International Journal of Construction Management

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tjcm20

The integration of building information modeling (BIM) and system dynamic modeling to minimize construction waste generation from change orders

Atul Porwal, Mohammadsaeid Parsamehr, Dylan Szostopal, Rajeev Ruparathna & Kasun Hewage

To cite this article: Atul Porwal, Mohammadsaeid Parsamehr, Dylan Szostopal, Rajeev Ruparathna & Kasun Hewage (2023) The integration of building information modeling (BIM) and system dynamic modeling to minimize construction waste generation from change orders, International Journal of Construction Management, 23:1, 156-166, DOI: 10.1080/15623599.2020.1854930

To link to this article: https://doi.org/10.1080/15623599.2020.1854930

INTERNATIONAL JOURNAL OF CONSTRUCTION MANAGEMENT
2023, VOL. 23, NO. 1, 156–166
https://doi.org/10.1080/15623599.2020.1854930

The integration of building information modeling (BIM) and system dynamic modeling to minimize construction waste generation from change orders

Atul Porwal[a], Mohammadsaeid Parsamehr[b], Dylan Szostopal[b], Rajeev Ruparathna[b] and Kasun Hewage[a]

[a]School of Engineering, University of British Columbia, Kelowna, BC, Canada; [b]Department of Civil & Environmental Engineering, University of Windsor, Windsor, ON, Canada

ABSTRACT

Change iterations in construction create uncertainties and make the project management dynamic and unstable. Published literature shows that 30% of the construction cost is attributed to rework. Moreover, change orders are considered as the largest source of construction waste. Construction professionals have to make change decisions based on their previous experience and assumptions supported by incomplete information. Objective methods based on state-of-the-art technology can be systematically used to address the above challenge. Despite its promise, Building Information Modeling (BIM) based dynamic modeling has not been researched to estimate waste generation from change orders. In this paper, Building Information Modeling (BIM) was used to simulate the field data over the project lifecycle to analyze the ripple effects of construction changes. A system dynamic model was developed to map interactions in the system. Virtual BIM data was used to analyze the dynamic behavior of the variables due to the changes in the scope of work. Case study results showed that the client's commitment to decrease waste in the pre-project planning stage, with coordinated BIM design efforts, could reduce construction waste by up to 25%.

KEYWORDS

Construction waste management; pre-project planning; building information modeling (BIM); system dynamic modeling; change management

1. Introduction

Recently, the construction industry has been embracing sustainability principles more than ever in the past (Kamali and Hewage 2017). Statistics show that the construction industry is responsible for more than 12% of the landfill waste generated in Canada (CCME 2014). Construction waste generation creates cost escalations, schedule delays while impacting the sustainability performance of the project (Napier 2016). Additionally, sourcing and transporting replacement material will increase the environmental burden of a construction project (WBDG 2010). Change orders can be commonly observed in all construction projects. A change order made in one element can lead to a cascading effect on other adjoining elements (Sterman 1992; Ogunlana et al. 1998; Sacks et al. 2018). Design alterations corresponding to scope changes are a major cause of uncertainty, creating unacceptable levels of construction waste and schedule delays (Lee et al. 2003). Hence, on-site waste prevention through better coordination and advanced planning is vital for the economic and environmental performance of the construction industry (Wan et al. 2009; GSA 2012; Al-Nassar et al. 2016).

A large number of waste reduction techniques are adopted during the construction stage, yet construction waste minimization techniques during the preconstruction stage have been seldom used (Liu et al. 2011; Porwal and Hewage 2012). Love et al. (2000) emphasized the importance of establishing a top-down dynamic relationship between flow activities in the construction process to predict the construction waste generation. Ekanayake and Ofori (2004) applied multi-attribute value techniques under design, operation, material handling, and procurement related areas; and suggested that poor design is a main contributor to construction waste. Formoso et al. (1999) stated that enhanced managerial capacity in design, procurement, and production could maximize the on-site waste management programs. The Waste and Resources Action Programme in the United Kingdom developed Designing out Waste Tool for Buildings (DoWT-B) that helps design teams forecast the amount of waste generated based on the project data (WRAP 2013). There are many published research studies on waste quantification and source evaluation (Bossink and Brouwers 1996; CURT 2004), planning waste management, and construction process dynamics (Teo and Loosemore 2001; Chandrakanthi et al. 2002; Ruwanpura et al. 2003). However, previous researchers have overlooked adopting virtual construction techniques for waste minimization at the source during the project design (Osmani 2013). Moreover, no comprehensive forecasting tools or methods are available to predict the construction waste generation as a result of a change order (Formoso et al. 1999).

Yuan et al. (2012) stated that a change in traditional construction culture and behavior can considerably reduce construction waste Building Information Modeling (BIM) is a construction process simulation technique that can be adapted to obtain construction process data before the commencement of construction (Love et al. 2011, Sacks et al. 2018). BIM has been successfully used to define connections between elements, simulate construction activities, and enhance the sustainability performance of construction (Song et al. 2012; Yun et al. 2014; Mohammed 2019). System dynamic modeling is a systematic method for understanding and modeling the behavior and performance of complex systems over time (Zhang et al. 2009; Karamouz et al. 2012). System dynamic modeling has been used to model the dynamic nature of systems. BIM integrated System Dynamic

CONTACT Kasun Hewage Kasun.Hewage@ubc.ca

Model (SDM) can model the impacts of project changes as early as in the pre-project planning stage and will aid construction management decision making (Porwal 2013).

BIM-based construction waste management research has grown over the years (Won and Cheng 2017). Guerra et al. (2019) used BIM to present automated algorithms for estimating construction waste (Guerra et al. 2019). Xu et al. (2019) presented a BIM-based system to manage construction and demolition waste information for greenhouse gas quantification and reduction (Xu et al. 2019). Akinade et al. (2015) developed a BIM-based Deconstructability Assessment Score (BIM-DAS) to minimize waste through deconstruction (Akinade et al. 2015). Bakchan et al. (2019) presented a BIM-based method for the estimation of wood waste in institutional building projects (Bakchan et al. 2019). Other focuses of previous studies include demolition waste estimation (Kim et al. 2017), automated waste estimation (Bakchan et al. 2019; Guerra et al. 2019), and estimation of reinforcement waste (Porwal and Hewage 2012). According to the author's knowledge, no previous study has focused on construction waste management resulting from change orders by integrating BIM with a SDM.

The objective of this paper is to adopt BIM for construction waste reduction at the source. A BIM-based dynamic model was developed to forecast waste generation from change orders. This research focuses on the redesign process after the owner initiated scope changes. The developed method was demonstrated for a building construction project in Okanagan, BC, Canada, delivered using the design bid build (D-B-B) method project delivery. The proposed method can assist construction managers in waste minimization, cost-saving, and achieving a superior sustainability performance.

2. BIM for waste management

National Institute of Building Sciences defines BIM as a technique that enables digital representation of physical and functional characteristics of a facility (WBDG 2010; Sacks et al. 2018). BIM has been a paradigm shift in the construction industry, enabling virtual planning and realization of the actual construction project (NBS 2012; Abdulaal and Bouferguene 2017; Badi and Diamantidou 2017; Koutamanis 2017; Bruno et al. 2018). A virtual construction project makes it possible to simulate construction, trial test methods, and assess the impacts of adjustments before the project materializes (Eastman et al. 2008; Popov et al. 2010).

