Sustainable Construction: An Information Modelling Approach for Waste Reduction

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Abstract

Construction waste is considered as a major contributor of solid wastes in municipal landfills. Construction, renovation, and demolition (CRD) waste generated by the Canadian construction industry accounts for 27% of total municipal solid waste disposed in landfills. However, many researchers stated that 75% of what the construction industry generates as waste has a residual value and therefore recycled, salvaged, and/or reused. With the same philosophy, municipal landfill facility of the city of Vancouver and Kelowna, Canada restricted the acceptance of construction waste. In such circumstances construction waste has to go for recycling, which is as costly as to go for new material. Sustainable and practical solutions then have to: 1) maximize the reuse of construction waste during the project construction phase, and 2) optimize the material usage of the ‘proposed construction’ in the design phase itself. To achieve both of these objectives, real-time information system - that can forecast potential waste of given project/s with material properties, cost, time, life cycle, and manufacturer specifications - is required.

Building Information Modeling (BIM) is a relatively new and much unexplored area in construction waste management, which has immense potential with today’s computing power and technology. BIM can be used to optimize construction material use (and reuse) by micro-mapping construction lifecycle with virtual resource management. An optimized building model can be obtained by simulating the objects and spaces in the BIM with a novel use of dynamics modeling techniques and multi-criteria decision making methods. In addition, the proposed system dynamics modeling approach allows real time optimization of material discrepancies due to changes in the scope of construction projects. BIM as a virtual construction tool, integrated with project scheduling tool and proposed simulation technique, will facilitate waste minimization, right at the source, and allows construction managers to pre-plan sustainable construction by reusing waste material throughout the project lifecycle.

Key Words: Sustainability, Construction waste management, Building information modelling, System dynamics modelling, Waste prediction and reuse
1. Introduction

Environmental sustainability has become a major concern for many industries in Canada and sustainable development practices are well recognized and enforced by all governments (local and federal) in Canada. However, Environment Canada estimated 9 million tons of construction and demolition wastes on annual basis in Canada (The Canadian Construction Association, 1992). This figure accounts for 1/3 of the country’s solid waste stream and therefore construction waste management should be considered on priority basis. The construction industry, like many other industries, need to adopt advancements in technologies to overcome adverse impacts of construction waste. Leadership in Energy and Environmental Design (LEED) is one of the most accepted and widely recognized sustainable building rating systems (Syal et al. 2007). Construction waste management often focuses on reuse, recycle, and proper disposal of waste materials at landfills; reduction is the best and most efficient method for minimizing the generation of waste and eliminating many of the waste disposal problems (Begum et al. 2006). Over the past years, though focus on reduction of waste has been negligible, employing waste reduction strategies may still be the best approach towards minimizing the intensity of the construction waste problem.

Contractors usually have a low priority on environmental aspects compared to meeting budget targets and schedules (Poon et al. 2001). Immediate economic benefits are not usually revealed from waste reduction, reuse, and recycling activities, however managing building material waste can in fact lead to achieve higher construction productivity, time savings, and improve on-site safety (Gavilan and Bernold 1994; Poon et al. 2001). It is necessary to incorporate general strategies related to improving the managerial capacity at design, procurement, and production stages, including financial and nonfinancial measures, to achieve economic benefits of an on-site waste management program (Carlos et al. 2002). There are many research studies on waste quantification (Cochran et al. 2007), source evaluation (Bossink et al. 1996) and planning waste management (Tam 2008; Ruwanpura et al., 2003; Chandrakanthi et al. 2002); however fully integrated waste control in production planning and construction process, in real time is yet to be achieved. Authors recognized that construction waste management process must involve not only the site management team, but also the Architect and Engineers involved in the design process.

Change in scope of work usually creates rework cycle (James et al. 2007). The rework cycle is recursive nature in which rework generates more rework that creates more waste material. Changes, which are documented in the form of change orders, occur for many reasons on construction projects. The primary causes of changes as classified by U.S. federal govt. studies (National Research Council 1986) are- design deficiencies, criteria changes, unforeseen conditions including differing site conditions, change in scope directed by the owner. The research work at the University of British Columbia - Okanagan aims to predict construction waste generation and generation pattern due to rework, in the dynamics system, over the entire project life cycle. The main objectives of the research project are to develop a System Dynamics Model (SDM) which can predict the waste in integration with a Building Information Model (BIM).
2. Background

