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Development and validation of a building design waste reduction model

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ABSTRACT

Reduction in construction waste is a pressing need in many countries. The design of building elements is considered a pivotal process to achieve waste reduction at source, which enables an informed prediction of their wastage reduction levels. However the lack of quantitative methods linking design strategies to waste reduction hinders designing out waste practice in building projects. Therefore, this paper addresses this knowledge gap through the design and validation of a Building Design Waste Reduction Strategies (Waste ReSt) model that aims to investigate the relationships between design variables and their impact on onsite waste reduction. The Waste ReSt model was validated in a real-world case study involving 20 residential buildings in Spain. The validation process comprises three stages. Firstly, design waste causes were analyzed. Secondly, design strategies were applied leading to several alternative low waste building elements. Finally, their potential source reduction levels were quantified and discussed within the context of the literature. The Waste ReSt model could serve as an instrumental tool to simulate designing out strategies in building projects. The knowledge provided by the model could help project stakeholders to better understand the correlation between the design process and waste sources and subsequently implement design practices for low-waste buildings.

1. Introduction

The large amounts of waste generated by the construction industry represent a growing problem that requires effective planning, management and monitoring in many countries. The construction industry in the EU-28, is the greatest producer of waste among all European industries, being responsible for 34% of total waste generation (Eurostat, 2013). Construction activities also represent a significant source of toxic substances accounting for 22% of all EU hazardous waste (Eurostat, 2010). Additionally, construction and demolition waste (CDW) recovery and backfilling rates in some EU Member states such Cyprus, Greece and Finland are as low as 10% (European Commission, 2011) of the overall landfilled waste. Furthermore, CDW production has adverse effects on the environment and involves a significant project budget increase due to the loss of tonnage of materials being sent to landfill in addition to labor double handling, transportation and landfill costs. In the UK, for example, where CDW equates to three times the combined waste produced by all households (Defra, 2007), their disposal costs the industry around £1 billion per year (WRAP, 2008). Consequently, over several decades, an ever-increasing social awareness has prompted governments to develop environmental policies to curb CDW. Particularly, CDW prevention and reduction at source has become a priority in the EU waste management hierarchy (European Commission, 2008). However, the latest European statistics revealed that while the generation of some waste streams, such as in the household sector, remained constant and others fell, namely manufacturing waste which decreased by 26% between 2004 and 2012; the levels of CDW grew at a rapid pace reaching 45% increase in the same period (Eurostat, 2015). Therefore, governmental-driven legislative and regulatory measures are proving ineffective as they have failed to reduce CDW generation resulting in a lack of quantitative waste reduction targeting and benchmarking data that would help designers and contractors minimize waste in their construction projects.

There is consensus in the literature that to prevent or minimize construction waste (CW), it is necessary to consider its reduction during design (Osmani et al., 2008; Innes, 2004; Coventry and Guthrie, 1998; Bossink and Brouwers, 1996). Nevertheless, the bulk of international academic research endeavors over the past decade have been focused on methods and strategies to manage CW that has already been generated if compared with design waste (DW) reduction research, which is "limited and piecemeal" (Osmani, 2013). As such, Lu and Yuan (2010) acknowledged there is a pressing need to investigate CW issues in project design.

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Furthermore, approaches of existing-methods on DW reduction are largely unfitting because "they do not specifically identify waste-stream components in relation to their occurrence during the architectural design" (Osmani et al., 2008). Therefore, this paper aims to develop and validate a model for Building Design Waste Reduction Strategies (Waste ReSt) that accentuates and assesses the relationships between design variables and their impact on onsite waste reduction using a structured, traceable and quantitative approach. A case study was conducted to apply the proposed model to 20 Housing buildings in Andalusia in Spain. It is expected that the identified variables associated with DW reduction strategies and their inter-relationships could assist project stakeholders in understanding and addressing DW sources in building projects.

Within the context of this paper '*design waste* (*DW*)' is defined as construction waste that could be avoided during the design stage; waste '*sources*' are associated with DW generation provenance in the building site (e.g., damaged materials and excavated soil); waste '*parameters*' refer to variables considered in the design stage that affect the DW *sources*; '*building element*' is a key component of a building (e.g., beam, wall and door); and '*building system*' represents a group of building elements that are interrelated and coordinated among themselves through the project (e.g., structure, masonry, carpentry).