A BIM model contains the construction process and related data throughout the construction phase (Goedert and Meadati 2008). Hence, BIM can be used to reduce construction waste generation through enhanced communication and collaboration, increased efficiency, and reduced errors (AIA 2012; Abdulaal and Bouferguene 2017; Edirisinghe et al. 2017; Koutamanis 2017; Singh et al. 2019). BIM model help identifying design conflicts, design errors, sequencing constraints, access issues, fabrication details, and procurement constraints that impact the efficiency of the project. For example, Porwal and Hewage (2012) investigated the reduction of structural reinforcement waste in preconstruction stages using BIM (Porwal and Hewage 2012). Popov et al. (2010) used BIM and construction process simulation to investigate the most effective project alternative. Won et al. (2016) used a BIM-based design validation process to investigate the amount of construction waste that can be prevented due to design errors. Previous researchers have used BIM for real-time project monitoring (Arno and Frank 2008; Nepal et al. 2009; Popov et al. 2010; Koutamanis 2017). Jalaei et al. (2019) used BIM and LCA for life cycle waste production in construction projects. Yet, BIM's ability to forecast construction waste from change orders have been overlooked in the literature.

2.1. SDM in construction management

Published literature has revealed that top-down dynamic analysis of a change process with the help of BIM data could be used to predict the waste generation. System Dynamics enables analyzing a complex system by imitating the system over time through numerical calculations (Forrester 1958). SDM has been successfully used in a wide array of industries, including engineering, finance, and business management (Lyneis and Ford 2007). Due to the complexity, dynamic nature, and interdependencies of construction projects, SDM would be one of the most suitable methods to simulate the dynamic nature of a construction project.

Previous researchers have used SDM in project management, including large-scale civil construction projects (Sterman 1992; Chritamara et al. 2002; Park 2005; Chen and Liu 2016; De Marco et al. 2016; Wang et al. 2017). Richardson and Pugh (1981) were one of the first applications of SDM in general project management. This model was further extended for different project phases, such as the construction phase (Chang 1990), and the design phase (Lim 1994 and Ogunlana et al. 1998).

Cooper (1993) illustrated the rework cycle and construction project's developmental progression. Similarly, Love et al. (2000) observed how changes and rework impact project management. Chritamara et al. (2002) developed a detailed SDM for a Design-Build project to observe its interdependencies. Rodrigues and Williams (1998) used SDM to investigate schedule adjustments to minimize the downstream effects due to change orders. Robert (1998) used SDM to analyze the degradation of design productivity due to staff changes. Zhang et al. (2014) developed a prototype SDM that incorporates the effects of dynamical factors on the sustainability of construction projects. Maryani et al. (2015) utilized SDM in order to identify Occupational Safety and Health (OSH) cost components that need to be proactively controlled and improvements that can be made in the supply chain.

3. Research methodology

This research proposes a BIM integrated SDM model to predict construction waste generation during the design process. The proposed SDM consists of (i) earned schedule management technique, (ii) 'crew' concept for person-hour calculation, and (iii) total productivity factor integration. The research methodology consisted of four interlinked phases:

Firstly, the forecasts for cost and time overrun due to a change in scope of work were established. The initial BIM model (i.e. the original BIM model of the building) was revised to the owner requested changes. The parametric relationships defined for building elements automatically coordinates most of the changes made to the model. This is the unique feature of defining parametric relationships. The BIM model was checked for any discrepancies, and corrections should be made if needed.

Secondly, virtual project data was generated through BIM was used to assess the impact of changes in the construction process. A revised BIM model was used to obtain the revised data about the schedule, cost, and required materials. BIM is capable of conducting a clash detection that enables locating conflicts among the building components. BIM's scheduling dimension (BIM 4D)

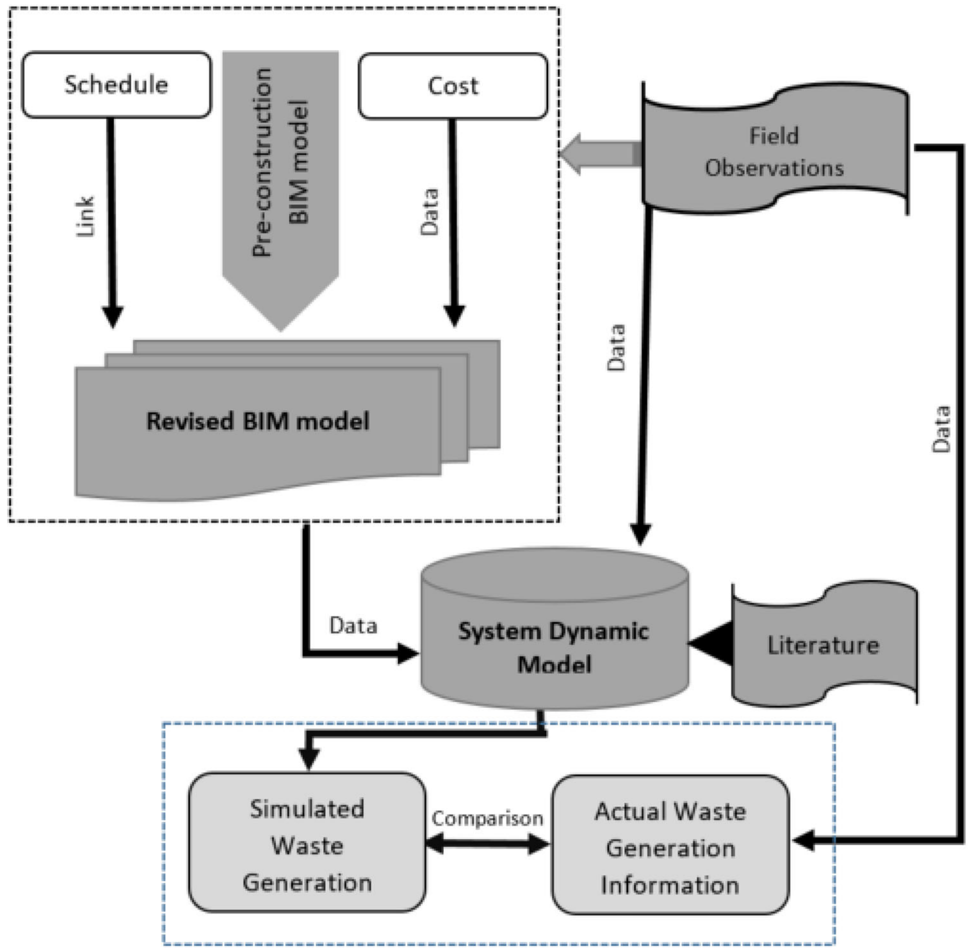

Figure 1. Integration of BIM and SDM.

links the Critical Path Method (CPM) schedule activities with 3D objects in the BIM model. Cost data associated with each model element (BIM 5D) will generate a detailed cost schedule. The subsequent changes in the design, resulting from a change in the scope of work, were analyzed with estimated quantities.

Thirdly, a SDM was developed to evaluate the impacts of changes on project performance. Additional material requirements for reconstruction were forecasted with the time. BIM data (in step 2 above), literature, and the field observations inform the exact material quantities for reconstruction and corresponding. This will be fed into the SDM to predict the resulting construction waste. File-based exchange is a popular method for interoperability between BIM and other platforms (Sacks et al. 2018). SDM and BIM were linked via file-based exchange. Finally, the SDM was demonstrated in a real construction project. Figure 1 illustrates the proposed BIM-based SDM.

