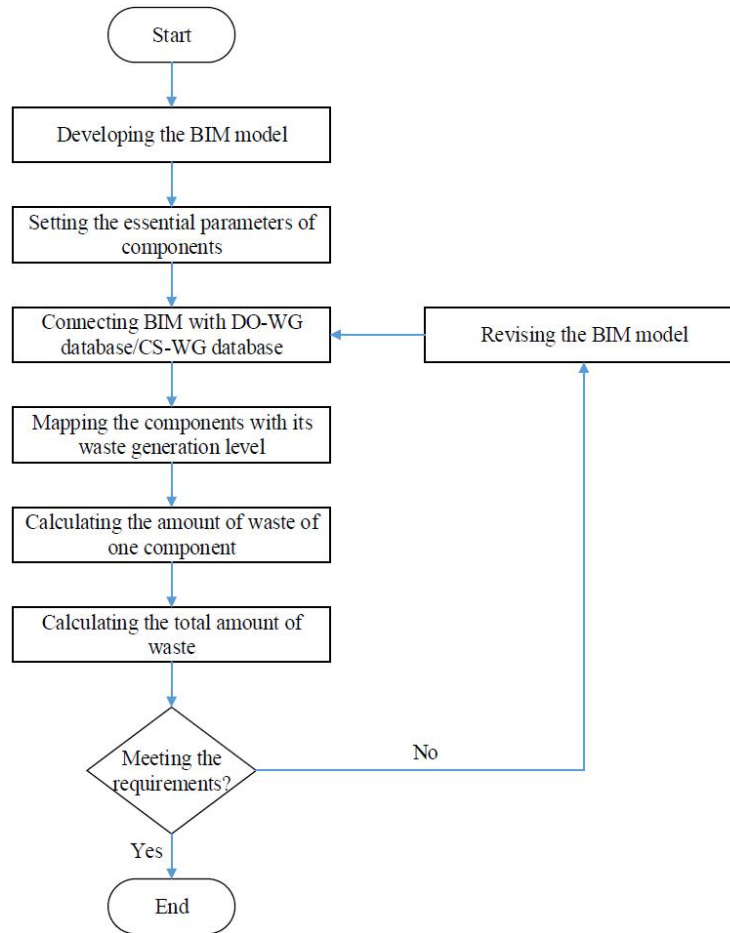


Fig. 5 Flowchart of developing computational BIM for construction waste minimization

```

namespace wastegeneration
{
    [TransactionAttribute(Autodesk.Revit.Attributes.TransactionMode.Manual)]
    public class RevitCommand : IExternalCommand
    {
        public Result Execute(ExternalCommandData commandData, ref string messages, ElementSet elements)
        {
            UIApplication app = commandData.Application;
            Document doc = app.ActiveUIDocument.Document;

            string connStr = "SERVER = 127.0.0.1; UID=root; DATABASE=waste; PASSWORD=123";
            MySqlConnection conn = new MySqlConnection(connStr);
            conn.Open();

            FilteredElementCollector collector = new FilteredElementCollector(doc, doc.ActiveView.Id);
            foreach (Element elem in collector)
            {
                string elemName = elem.Name;

                string sql = "SELECT design_component, average_waste_generation_level FROM design_options_waste_generation";
                MySqlDataAdapter SqlDap = new MySqlDataAdapter(sql, conn);
                DataSet thisDataset = new DataSet();
                SqlDap.Fill(thisDataset, "design_options_waste_generation");
                DataTable dataTable = thisDataset.Tables["design_options_waste_generation"];

                foreach (DataRow row in dataTable.Rows)
                {
                    if (elemName == row["design_component"].ToString())
                    {
                        Transaction transaction = new Transaction(doc, "waste generation");
                        transaction.Start();
                        Parameter p = elem.LookupParameter("Design_waste_generation_level");
                        p.Set(row["average_waste_generation_level"].ToString());
                    }
                }
            }
        }
    }
}

```

Connecting to the database

Acquiring the waste generation level

Setting the properties of components

Fig. 6 Part of the codes for calculating the amount of waste relating to each design option

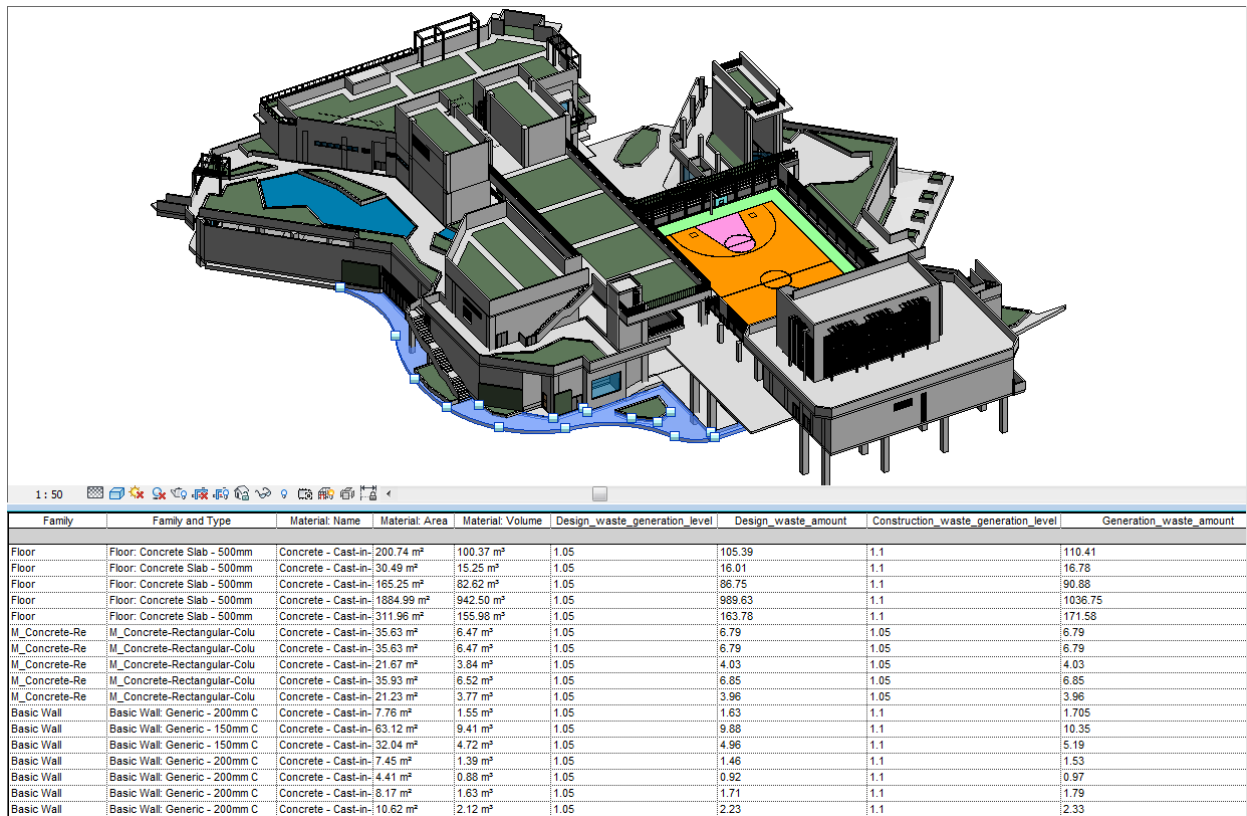


Fig. 7 Screenshot of computational BIM for construction waste management at construction planning stage