Research studies on estimation of construction waste quantities often identify the quantity of waste generation related to net worth of construction, demolition and renovation, building category, and size (Cochran et al. 2007). Another most common method in estimating construction waste quantities is based on per capita multipliers, especially in estimating municipal solid waste. Yost and Halstead (1996) proposed a method based on the financial value per square footage of the building, and empirically estimated waste quantity by weight per square foot of the building, to overcome the limitations of per capita multipliers based estimates. A definition of construction waste, based on direct and indirect waste, was then introduced in 2002 where the concept of waste was directly associated with the use of resources that do not add value to the final product (Carlos et al. 2002). The amount of material waste was defined in Equation 1, as the difference between the amount of materials effectively purchased by the company \((M_{\text{purchased}})\), less the amount of existing inventories \((\text{Inv})\), in relation to the amount of materials defined by the measurement of work done \((M_{\text{designed}})\),

\[
\text{Waste (\%)} = \frac{\left(M_{\text{purchased}} - \text{Inv}\right) - M_{\text{designed}}}{M_{\text{designed}}}
\]

The percentage represented in Equation 1 includes material waste of both direct and indirect waste. However it does not consider possible losses of materials that are implicit in the design of components. Carlos et al. (2002) suggested an option to use off-site preassembled materials, which may drastically reduce waste (such as steel reinforcement), however no further research on the economic benefits of such an approach has been published. A system analysis tool for construction and demolition waste management was then introduced in 2004 where the material quantities for each building category were determined as a function of 1) number of building permits issued, 2) the average floor area of a building of the category in concern, and 3) the weight of the materials contained in a unit area of a building (Wang et al. 2004). This method assumes 10% of the material quantity generated as debris, while 100% of the material quantity physically present in a building as debris for demolition projects. Cochran et al. (2007) developed an approach for estimating regional building-related C&D generation and composition. This methodology predicted regional waste quantities and composition construction (both residential and non residential), renovation, and demolition projects. It estimated waste as a product of “activity level of construction, demolition, or renovation in a region” and “waste produced per activity”. This quantification has an applicability on on-site waste management.

Almost all published research studies found in literature failed to focus on the causes of construction waste generation real-time control and management of on-site waste generation. Moreover, current methods are incapable of predicting the “time variable nature” of waste generation due to changes in scope of work and designs. It is evident that a few researches identified the origins and causes of waste generation and contributory factors (Bossink and Brouwers 1996; Gavilan and Bernold 1994; Osmani et al. 2008b). These researchers identified causes of construction waste generation during various project phases/stages related to process and operation. Major categorized sources were 1) direct waste as the residual of scrape resulting
from cutting of materials and 2) indirect waste used as aid in production process but did not end up as a part of the structure. Other identified causes of waste generation were based on various stages throughout the project lifecycle such as initiation stage, design stage, and procurement stage. Main causes were categorized as design coordination, lack of planning in delivery of materials, deviation in dimensions under the different stages of project life cycle. Weather, theft, and vandalism were identified as minor causes. Osmani et al. (2008a) mainly focussed their study on reduction of waste during the design phase and the study considered factors contributing to waste generation in designs. Hao et al. (2008) adopted a different approach for managing construction waste by using system dynamics modelling (SDM), where construction waste quantities were estimated as a fixed percentage of the purchased quantity of material. His simulation model emphasised on on-site waste sorting methods, to minimize landfill unit charges and transportation charges.

To date, no methodology to optimize construction waste by integrating real-time digital information of the project model and system dynamics has been developed. The proposed methodology in this paper integrates BIM data with System Dynamics to predict construction waste, to maximize reuse of waste material during the entire project lifecycle. Parametric engine of BIM makes it possible to generate revised material quantities created due to change in scope of work during the construction process. This information of revised material quantity was modelled by mapping with the dynamic factors which influence waste generation during project lifecycle to predict waste quantities. This paper presents a real-time BIM and SDM based methodology, to minimize construction waste generated due to rework, lack of coordination, and poor integration of building subsystems, by considering construction project dynamics.

3. Modelling of Construction Waste Management Process

As per the Figure 1, the waste modelling approach proposed in this paper incorporates information generated through BIM model into the SDM. The model compares bill of material quantities generated in a particular project phase, at a particular time by incorporating changes, with original bill of material quantities of the project. This approach provides anticipated percentage waste at a given moment (refer Equation 1). The first and core component of the concept is 3D model of the building (BIM) comprising of all the constituent parts of the construction process such as architectural, structural, mechanical, technological and construction process management and evaluation. One specific feature of BIM is that segmented work at the design stage is replaced by a continuous process and design is treated as an integral part of the building life cycle.