3.1. The SDM development

The SDM for evaluating the effects of design changes on construction waste was formulated in the STELLA software package (isee systems Inc. 2018). STELLA software can illustrate the interrelationship between any two variables graphically. STELLA software package is an efficient and user-friendly software package for system dynamic modeling. Previous researchers have used STELLA to model water supply systems (Chhipi-Shrestha et al. 2017a), predicting municipal solid waste generation (Kollikkathara et al. 2010), water-energy-carbon nexus modeling (Chhipi-Shrestha et al. 2017b), budgeting (Srijariya et al. 2008), and urban carbon dioxide emissions (Du et al. 2018). The SDM developed for this study is similar to several system dynamic models proposed by previous researchers (Hamid-Abdel 1989; Cooper 1993; Ford and Sterman 1998; Lyneis et al. 2001; Yuan et al. 2012). This study adopted a five-step procedure to construct and simulate the model:

1. Step 1: Causal loop diagrams: describe major feedback loops in the construction system
2. Step 2: Stock-flow diagrams: convert causal loop diagrams into a stock-flow diagram
3. Step 3: Model validation: validate the model following typical model testing rules
4. Step 4: Base run and: test model outputs
5. Step 5: Model simulation: analyze BIM-Dynamics and results

The initial component list of the SDM can be separated into two groups; endogenous and exogenous:

i. Endogenous variables are dynamic variables that are directly involved in the feedback loops of the system
ii. Exogenous components can be time-varying constants or constant parameters and are termed 'quantitative variables.'

Dependent variables are another stream of variables. Their values are calculated using the values of other variables in the system dynamic model and the defined function (Yuan et al. 2012).

The BIM and project records were used to obtain values for quantitative variables. BIM enables extracting information in the database or visual format that cannot be visually observed. This information can include quantity takeoff, cost estimate, floor area, space, volume, parametric, and other interpretive values. The qualitative analysis focuses on issues of that construction project that can be visually observed. Qualitative observations include constructability analysis, system coordination, clash detection, and sustainability analysis. Several values for variables were obtained through a chronological analysis of the BIM model considering time, both in duration and sequence. These included assembly and installation sequences.

Published literature was used to identify variables that significantly influence the behavior of the system. Eighty-five essential variables were identified and included in the model. Identified variables were integrated with causal-loop diagrams. The Stock-flow diagram was finalized with equations developed based on literature data. In order to validate the SDM, a series of tests were conducted.

This research has a specific emphasis on D-B-B project delivery method. Barrie and Paulson (1992) illustrated five subsystems governing the Design Bid Build (D-B-B) project construction dynamics (i.e. (i) construction progress, (ii) material procurement, (iii) budgeted cost of work, (iv) scope change, and (v) productivity). The SDM developed in this research consists of the assembly of six sub-systems: Construction, Scope change, Productivity, Procurement, Waste, and Earned value sub-systems, which are vital for a D-B-B project. The functions of these subsystems are as follows:

- Construction sub-system: This sub-system describes the scheduled physical progress of the project. The total construction work was distributed into six main items of work: Earthwork, Concrete, Steel, Masonry, Mechanical, Electrical, Plumbing (MEP), and Finishes.
- Scope change sub-system: Scope change sub-system accounts for an additional quantity of work due to change.
- Productivity sub-system: The productivity sub-system describes the effects of factors on the progress of work.
- Procurement sub-system: The procurement sub-system simulates the logistical requirements (i.e. materials, stock quantity, and productive material) based on the construction activity and change quantities of work.
- Waste sub-system: The waste sub-system accounts for waste generation estimation.
- Earned value sub-system: Earned value sub-system accounts for the earned value.

3.1.1. Description of the proposed system with causal-loop diagrams

A causal loop illustrates the chain effects of a dynamic process where the causes are traced through a set of related variables and back to the original cause. The causal loop diagram developed for this research is comprised of eight major feedback loops. Out of these eight feedback loops, four are positive (i.e. R1, R2, R3, and R4), and the other four are negative (i.e. B1, B2, B3, and B4) (Figure 2).

The loops defined in Figure 2 are explained below:

- The loop B1 depicts the dynamic behavior of schedule management. It was identified that a stretched estimated completion date provides the flexibility to establish a longer revised schedule. Consequently, this will smoothen the schedule value, the work schedule progress curve, and the schedule performance index (SPI). However, in a time-constrained project, those above will engender a schedule oscillation. Subsequently, the project could be unstable due to fluctuations in resource usage, logistical complexities, and performance. In such a situation, stabilizing the project to the equilibrium status could take several months.
- Increased schedule pressure produces another balancing feedback loop B2. The loop B2 helps the first loop to control schedule delays. Schedule pressure created by a short delay, will eventually lower productivity due to overwork and stress on human resources. Moreover, there will be an increased resource waste. Restoring the project in line with the schedule requires additional resources. Committing additional resources for the project will improve the SPI and estimated the date of completion.
- The balancing loop B3 is defined by adding the variable, 'work scheduled remaining,' which incorporates the extra work created due to the scope alternations. Consequently, increased work quantities will adversely affect the construction progress rate.
- R1 is a reinforcing loop that describes the increase in construction complexity as an outcome of the construction overlaps due to construction changes. Construction overlaps forces changes to the project schedule and delays the project finish.
- The positive feedback loop R2 explains one of the feedback effects of the scheduling process that would stabilize schedule oscillations by reducing the balancing effect of B1. Loop R2 scrutinize errors in time estimations. More precisely, a longer estimated completion date makes a greater estimated delay and increased work pressure. Consequently, this will diminish work quality and productivity. This loop results in a weaker SPI and delayed completion.
- The feedback loop R3 illustrates a coordinated design process with the use of BIM. This process is the key to solving many constructability issues in the design phase, which will eventually reduce construction waste.
- Feedback loop R4 describes the coordination among the key stakeholders (i.e. Architectural Engineering and Construction (AEC)). More importantly, having a coordinated redesign process reduces the possibility of design changes during the construction process, which could result in reduced construction waste.
- The negative feedback loop B4 follows a similar pattern as the feedback loops R3 and R4 and is differed by added variable complexity. The involvement of the AEC team will positively influence the design quality while decreasing the construction complexities and potential changes. Consequently, this will result in reduced construction waste.

3.1.2. Model formulation through stock-flow diagrams

Identified variables have to be quantified, and their interrelationships must be mathematically defined. The conceptual model presented in Figure 2 was converted into a stock-flow diagram in the STELLA software. Equations 1–9 were used to mathematically define interrelationships.

The definition of "productivity" in the construction industry varies based on its area of application (TBR 1982). For this study, the TFP model was used to define productivity as Equation 1 (RCD 2013):

