Waste Management xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Quantification of construction waste prevented by BIM-based design validation: Case studies in South Korea

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A R T I C L E   I N F O

Article history:
Received 28 May 2015
Revised 23 September 2015
Accepted 28 December 2015
Available online xxxx

Keywords:
Construction waste
Building information modeling (BIM)
BIM-based design validation
Quantification
Prevention
Likelihood

A B S T R A C T

Waste generated in construction and demolition processes comprised around 50% of the solid waste in South Korea in 2013. Many cases show that design validation based on building information modeling (BIM) is an effective means to reduce the amount of construction waste since construction waste is mainly generated due to improper design and unexpected changes in the design and construction phases. However, the amount of construction waste that could be avoided by adopting BIM-based design validation has been unknown. This paper aims to estimate the amount of construction waste prevented by a BIM-based design validation process based on the amount of construction waste that might be generated due to design errors. Two project cases in South Korea were studied in this paper, with 381 and 136 design errors detected, respectively during the BIM-based design validation. Each design error was categorized according to its cause and the likelihood of detection before construction. The case studies show that BIM-based design validation could prevent 4.3–15.2% of construction waste that might have been generated without using BIM.

1. Introduction

The amount of waste generated in construction and demolition (C&D) processes is enormous. C&D waste comprised of 26% of the solid waste in the United States in 2007 (USEPD, 2009) and 48% of the solid waste in South Korea in 2013 (Ministry of Environment and Korea Environment Corporation, 2014). C&D waste issues have received increasing attention from both practitioners and researchers around the world (Lu and Yuan, 2011). However, the amount of C&D waste is still growing continuously and is not effectively managed in most of the countries in the world (Cheng and Ma, 2013). Therefore, it is vital that the architectural, engineering, and construction (AEC) industry strives to reduce and manage C&D waste more effectively (Cheng and Ma, 2013). Many previous studies proposed methods to minimize C&D waste by reduction, reuse, and recycling of C&D waste (Hewage and Porwal, 2011; Jaillon et al., 2009; Meibodi et al., 2014; Yu et al., 2012). Reduction of construction waste is the first step to minimize C&D waste by eliminating the root causes of construction waste generation. Design errors are commonly detected in the AEC industry because a building consists of components which are designed by different project participants and are corrected only after the construction work has started on site, which can lead to rework and construction waste. Improper design (Craven et al., 1994; Gavilan and Bemold, 1994) and unexpected changes in design (Craven et al., 1994; Gavilan and Bemold, 1994; Jaillon et al., 2009) were identified as major causes of construction waste generation. Especially, inappropriate design decision making and unexpected design changes may lead to an increase of up to 33% of the volume of construction waste (Innes, 2004). These causes of construction waste can be resolved through integrated building design that can avoid design problems and changes, thereby reducing construction waste generation (Cheng et al., 2015). Integrated building design can be facilitated by building information modeling (BIM), which is a modeling technology and associated set of processes to produce, communicate, and analyze building models (Eastman et al., 2010). BIM technology has been widely utilized to reduce cost and time and improve productivity in the AEC industry in the last decade. The potential uses of BIM technology to minimize construction waste has also been introduced by Rajendran and Gomez (2012), Liu et al. (2011), Ahankoob et al. (2012), and Cheng et al. (2015). Various BIM uses like design validation, quantity take off, and prefabrication were proposed for minimization of construction waste. Especially, they have claimed that clash detection and design review have high potential to reduce construction waste generated on construction

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http://dx.doi.org/10.1016/j.wasman.2015.12.026
0956-053X/

sites by virtually identifying during design phase those constructability issues that can be resolved ahead of time (Ahankoob et al., 2012; Cheng et al., 2015; Liu et al., 2011; Rajendran and Gomez, 2012). Detecting building-element clashes and other causes of rework were chosen as the most beneficial way of using BIM by owners (Young et al., 2009), now becoming a common BIM practice (Lee et al., 2012) called the BIM-based design validation process. BIM-based design validation can improve design quality by reducing the number of design errors, change orders, and rework in the planning, design, preconstruction, and construction phases (Anumba et al., 2010; Khanzode et al., 2008; Williams, 2011; Young et al., 2009). Whereas 1–2% of electrical work costs are generally incurred in rework due to design changes in similar projects, rework costs were reduced to 0.2% of the work costs by using BIM in a hospital project (Khanzode et al., 2008). Williams (2011) documented that the number of mechanical change orders that occurred in BIM-assisted projects of the Messer Construction Company was reduced by 47%. Consequently, design validation can reduce the amount of construction waste since construction waste is mainly generated due to improper design and unexpected changes in the design and construction phases. However, these previous studies have not quantified how much construction waste could be avoided by reducing design errors, change orders, and rework through BIM-based design validation.