The term parametric refers to the relationship among the elements of building model. These automatically created relationships enable to coordinate and manage the changes made to the building model. All elements of real structure are defined by their quantitative information (length, area, volume) and qualitative information (material, contents). Another component of the model is time related data. The computer-aided evaluation system in construction based on BIM concept interconnects structural design, evaluation and scheduling gives estimated quantitative data of material for a particular construction activity (construction phase). All
information about the operations and resources can be passed from the estimate to scheduling applications, such as MS Project. Any changes in the design occurred due to change in scope of work, when compared with estimated quantities, gives a number, as the fraction of quantity change. Fraction of material required for the particular construction phase due to created rework is analysed with time for different variables (material requirement rate, construction change rate, material inflow, estimate fraction, consumption fraction etc.) to predict waste material and possible reuse in the construction. In case of large infrastructure project with different site locations, complete data can be used on server for multiple accesses by built team in real time.

Industry Foundation Class (IFC) developed by International Alliance for Interoperability (IAI) is widely used to exchange digital information through BIM model to different users.

4. BIM as an Approach for Real-Time Construction Waste management

BIM is a process by which digital representation of physical and functional characteristics of a facility are built, analyzed, documented, and assessed virtually, and then revised iteratively until the optimal “model” is documented (National Institute of Building Sciences 2010). The BIM process continues throughout lifetime of a facility (NIBS 2010). Although, 3D model is the geometric platform on which BIM operates, the core of BIM has a digital database where objects, spaces, and facility characteristics are each defined and stored (Building Smart Alliances 2010). The digital database allows BIM to act as a virtual representative of a physical facility to perform qualitative and quantitative analyses. BIM could significantly enhance the
efficiency and efficacy of design, planning, and building processes (Autodesk user group International Inc 2010). BIM provides a superior design environment with an ability to parametrically capture design; i.e. a change made anywhere in the model is instantly reflected in all the respective parameters in the model.

Lee et al.(2007) proposed a BIM model that could support project financial decision-making process, by providing real-time cost information, based on the planned and changed interior design. Stumpf et al. (2009) utilized a BIM based modelling technology in energy simulations at the early design process. Several other real time BIM based approaches have been used in construction management (James et al. 2008; Umit et al. 2008; Aron et al. 2008; Nepal et al. 2009; Valdimit et al. 2009), however no work has been noted in the field of construction waste management. A conceptual map of the proposed BIM platform is shown in Figure 2.

Figure 2: Concept Map of Building Information Modelling

BIM is the driver with discipline-specific solutions working together (Figure 2). All information about the facility and its lifecycle defining and simulating the building, information related to
HVAC, structure, electrical and plumbing, mechanical and design, planning and management is included. BIM integrates the works, processes and information for multiple disciplines, multiple companies, and multiple project phases. Information exchange is performed by exporting data to spreadsheets, by use of IFC, green building extensible mark-up language (gbXML) and application program interface (API). BIM can be used on location independent cloud computing system whereby shared servers provide resources, software and data to computers and other devices on demand.

A 4D BIM scheduling application (time as the 4th dimension) could link Critical Path Method (CPM) schedule activities with 3D objects in a BIM model. In addition, cost data can be associated with each element of the BIM model, which generates a detailed cost schedule. Cost attribution in BIM is parametric and dynamic, therefore any change to the model will result a change to the bill of materials and project cost estimate. Principle of BIM-based waste management utilizes the bill of materials generated, in relation with real time dynamics of a construction project. It predicts waste generation due to a change in the scope of work and lack of modular coordination. As per Equation 2, the proposed principle assumes that –

$$Q_T (%) = \frac{Q_E - (Q_R - Q_S)}{Q_E} \times 100$$

Where,

- $Q_T$ = Total quantity of waste generated at a particular time
- $Q_E$ = Original estimated quantity
- $Q_R$ = Quantity required at that particular time
- $Q_S$ = Quantity in stock

The following two main factors were considered in the research study to predict construction waste generation in real-time basis:

- **Rework created due to Change in Scope of Work:**
  On-site waste generation is dynamic in nature and any change in scope of work during the construction process creates “rework” which in turn generates more waste.

- **Lack of modular coordination:**
  Much of construction waste is generated due to deviation in dimensions and lack of integration in designs.
5. A System Dynamics Simulation Approach

System Dynamics, originated by Forrester (1958), is a system analysis approach that is concerned with creating models or representations of real world systems and studying their dynamics. It is the methodology used to understand variations in behaviour between component variables over time by imitation of the system through numerical calculations performed by a computer on the model. Real life does not allow one to go back in time and change the way things are, but simulation gives power to change system and analyse it in different conditions.