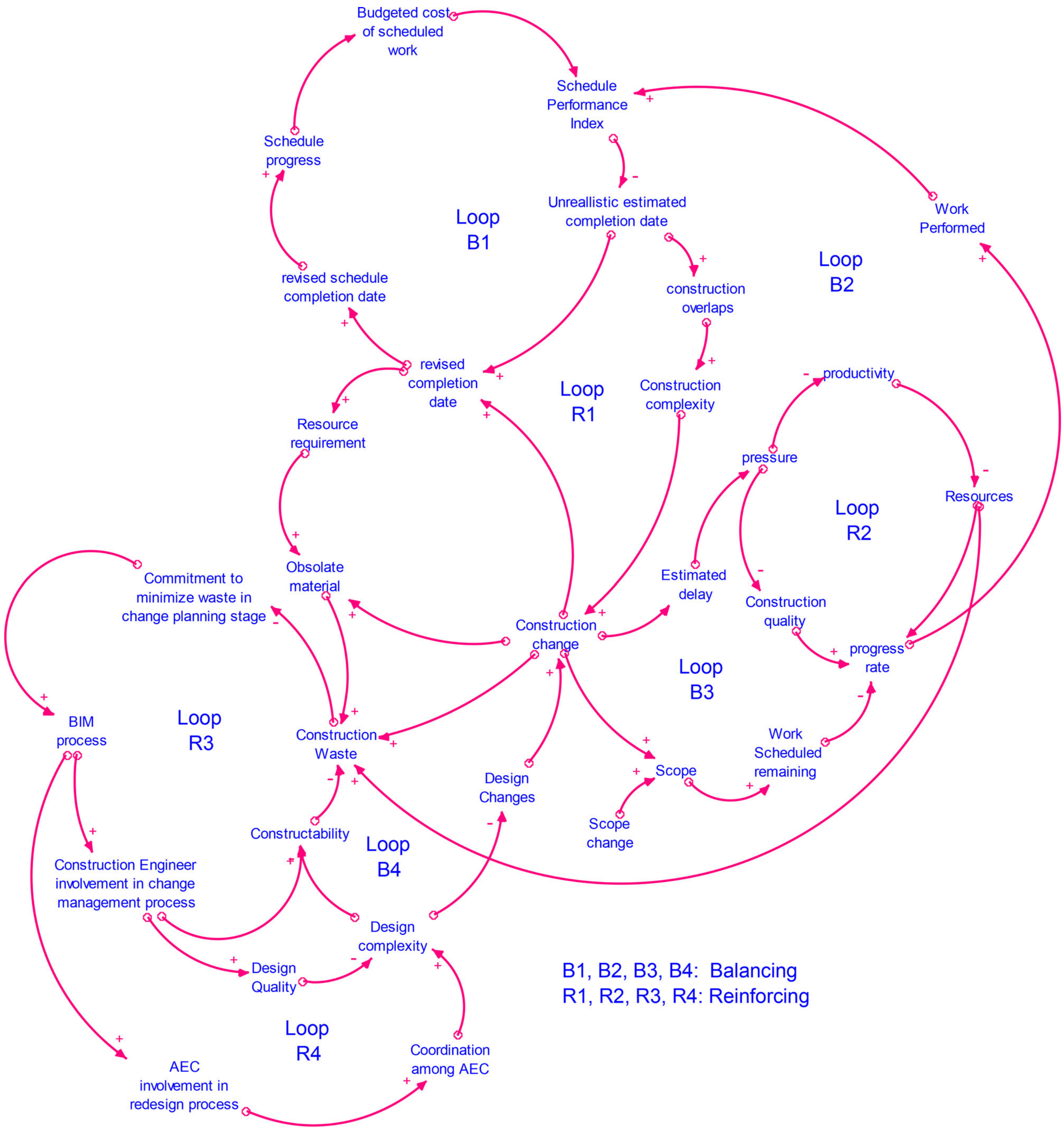

Figure 2. Causal loop diagram of waste management at source.

$$Productivity = \frac{Total\ Output}{Labour + Material + Equipment + Energy + Capital} \tag{1}$$

where '(Labour + material + equipment + Energy + capital)' was defined as 'crew'

Gross productivity was defined as (Equation 2):

$$\text{Gross Productivity} = \text{Total Output/Crew} \tag{2}$$

Productivity varies with 'item of work.' Required data were obtained from the RSMeans cost data. Afterward, the construction progress was calculated by multiplying the crew, labor productivity, and planned construction activities.

The construction progress rate is affected by delays in resuming the construction work following an interruption. In order to avoid the schedule variance construction manager decides to engage additional crews. Equation 3 was defined to derive the additional construction progress rate:

$$\text{Additional construction progress rate} = (\text{Apparent Productivity}) * \frac{\text{crew}}{\text{delay}} \tag{3}$$

The fraction of expected material waste was considered in determining the material inventory level (Equation 4):

$$\text{Concrete consumption rate} = \text{Concrete in inventory} * (1 - \text{Concrete waste factor}) \quad (4)$$

Waste factor and waste reduction rate were used to define the material wastage rate (Equation 5). The material waste factor accounts for the percentage that ends up as waste during the construction and installation process. The waste reduction rate is derived by analyzing the BIM.

$$\text{Material wastage rate} = (\text{Material in inventory}) * (\text{Material waste factor}) * (\text{Waste reduction rate}) \quad (5)$$

The organization's commitment to reduce waste is derived through the implementation of BIM (loop R3, Section). The commitment to implementing the BIM results in improvement of management capacity and traditional construction culture and behavior (Equation 6):

$$\text{Changing of traditional construction culture and behavior} = \text{Commitment to Implement BIM in thedesignphase} \quad 6$$

'Impact of BIM technology on constructability' is defined by 'influence on constructability', which is the ratio of construction engineer involvement in design and level of design complexity (Equation 7):

$$\textit{Impact of BIM technology on constructability} = \frac{\textit{Construction engineer involvement in design}}{\textit{Level of design complexity}} \quad (7)$$

The increased coordination between AEC and the construction engineer decreases the project complexities. Equation 8 was used to define the design complexity on a Likert scale of 0 to 5, with 0 being the lowest:

$$\text{Level of design complexity (t)} = \text{Level of design complexity (t} - \text{dt)} + (-\text{ Decreasing complexity}) * \text{dt;} \quad \text{dt: Fraction of time} \quad (8)$$

Initial Level of design complexity = 3;
(Decreasing complexity) = (Coordination among AEC);
(Construction change) = (Design change)/3.

The waste reduction rate varied between 0 and 0.65 based on waste reduction efforts. Equation 9 was used to define waste reduction efforts:

$$\text{Efforts to reduce waste)} = (\text{Effect of complexity on waste}) + (\text{Impacts of conflicts on waste reduction}) + (\text{Impact of constructability on the waste reduction}) \quad (9)$$

4. Case study

A new framed-structure institutional building located in western Canada was used for the case study. Project details are as follows:

- The gross floor area of the building: 16,250 m^2.
- The budgeted cost: CDN 44.60 million
- Scheduled time of completion: 25 months

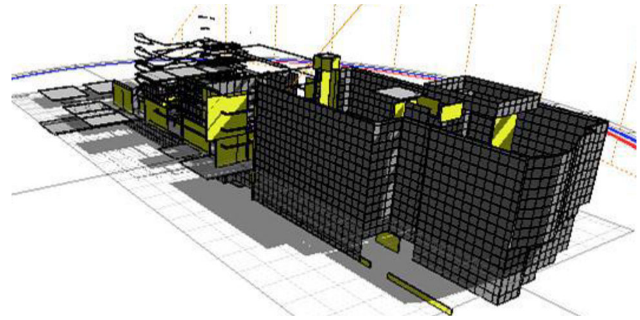

Figure 3. BIM model.

- The building details: Five floors LEED Gold certified building. The project was delivered using D-B-B method. The design team consisted of an architectural firm and an engineering design team.
- Construction start date: March 2009.

The authors closely followed the construction from January 2010 to April 2012 to obtain the required data. BIM was not used in this project during the preconstruction stage. The following work packages were used to deliver the project:

i. Earthwork
ii. Concrete
iii. Steel
iv. Masonry
v. MEP
vi. Finishes (Includes remaining works such as flooring, walls, ceiling, doors/windows, painting, etc.)