This paper aims to quantify the construction waste reduction by a BIM-based design validation process. Two projects in South Korea were analyzed to quantify the amount of the reduced construction waste in the preconstruction and construction phases because BIM models in the two projects were created after their design processes were completed. Some practitioners argue that experienced construction engineers can find most design errors before or during construction without using BIM and that the number of errors is meaningless because many design errors found using BIM may have little impact on a project (Lee et al., 2012). To avoid such arguments, Lee et al. (2012) proposed a BIM return on investment (ROI) analysis method in design error detection that considers the likelihood to detect errors without using BIM. This paper adopted this likelihood-based BIM ROI analysis method in analyzing the amount of construction waste prevented by BIM-based design validation. If the likelihood of detecting an error without BIM is high, the effects of BIM on reducing construction waste associated with the error is low, and *vice versa*. This study compares and reports on the differences in the amount of calculated construction waste when the likelihood of detecting errors without BIM is either not considered or considered.

This paper is organized as follows. The next section reviews various previous studies on minimization of construction waste and BIM implementation. Section 3 describes the two projects that are analyzed in this paper and discusses the data collection process. Section 3 also describes the distribution of design errors detected by BIM-based design validation by their cause and the likelihood of detection without BIM. Section 4 quantifies the construction waste prevented by the BIM-based design validation process. Section 5 concludes the paper.

2. Literature review

Many research studies have been conducted to minimize the amount of C&D waste by introducing new technologies and processes (Jaillon et al., 2009; Lawton et al., 2002; Meibodi et al., 2014; Nahmens and Ikuma, 2012; Yu et al., 2012). Yu et al. (2012) developed a checklist to be considered in residential building projects to reduce construction waste on sites. Meibodi et al. (2014) explored various methods to minimize concrete waste on site and identified key factors for waste minimization by conducting a questionnaire survey. Prefabrication and procurement management were identified as the most recommended methods for minimizing concrete waste (Meibodi et al., 2014). Jaillon et al. (2009) analyzed the impact of prefabrication on waste reduction in Hong Kong in which the average wastage was reduced by 52%. Lawton et al. (2002) estimated a reduction of 70% in concrete waste by using prefabrication. However, there are insufficient techniques and tools for reducing construction waste during the design and procurement stages (Liu et al., 2011). To minimize and manage C&D waste, an integrated building design process is required because C&D waste is mostly generated by improper design and unexpected changes in building design (Poon et al., 2004; Yeheyis et al., 2013). Lean strategies have proven effective in improving processes and performance (Song and Liang, 2011) by eliminating waste from the process (Nahmens and Ikuma, 2012). Lean construction resulted in a significant environmental effect by reducing material waste by 64% (Nahmens and Ikuma, 2012).

Recently, BIM has been also identified as an effective means to minimize the amount of C&D solid waste by improving the quality and accuracy of design and construction, thereby reducing design errors, rework, and unexpected changes. To this end, several previous studies have proposed BIM-based systems or methods to manage C&D waste effectively (Cheng and Ma, 2013; Hamidi et al., 2014; Hewage and Porwal, 2011; Park et al., 2014) and have introduced potential uses of BIM to minimize C&D waste (Ahankoob et al., 2012; Cheng et al., 2015; Liu et al., 2011; Porwal and Hewage, 2012; Rajendran and Gomez, 2012). Park et al. (2014) developed a demolition waste database system based on BIM and Hamidi et al. (2014) proposed a BIM-based demolition waste management system. Cheng and Ma (2013) leveraged BIM technology to develop a system for demolition waste estimation, disposal charging fee calculation, and pick-up truck planning. However, these studies focused more on C&D waste management than minimization of fundamental causes of C&D waste (i.e., design errors and rework). To minimize C&D waste, they are required to eliminate the causes of C&D waste and focus more on the reduction of C&D waste than reuse and recycling of C&D waste.

Hewage and Porwal (2011) developed a system dynamics model and integrated it with BIM models to predict the generation of construction waste. Later, Porwal and Hewage (2012) proposed a BIM-based method to analyze reinforced concrete structures to reduce reinforcement waste by selecting proper lengths of rebars and considering available cut-off lengths. BIM was utilized to simulate architectural and structural design requirements and to compare results in order to make the necessary changes in the design to reduce and reuse rebar waste.

Similarly, Rajendran and Gomez (2012) claimed that waste could be minimized through designing-out-waste by using BIM tools. They defined waste minimization as a technique which avoids, eliminates or reduces waste at its source. Liu et al. (2011), Ahankoob et al. (2012), and Cheng et al. (2015) explored a potential application of BIM to minimize waste on a construction site by conducting an in-depth literature review and analyzing causes of construction waste and current practices of waste minimization. These studies suggest potential uses of BIM for reducing the amount of C&D waste by avoiding design errors, rework, and C&D waste. They claimed that clash detection, design review, quantity take-off, and prefabrication could be used for minimization of C&D waste. Among them, BIM-based design validation, including clash detection and design review, was an approach commonly proposed in previous studies in order to reduce the amount of C&D waste including concrete, glass, as well as reinforcement. In summary, previous studies have focused on development of BIM-based waste management systems, reduction of specific types of waste using BIM, and general BIM-based waste reduction methods. The amount of construction waste that can