Although, system dynamics has been widely used in different fields of business management, one of the most relevant areas for application is project management (James et al. 2007). These researchers studied SDM applications in project management in the context of the underlying structures that create adverse dynamics and effects due to rework. A comprehensive study has been carried out by Mashayekhi (1993), Sudhir et al.(1997), and Karavezyris et al. (2002) to analyse solid waste in system dynamics of a particular area to forecast municipal waste. Hao et al. (2007) presented a simulation model to manage construction waste, with a focus on cost saving, by organised sorting of on-site waste materials. They assumed a waste ratio based on purchased quantity of material. In general, material is procured based on the forecasting of material use and expected time delay due to procurement process such as ordering and inspection time. Important factors controlling the cost of material are requisition procedure, minimization of multiple handling and shortages (Barrie et al. 1992).

![Stock flow diagram for Rework and material waste.](image)

The proposed SDM in Figure 3 for construction waste management is developed using Vensim PLE software package. Figure 3 shows underlying structure of the SDM system with its behaviour. System Dynamics Models are made up of four building blocks; 1) rectangles (in figure 3) represent the stocks of any product accumulates or drains, 2) butterfly valves represent rate change of flows, 3) arrows represent connectors which allow information to pass between
two convertors, and 4) link connecting flow with stock is the material link. Information link and material link help to determine the behaviour of the system over time. Information is processed iteratively within stock and flows forming feedback loop. Value of stock at any particular time is calculated by using Equation 3 (Forrester 1958)-

\[ \text{STO.K} = \text{STO.J} + (dt) \times \text{FLO} \]

Where,
- \( \text{STO.K} \) = present stock at time \( t \)
- \( \text{STO.J} \) = stock before time \( t \), i.e., \((t-dt)\)
- \( (dt) \times \text{FLO} \) = flow in time \( dt \)

A Positive feedback drives growth and change, while negative feedback negates change and stabilizes the systems.

As shown in Figure 3, material waste rate is depended on the rework rate which is a function of change in scope of work and material requirement rate. Any change in scope of work creates rework, which generates modified requirement of materials than originally estimated. A quantity of material required, originally and after the change in design, during construction process, is obtained from the BIM model of the facility. For example, stock of material at site is calculated by Equation 4 and flow of material waste is calculated with Equation 5 –

\[ \text{Material at site (}t\text{)} = \text{Material on site (}t-dt\text{)} + (\text{Material delivery rate-Material waste rate-Material productive rate}) \times dt. \]

\[ \text{Material wastage rate} = \text{Material on site} \times \text{Fraction of waste material}. \]

Behaviour of the construction project with time parameter is analysed by varying the cause variables in the model, and the most dominant variable affecting the waste rate for a particular material is obtained at a given time. Factors affecting the construction process as a result of rework, such as the requirement for overtime, contractual or other deadlines, quality of work, fatigue, reduced safety, low morale etc. are ignored to maintain simplicity of the model, as these have more negative effect on productivity than waste generation. It is possible to perform real-time planning and execution of waste management strategies effectively using results from the proposed model. The model outputs are obtained both in graphical and tabular format such as variation of waste with type of rework, impact on cost, time of completion, and most affected material in its quantity variation. Hypothesized reference data has been used instead of historic or actual data to understand the behaviour of the system and to create the model.

6. Conclusion

Minimization of construction waste quantities is of paramount importance for sustainable construction waste management and planning. Construction process is highly dynamics in
nature. Optimization of construction waste using real-time information of BIM integrated with a
dynamics simulation technique is more realistic than the historical data analysis techniques.

A major quantity of construction waste is created due to rework and poor material management
practices. Construction projects often experience time and cost overruns due to changes in scope
of work. Changes in design, lack of modular coordination, and poor integration of building
system are the main causes for changes in scope in construction projects. Rework makes
material management more complex during the construction process as it immediately attracts a
change in material requirement. BIM has a unique capability of instantly generating the bill of
material quantities, in real-time, for changed design. Such changes in material requirements
affect the whole material management system of a project and therefore managers need a
decision supporting tool to plan the delivery, distribution, reuse, recycling, and disposing of
materials as per the time schedule restrictions.

The study discussed in this paper proposed a modelling methodology to address material
management dilemmas in the construction process. The model used BIM with a generic SD
model to represent and simulate the interactive structure of construction work by considering
the dynamic nature of material requirement. Since the proposed model allows users to fine-tune
the input variables, it is flexible to adjust the model to better reflect the reality according to
different conditions. In the future, empirical data will be acquired to support the results of the
SD model described in this paper.

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