The standard productivity and crew hours were obtained from RSMeans cost database to compute the progress rate of each item of work (e.g. a cubic meter of concrete work). The budgeted cost of work was calculated based on the cost of labor, material, and equipment for the current year of proposed change execution. The project BIM model (Figure 3) was created after the start of construction work, using 2D drawings, designs, and the project Gantt chart. The BIM model (for example, structural and HVAC conflict detection analysis) was verified during the construction process. The authors performed detailed site investigations, collected the project data for the system dynamic model input, coordinated with the design and construction teams at the site, and created a partial BIM model of the project for research purposes.

The SDM development, testing, and validation were performed after the completion of the construction work. Equations embedded in the system dynamic model were determined by various sources, including BIM model data, site surveys, and published literature. The site survey included formal and informal meetings with the project manager, on-site manager, and two professional engineers. Further data was collected through consultations with the other AEC companies in the neighborhood. The SDM was developed to run for a total period of 25 months using actual project data.

The BIM integrated SDM was validated by performing the following four tests:

i. Testing the causal loop diagram for modeling waste management at the source that corresponds to the statement of the problem,
ii. Testing the equations corresponding to the causal loop diagram,
iii. Dimensional validation of the model

Table 1. Quantities of items of work.

Item of work	Quantity
Initially planned Quantities	
Earth Work	84,094 m^2
Concreting work	7977 m^2
Steel work	1380 ton
Masonry work	2379 m^3
MEP	16,248 m^2
Finishes	16,248 m^2
Addition due to change in scope	
Concrete	268 m^3
Steel reinforcement	33 T
Masonry	15 m^3
Finishes	195 m^2

iv. Extreme condition test by changing variable values to extreme values

4.1. Model analysis with BIM data

The data obtained from the BIM was used to run the SDM for 25 months to validate the proposed method. The initial simulation assumed that the scope of work is not changed, and no efforts were made to reduce construction waste by using BIM.

The owner initiated a change in the scope of work in the 9th month, during the project construction phase. The owner had requested a change to the building design. Accordingly, the BIM model was revised considering the proposed changes. The major variables quantified through BIM after the proposed change in the scope of work are shown in Table 1. Changed quantities were synchronized with the system dynamic model to observe the effects of changes on the scope of construction work. The Likert scale was simulated for 30 months to forecast the construction waste generation.

The following assumptions were made during the simulation:

- The decrease in design complexity will reduce the 'frequency of design changes' (Mitchell 2005; Xia and Chan 2012). The decrease in design change is assumed to vary between 0 and 3 with increments of 0.5.
- The impact of constructability on waste reduction was assumed to vary between 0 and 9. Increases above with the improved involvement of the construction engineer in the BIM design process.
- 'Application of constructability during design process' was measured on a 0 to 100 Likert scale in increments of 10.
- The clash detection process among structural components and HVAC system stipulated that an average of five conflicts occur per 1000 m^2 of the floor area per month of the scheduled construction period.

5. Results and discussion

A comparison of the simulation results of quantitative variables such as cost, time, and waste was performed to confirm the credibility of the established model based on the error percentage between simulation results and the historical data. Simulation results showed that the estimated cost of work was $44.62 million, and the planned time of completion as 25 months. These results were near to the initially planned values. The forecast for the amount of waste was 507.33 tonnes, and based on project records, 529.95 tonnes of waste was generated at the end of the project.

Table 2. Variable quantification through BIM model after the proposed change in the scope of work.

Limit of work space	Model viewing
Design changes	70
Application Level of BIM Technology	67
Expected Level of Applying BIM Technology	40
Clash detection	75
Complexity level	3

5.1. Scope change scenario

The scope change scenario examines the dynamics and interdependences of major variables such as effects of BIM implementation, complexity and constructability assessment (Conducted by the AEC industry), conflict detections during the design stage, and frequency of design changes. The quantification of variables through BIM is listed in Table 2.

The owner initiated a change in the scope of work in the 9th month of the construction, and the BIM has been revised accordingly with suggested changes (Section 5). Based on the design changes in the BIM model, a revised schedule of quantities was calculated. The effects of the schedule change, over time, and material availability were considered to calculate the progress rate.

The construction manager had planned the fraction change for construction work based on the work available and parallel activities to be carried out. Changes to the scope of work were incorporated into the schedule linked to the modified BIM. Correspondingly the concrete work scheduled in the 9th, 10th, and 11th months was changed to 100 m^3, 100 $m^{3,}$ and 68 $m^{3,}$ respectively.

Analyzing BIM during the redesign phase was revealed to be the most effective way to resolve constructability issues as well as waste reduction. Here construction engineer's involvement ensures satisfactory coordination until the construction of structural components and the installation of the HVAC system:

Impact of constructability on waste reduction = GRAPH (Application of Constructability during design process) (0.00, 0.00), (10.0, 0.185), (20.0, 0.405), (30.0, 0.515), (40.0, 0.695), (50.0, 0.795), (60.0, 0.89), (70.0, 0.9), (80.0, 0.9), (90.0, 0.915), (100, 0.9)

The proposed SDM identified 75 major conflicts during the BIM analysis that could cause delays and generate construction waste (Table 2). (e.g. an extension of the mechanical room precipitated adjustment in the floor levels of the adjacent floors, the creation of roof joints, and modification of HVAC and ceiling). BIM was planned to be used at a moderate level of 50 on a scale of 0 to 100 during the preconstruction stage alone without any BIM coordination during the construction process. Eventually, simulations confirmed a BIM implementation level of 67 enables achieving the projected waste reduction at source.

5.2. Sensitivity analysis

Sensitivity analysis was conducted, assigning values to specific variables for extreme conditions. The generated behavior of system dynamic model reflected the real system behavior as anticipated and understood. The parameter' Total concrete change' of 'Concrete' work was selected out of six construction sub-systems (Section 4.1) as it contributes to the major waste quantity during a scope change. The total concrete change was increased to 15% of the initial quantity of work, i.e. 1200 $m^{3,}$ with the application of BIM technology up to 50 to know the system behavior. The parameter changes do not affect the general mode of behavior of

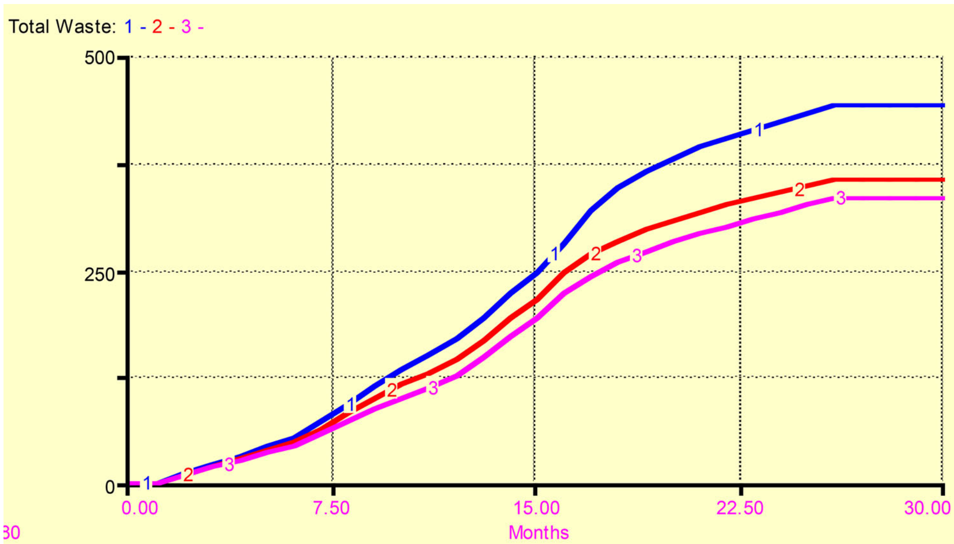

Figure 4. Model validation illustration (Curve 1 No BIM implementation; Curve 2 BIM implementation level 25; Curve 3 BIM implementation level 50).