2. A review of design waste literature

2.1. Design waste causes

Several studies identified design as a key stage of a project life cycle to identify and adopt specific waste minimization actions that could be implemented throughout the construction phase. Innes (2004) estimated that 33% of on-site waste is due to architects' failure to implement waste reduction measures during design stages. Uninformed design decisions such as inadequate dimensional coordination during the design stage tend to generate off-cuts, which were identified as a major waste cause (Bossink and Brouwers, 1996). Similarly, Ekanayake and Ofori (2000) rated lack of information on drawings, complexity of detailing, selection of low-quality materials and lack of familiarity of alternative products as the most significant causes of waste. Furthermore, Chandrakanthi et al. (2002) attributed DW causes to lack of knowledge about construction techniques during design activities, alternative products and standard sizes available in the market.

Several research studies identified last minute design changes, which result in rework and partial demolition, as a significant DW cause. This was attributed to various design related inefficiencies, including errors in specifications and contract documents (Poon et al., 2004; Poon and Jaillon, 2002); last minute client requirements (Poon et al., 2004; Poon and Jaillon, 2002; Coventry et al., 2001); and the complexity of detailing drawings or changes in the type or quantity of building materials required at later stages (Osmani, 2013). A recent study categorized causes of design errors into three types: illogical design such as clashes between different building elements as well as drafting errors; discrepancies between drawings; and missing items (Won et al., 2016). These causes could be addressed through an integrated building design that can avoid design changes, thereby reducing onsite construction waste generation (Cheng et al., 2015).

Additionally, there is general agreement in the literature that poor communication between project stakeholders' leading to mistakes and errors; 'overlapping of design and construction' (Keys et al., 2000); and long project durations that allow the design to be modified to suit changes in the market, research or legislation (Poon et al., 2004; Ekanayake and Ofori, 2000) are significant DW causes.

Waste estimation tools provide the essential basis for understanding causes, types and quantities of construction waste arising from building designs (Wu et al., 2014). Prior knowledge of waste in a project will enable assessment of their management possibilities, including the waste prevention (Llatas, 2013). However, the complexity of the construction process and the involvement of a diverse number of stakeholders across different project stages make it difficult to realistically predict the types and quantities of onsite waste streams. This is further hindered by an imperceptible stakeholders' allocation of waste minimization responsibilities. As such, a recent study defined and related origins, causes and sources of waste across all project life stages and concluded that "waste generation is affected by a wide practice of not embedding waste reduction in briefing and contractual documents, no baseline setting, and lack of designers' understanding of design waste origins, causes and sources" (Osmani, 2013).

2.2. Design waste reduction strategies

A growing body of literature (Osmani et al., 2008; Baldwin et al., 2006; Poon et al., 2004; Greenwood, 2003) indicates that designers play a pivotal role in reducing onsite CW. Coventry and Guthrie (1998) assigned to architects a triple role in reducing waste: giving advice to customers, improving design practices and initiating waste reduction at project level. Over the past decade, several studies with different approaches identified strategies to reduce DW in the project that can be grouped into soft and hard strategies. Within the first group, modulation, standardization and optimization were identified as effective designing out waste strategies for several reasons. The modulation of the project and dimensional coherence of products improve coordination at project level as it prevents design modifications and abortive work during site operations (Coventry and Guthrie, 1998). The standardization of design applied to both the use of standard dimensions and units, such as the use of standard materials, reduces the off-cuts and improves buildability (Hylands, 2004). The optimization of buildability solutions was deemed as an appropriate waste minimization strategy to streamline designs that conventionally require more material than necessary as a result of over-specification resulting in unused materials that generally skipped and landfilled (Greenwood, 2003).

Other studies focused on hard strategies to recover waste through the development of cleaner technologies. Regarding the use of reclaimed CDW, designers can influence reusability and recyclability potential through the selection and specification of appropriate materials and structural systems, component types and their connections (Kartam et al., 2004; Gibb, 2001; Coventry and Guthrie, 1998). Cleaner technologies, pre-casting and prefabrication were identified as efficient design strategies because they offer significant opportunities to reduce waste (Baldwin et al., 2006) and better control of waste and damage avoidance (Dainty and Brooke, 2004). A limited number of research studies quantified the levels of waste reduction achieved with the use of prefabrication in buildings. These studies obtained overall wastage reduction levels up to 52% (Jaillon et al., 2008); 84.7% (Tam et al., 2007a) and even 100% (Tam et al., 2007b). In addition, these investigations identified building systems that were most affected, estimating reduction of 74–87% in timber formwork and 51–60% in concrete works (Tam et al., 2005) and 70% in building finishing works on site concreting (Lawton et al., 2002). Table 1 highlights the key literature causes that related waste streams to their respective sources and used prefabrication systems to quantify the levels of CW reduction.

However, there is a lack of quantitative approaches to assess the effects of each prefabricated component on the overall waste reduction rate in buildings. Studies that adopted a qualitative approach evaluated alternative building elements and developed