Table 3. Comparison of simulation results with real values.

	Actual field data	BIM (Level 50) implementation	Deviation (%)
Time of completion	30 month	31.32 month	+ 1.044
EV (ACWP)	$ 47.60 M	$ 48.18 M	+ 1.015
Total waste	529.95 T	394.77 T	−25.510

the system. Figure 4 illustrates the variation in total waste generation with various BIM implementation levels. Curve-1 and Curve-3 show waste generation without BIM implementation and BIM implementation at a level of 50, respectively.

Table 3 compares the model-generated behavior vs. real system behavior. Results revealed that design coordination has the highest impact on waste generation. By allowing BIM coordination early in the design phase of the project can reduce construction waste by up to 25% at source. The pattern of potential waste reduction during the construction period depicts a constant waste reduction rate from the 5th month to the 19th month, during which most of the structural and MEP works were completed (Figure 5). Waste generation ended from the 26th month (i.e. when finishing commenced).

6. Conclusions

The environmental impact of construction has been a much-discussed topic. There is an urgent need to find construction waste reduction methods at its source rather than managing those on site. BIM has been creating a paradigm shift in design and construction and has the potential to address many challenges associated with construction management (e.g. sustainability, facilities management, and safety management). BIM and system dynamic modeling integration is an effective strategy that could be used to predict the dynamic behavior of variables associated with the construction process.

An integrated prototype model proposed in this study is a novel method to assess and predict construction waste virtually. The proposed BIM-based SDM provides a reliable and comprehensive method to minimize construction waste. This approach is capable of accounting for the overall dynamic relationships between the main causes and origins of construction waste and make predictions about construction waste generation. By allowing BIM coordination early in the design phase of the project can reduce construction waste up to 25% at source.

This study also introduced a method to assess time overrun by incorporating the earned schedule management concept. A more practical crew concept has been introduced to simulate real-life man-hour calculations, which can further be improved to simulate cost forecast. The combination of BIM simulation, dynamic feedback process, and other management techniques (earned schedule, crew, and total factor productivity) leverages the strength of BIM in the attainment of sustainable development. It can be concluded that the BIM-based SDM integration is a practicable waste management methodology.

Project delivery methods could range from a simple design and build formation to public-private partnerships with a complex design, build, financing, and operating responsibilities involving multiple stakeholders (Kangari and Riggs 1989; Ruparathna 2013). D-B-B is one of the most commonly used project delivery methods for public construction projects (PCCBC 1998). D-B-B is a two-phase procurement method, where design and construction acquisitions are performed as separate phases (Ibbs et al. 2003; GSA 2012; Ruparathna and Hewage 2015). Lack of contractor input on the design impacts the constructability of the project. Moreover, the construction process is frequently obstructed by design mistakes, incompatible drawings, incomplete details, and thus adjustments and change orders that result in waste generation and cost overruns.

D-B-B was selected as the case study in this research. The aim was to ensure the best value for the public in D-B-B project delivery method. The method developed in this research could be extended to other areas in construction management, including cost, safety, and quality as a future research direction. The level of detail in the SDM has been a limitation of this study. The outcome of the proposed method could be improved by creating a comprehensive SDM with greater details of the

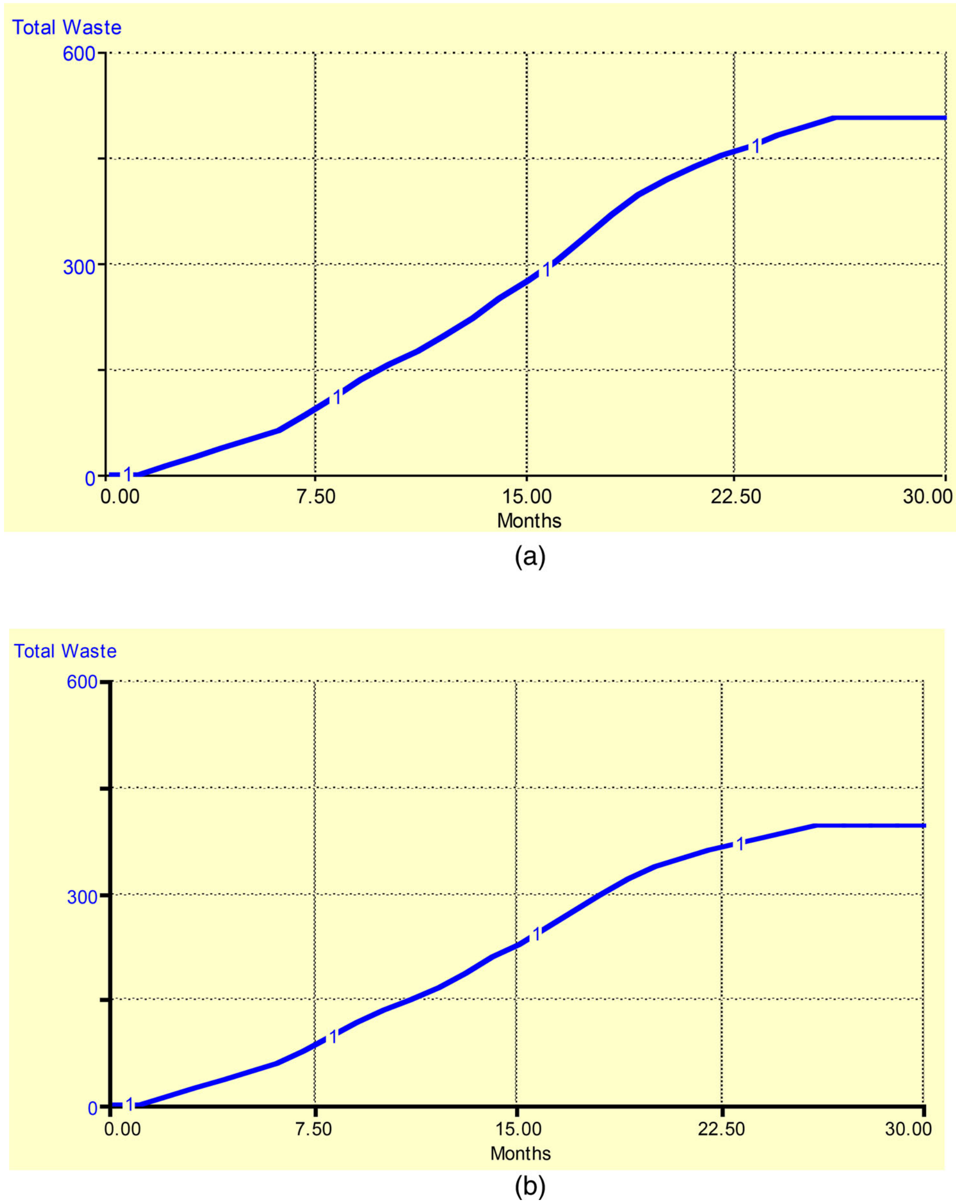

Figure 5. (a) Before BIM implementation – 529.95 tones (Without BIM). (b) After change in scope – 394.77 tones (With BIM).

construction process and its outcomes. Moreover, the proposed model can be validated by a qualitative comparison between the model structure and the real system and investigating model behavior in extreme scenarios. More importantly, the proposed method complements the BIM induced paradigm shift in the construction industry.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Abdulaal B, Bouferguene A. 2017. Benchmark Alberta' s architectural, engineering and construction industry knowledge of building information modelling (BIM). Can J Civ Eng. 67:1–34.

AIA. 2012. Integrated project delivery: a guide. [accessed 2012 Jan 10]. www.aia.org/contractdocs/AIA. S07 7630.

Akinade OO, Oyedele LO, Bilal M, Ajayi SO, Owolabi HA, Alaka HA, Bello, SA. 2015. Resources, conservation and recycling waste minimisation through deconstruction: a BIM based Deconstructability Assessment Score (BIM-DAS). Resour Conserv Recycl. 105:167–176. https://doi.org/10.1016/j.resconrec.2015.10.018.

Al-Nassar F, Ruparathna R, Chhipi-Shrestha G, Haider H, Hewage K, Sadiq R. 2016. Sustainability assessment framework for low rise commercial buildings: life cycle impact index-based approach. Clean Techn Environ Policy. 18(8):2579–2590.

Arno S, Frank T. 2008. Building information model based energy/exergy performance assessment in early design stages. Autom Constr. 18 :153–163.

Badi S, Diamantidou D. 2017. A social network perspective of building information modelling in Greek construction projects. Architect Eng Des Manage. 13(6):406–422.

Bakchan A, Faust KM, Leite F. 2019. Seven-dimensional automated construction waste quantification and management framework: integration with project and site planning. Resour Conserv Recycl. 146:462–474.

Barrie DS, Paulson BC. 1992. Professional construction management. In: McGraw-Hill Series in Construction Engineering and Project Management. 3rd ed. New York: McGraw-Hill.

Bossink BAG, Brouwers HJH. 1996. Construction waste: quantification and source evaluation. J Constr Eng Manage. 122(1):55–60.

Bruno S, De Fino M, Fatiguso F. 2018. Historic building information modelling: performance assessment for diagnosis-aided information modelling and management. Autom Constr. 86:256–276.

CCME. 2014. Current priorities. [accessed 2018 Jun 30]. https://www.ccme.ca/en/current_priorities/waste/waste/crd-waste.html.
Chandrakanthi M, Hettiaratchi P, Prado B, Ruwanpura JY. 2002. Optimization of the waste management for construction projects using simulation. Proceedings of the 2002 Winter Simulation Conference, Institute of Electrical and Electronics Engineers Inc, San Diego (CA); p. 1771–1777.
Chang C. 1990. Applying R&D project dynamics to construction management, AIT Research No. IE-90-1. Bangkok (Thailand): Asian Institute of Technology.
Chritamara S, Ogunlana SO, Bach NL. 2002. System dynamics modeling of design and build construction projects. Constr Innov. 2(4):269–295.
Chen X, Liu YS. 2016. The construction of the coordinated dynamic model of owners' integrated management organization of governmental non-profitable investment projects. J Discrete Math Sci Cryptogr. 19(3): 663–676.
Chhipi-Shrestha G, Hewage K, Sadiq R. 2017a. Impacts of neighborhood densification on water-energy-carbon nexus: investigating water distribution and residential landscaping system. J Cleaner Prod. 156:786–795.
Chhipi-Shrestha G, Hewage K, Sadiq R. 2017b. Water–energy–carbon nexus modeling for urban water systems: system dynamics approach. J Water Resour Plann Manage. 143(6):04017016.
Cooper KG. 1993. The rework cycle… How it really works… and reworks… PMNetwork magazine. *Project Management Journal*, USA.
CURT. 2004. Collaboration, integrated information, and the project lifecycle in building design. Construction Users Roundtable, Construction and Operation, August (2004), P16 United States.
De Marco A, Rafele C, Thaheem MJ. 2016. Dynamic management of risk contingency in complex design-build projects. J Constr Eng Manage. 142(2):04015080.
Du L, Li X, Zhao H, Ma W, Jiang P. 2018. System dynamic modeling of urban carbon emissions based on the regional national economy and social development plan: a case study of Shanghai city. J Cleaner Prod. 172:1501–1513.
Eastman C, Teicholz P, Sacks R, Liston K. 2008. BIM handbook: a guide to building information modeling for owners, managers, designers, engineers, and contractors. Hoboken (NJ): John Wiley & Sons, Inc.
Edirisinghe R, London KA, Kalutara P, Aranda-Mena G. 2017. Building information modelling for facility management: are we there yet? Eng, Const Arch Man. 24(6):1119–1154.
Ekanayake EL, Ofori G. 2004. Building waste assessment score: design-based tool. Building Environ. 39(7):851–861.
Ford DN, Sterman JD. 1998. Dynamics modeling of product development process. Syst Dyn Rev. 14(1):31–68.
Formoso CT, Isatto EL, Hitomi H. 1999. Method for waste control in the building industry. Proceedings IGLC-7, 7th Conference of the International Group for Lean Construction, Berkeley, CA.
Forrester JM. 1958. Industrial dynamics: a major breakthrough for design makers. Harv Bus Rev. 26 (4) :37–66.
Goedert JD, Meadati P. 2008. Integrating construction process documentation into building information modelling. J Constr Eng Manage. 134(7): 509–516.
GSA. 2012. Bidding on federal construction projects. U.S. General Service Administration [accessed March 2012]. http://www.gsa.gov/portal/content/103328.
Guerra BC, Bakchan A, Leite F, Faust KM. 2019. BIM-based automated construction waste estimation algorithms: the case of concrete and drywall waste streams. Waste Manage. 87:825–832.
Hamid-Abdel T. 1989. The dynamics of software project staffing. A system dynamics based simulation approach. IEEE Trans Softw Eng. 15(2): 109–119.
Ibbs CW, Kwak YH, Ng T, Odabasi AM. 2003. Project delivery systems and project change: quantitative analysis. J Constr Eng Manage. 129(4):382–387.
Jalaei F, Zoghi M, Khoshand A. 2019. Life cycle environmental impact assessment to manage and optimize construction waste using Building Information Modeling (BIM). Int J Constr Manage. 19:1–18. https://doi.org/10.1080/15623599.2019.1583850.
Kamali M, Hewage K. 2017. Development of performance criteria for sustainability evaluation of modular versus conventional construction methods. J Cleaner Prod. 142:3592–3606.
Kangari R, Riggs LS. 1989. Construction risk assessment by linguistics. IEEE Trans Eng Manage. 36(2):126–131.
Karamouz M, Goharian E, Nazif S. 2012. Development of a reliability based dynamic model of urban water supply system: a case study. Proceedings of the World Environmental and Water Resources Congress 2012: Crossing Boundaries; p. 2067–2078. https://doi.org/10.1061/9780784412312.208
Kim Y-C, Hong W-H, Park J-W, Cha G-W. 2017. An estimation framework for building information modeling (BIM)-based demolition waste by type. Waste Manag Res. 35(12) :1285–1295.
Kollikkathara N, Feng H, Yu D. 2010. A system dynamic modeling approach for evaluating municipal solid waste generation, landfill capacity and related cost management issues. Waste Manage. 30(11):2194–2203.
Koutamanis A. 2017. Briefing and building information modelling: potential for integration. Int J Architect Comput. 15(2):119–133.
Mohammed AB. 2019. Applying BIM to achieve sustainability throughout a building life cycle towards a sustainable BIM model. Int J Constr Manage. 0(0):1–18.
Napier T. 2016. Construction waste management. [accessed 2020 March 27]. https://www.wbdg.org/resources/construction-waste-management.
Lee S, Peña-Mora F, Park M. 2003. Dynamic quality and change management framework for con-current design and construction. ASCE Construction Research Congress. Honolulu (HI): ASCE (Electronic Book).
Lim J. 1994. Management of civil engineering design project: a system dynamics model [AIT Thesis No ST-94-10]. Bangkok (Thailand): Asian Institute of Technology.
Liu Z, Osmani M, Demian P, Baldwin AN. 2011. The potential use of BIM to aid construction waste minimization. Proceedings of the CIB W78-W102 2011: International Conference – Sophia Antipolis, France; p. 26–28.
Love PED, Edwards DJ, Han S, Goh YM. 2011. Design error reduction: toward the effective utilization of building information modeling. Res Eng Design. 22(3):173–187.
Love PED, Mandal P, Smith J, Li H. 2000. Modeling the dynamics of design error induced rework in construction. Constr Manage Econ. 18(5): 567–574.
Lyneis MJ, Cooper KG, Els SA. 2001. Strategic management of complex projects: a case study using system dynamics. Syst Dyn Rev. 17(3):237–260.
Lyneis MJ, Ford DN. 2007. System dynamics applied to project and management. Syst Dyn Rev. 23(2-3):157–189.
Maryani A, Wignjosoebroto S, Partiwi SG. 2015. A system dynamics approach for modeling construction accidents. Procedia Manuf. 4: 392–401.
Mitchell WJ. 2005. Construction complexity. In: Martens B, Brown A, editors. Computer aided architectural design futures. 1st ed. Springer Netherlands; p. 41–50.
NBS. 2012. National BIM report, building information modeling. The National BIM Library [accessed 2012 Feb 03]. www.thenbs.com/corporate/about.asp.
Nepal MP, Zhang J, Webster A, Staub-French S, Pottinger R, Lawrence M. 2009. Querying IFC-based building information models to support construction management function. In: Construction Research Congress, ASCE, Seattle, Washington; p. 506–515.
Ogunlana S, Lim J, Saeed K. 1998. DESMAN: a dynamic model for managing civil engineering projects. Comput Struct. 67 (5):401–419.
Osmani M. 2013. Design waste mapping: a project lifecycle approach. Proc ICE Waste Resour Manage. 166(3):114–127.
Park M. 2005. Model-based dynamic resource management for construction projects. Autom Constr. 14(5):585–598.
PCCBC. 1998. Procedures and guidelines recommended for use on publically-funded construction projects. Produced by the Public Construction Council of British Columbia [accessed 2012 Mar 15]. www.pccbc.com/.
Popov V, Juocevicius V, Migilinskas D, Ustinovichius L, Mikalauskas S. 2010. The use of virtual building design and construction model for developing an effective project concept in 5D environment. Autom Constr. 19(3): 357–367.
Porwal A. 2013. Construction waste management at source: a building information modelling based system dynamics approach [PhD dissertation]. Faculty of Graduate Studies, University of British Columbia.
Porwal A, Hewage KN. 2012. Building information modeling–based analysis to minimize waste rate of structural reinforcement. J Constr Eng Manage. 138(8):943–954.
RCD. 2013. RSMeans. Reed Construction Data Inc.
Richardson GP, Pugh AL. 1981. Introduction to system dynamics modelling with DYNAMO. Cambridge (MA): MIT.
Robert JC. 1998. The role of system dynamics in understanding the impact of changes to key project personnel on design production within construction projects. Int J Project Manage. 16 (4):235–247.
Rodrigues AG, Williams TM. 1998. System dynamics in project management: assessing the impacts of client behavior on project performance. J Oper Res Soc. 49(1):2–15.
Ruparathna R. 2013. Emergy based procurement framework to improve sustainability performance in construction [Masters dissertation]. Faculty of Graduate Studies, University of British Columbia.

Ruparathna R, Hewage K. 2015. Review of contemporary construction procurement practices. J Manage Eng. 31(3):04014038.
Ruwanpura J, Prado B, Hettiaratchi P. 2003. A computer simulation model to predict waste generation and promote sustainable construction practices at construction sites. Canadian Society for Civil Engineering – 31st Annual Conference: 2003 Building our Civilization, June 4, 2003–June 7, Canadian Society for Civil Engineering, Moncton, NB, Canada; p. 499–508.
Sacks R, Eastman C, Lee G, Teicholz P. 2018. BIM handbook: a guide to building information modeling for owner, managers, designers, engineers, and contractors. 3rd ed. Hoboken (NJ): Wiley Publishing.
Singh MM, Sawhney A, Borrmann A. 2019. Integrating rules of modular coordination to improve model authoring in BIM. Int J Constr Manage. 19(1):15–31.
Song S, Yang J, Kim N. 2012. Development of a BIM-based structural framework optimization and simulation system for building construction. Comput Indus. 63(9):895–912. https://doi.org/10.1016/j.compind.2012.08.013.
Srijariya W, Riewpaiboon A, Chaikledkaew U. 2008. System dynamic modeling: an alternative method for budgeting. Value Health. 11:S115–S123.
Sterman JD. 1992. System dynamic modelling for project management. Cambridge (MA): Massachusetts Institute of Technology.
TBR. 1982. The business roundtable, measuring productivity in construction. A-1 Report of the Construction Industry Cost Effectiveness Project, New York, NY.
Teo MMM, Loosemore M. 2001. A theory of waste behaviour in the construction industry. Constr Manage Econ. 19(7):741–751.
Wan SKM, Kumaraswamy MM, Liu DTC. 2009. Contributors to construction debris from electrical and mechanical work in Hong Kong infrastructure projects. J Constr Eng Manage. 135 (7):637–646.
Wang L, Kunc M, Bai S. j. 2017. Realizing value from project implementation under uncertainty: an exploratory study using system dynamics. Int J Project Manage. 35(3):341–352.
WBDG. 2010. Design guidance. Whole Building Design Guide, National Institute of Building Sciences [accessed 2012 Feb 16]. www.wbdg.org/design/.
Won J, Cheng JCP. 2017. Identifying potential opportunities of building information modeling for construction and demolition waste management and minimization. Automat Constr. 79:3–18.
Won J, Cheng JCP, Lee G. 2016. Quantification of construction waste prevented by BIM-based design validation: case studies in South Korea. Waste Manage. 49:170–180.
WRAP. 2013. Civil engineering projects: waste less and save money. Material change for a better environment, England [accessed 2013 May 08]. www.wrap.org.uk.
Xia B, Chan A. 2012. Measuring complexity for building projects: a Delphi study. Eng Constr Arch Man. 19(1):7–24.
Xu J, Shi Y, Xie Y, Zhao S. 2019. A BIM-based construction and demolition waste information management system for greenhouse gas quantification and reduction. J Clean Prod. 229:308–324. https://doi.org/10.1016/j.jclepro.2019.04.158.
Yuan H, Chini AR, Lu Y, Shen L. 2012. A dynamic model for assessing the effects of management strategies on the reduction of construction and demolition waste. Waste Manage. 32(3):521–531.
Yun S, Jun K, Son C, Kim S. 2014. Preliminary study for performance analysis of BIM-based building construction simulation system. KSCE J Civ Eng. 18(2):531–540. https://doi.org/10.1007/s12205-014-0174-2.
Zhang H, Zhang X, Zhang B. 2009. System dynamics approach to urban water demand forecasting: a case study of Tianjin. Trans Tianjin Univ. 15(1):70–74.
Zhang X, Wu Y, Shen L, Skitmore M. 2014. A prototype system dynamic model for assessing the sustainability of construction projects. Int J Project Manage. 32(1):66–76.