Developing a decision support tool for quantification and reduction of construction material waste

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Abstract: The construction industry has a major impact on the environment, both in terms of resource consumption and waste production. Given the high rate of raw materials wastage and ineffective waste management frequently conducted on construction sites, waste minimization strategies have become an important area of concern in the construction industry. However, the knowledge of origins and distribution of construction waste is very limited. This gap in knowledge limits the effectiveness of decisions made to reduce construction waste at the design and planning phase. The University of Alabama Construction Administration department (UACA) provides management and support for construction projects on campus. In this paper, the application of decision support system (DSS) technology is investigated to support UACA interest in construction material waste management. DSS are software systems that utilize sophisticated algorithmic approaches to solve problems. The utilization of technologies, such as Building Information Modeling (BIM), in construction has allowed for more efficient, better designed structures that limit the waste of resources, optimize energy use, and promote passive design strategies. The objectives of this research are to quantify construction waste, determine its causes, and lead to methods to minimize this waste. A prototype DSS was designed utilizing historical data at the University of Alabama. The design proposes a framework that integrates BIM with advanced analytical methods, within the DSS, to reduce the impact of construction waste materials. The current status of development of the prototype DSS, and future path forward, are discussed.

1. NATURE OF THE PROBLEM

Construction and demolition (C&D) materials constitute a significant waste stream in the United States (EPA, 2018). Millions of construction projects are conducted each year around the world, which generate tremendous volumes of construction waste and associated environmental problems. Typical components in C&D waste are inert materials (e.g., concrete, and bricks.), which are generally believed to do little damage to the environment beyond additional landfill volume (EPD, 2012). If some hazardous components (e.g. asbestos) are not disposed of properly, further negative impacts will be made on the environment. However, even relatively benign construction waste yields additional landfill volume is not a trivial consideration. In the latest report by the Environmental Protection Agency (2018), 548 million tons of C&D debris were generated. Concrete comprised the largest portion which is 70%, followed by asphalt concrete at 15%, C&D wood products were 7%, and the other C&D components added to 8% of the total C&D debris generation in 2015. According to the data in the report, over 90% (around 519 million tons) of total C&D debris were generated from demolition, while construction represents less than 10% (EPA, 2018).

1.1. Importance Of The Problem

The need to reduce construction waste is rising with the increasing number of construction projects worldwide. This need is strongly supported by the growing emphasis on implementing sustainable construction practices. Outside of these sustainable goals, there are three important but contradictory objectives in an ordinary building construction project – time, quality, and cost, which are usually difficult for project managers to optimize (Ashokkumar and Varghese, 2018). To most construction companies, the cost generated by managing construction waste decreases the profits. Significant extra cost could be generated from inappropriate handling and insufficient recycling of construction waste. Previous studies indicate that construction companies can benefit from reduced waste generation by lower disposal costs and lower purchasing costs of virgin materials (Bossink and Brouwers, 1996). Waste minimization has become an important area of concern in the construction industry (Dajadian and Koch, 2014). However, even though construction stakeholders are paying increasingly more attention to the negative impact to the environment caused by construction waste, the knowledge of the origins and distribution of this construction waste is very limited. Moreover, studies focused on developing and applying effective decision support tools within this domain are scarce. Therefore, it is essential that researchers develop useful tools that incorporates advances in information technology to support C&D minimization.

2. LITERATURE REVIEW

C&D waste minimization aims to apply techniques which can avoid, eliminate or reduce waste at its source. Previous research on construction waste minimization tends to focus on studying its origins (Osmani, 2012). Numerous studies state that design changes during the construction stage, resulting in rework, are major causes of waste generation (Liu et al, 2015). Al-Hajj and Hamani (2011) combined construction projects observation results with literature findings to design a questionnaire for assessing the main causes of material waste and waste minimization measures. The study posits that the main causes of material waste in the United Arab Emirates (UAE) are rework and variations, lack of awareness, and excessive off-cuts resulting from poor design; while staff training, adequate storage, and just- in time delivery of materials were the most frequent used minimization measures. Twenty-four interviews investigating the underlying origins, causes and sources of waste across all project life cycle stages were conducted by Osmani (2013). Results From the study indicates that the lack of embedding waste reduction requirements and expectation in contractual documents and contractor briefings and designers lack of understanding of waste origins are primary causes of waste generation in the built industry. Yuan (2013) identified 30 key indicators affecting the overall effectiveness of C&D waste management, he developed a C&D management effectiveness assessment framework through analyzing the data from literature review and semi-structured interviews.

Researchers have also adopted emerging technologies as a tool to enhance C&D waste minimization. For instance, Chen et al. (2002) implemented bar-coding technology to reduce construction waste in a group-based incentive reward program to encourage workers to minimize avoidable wastes of construction materials by rewarding them according to the amounts and values of materials they saved. Li et al. (2005) integrated Global Positioning System (GPS) and Geographacial Information System (GIS) technology for reducing construction waste and improving construction efficiency. Similarly, a combined GIS and Life Cycle Assessment (LCA) model was developed for construction resource and waste management using site-specific data (Blengini and Garbarino, 2010). Moreover, the advent of Building Information Modeling (BIM) in the construction industry has provided more opportunities to reduce C&D waste.

2.1. Relevance of BIM

BIM has been used in many aspects of construction. BIM represents the process of development and use of a digital computer building model to simulate and manage the planning, design, construction, and operation of a building facility (Ashokkumar and Varghese, 2018). BIM techniques enable both contractors and customers to check the constructability in the design stage before actual construction. As a visual database of building components, BIM can provide accurate and automated quantification, and assist in significantly reducing variability in cost estimates. This significantly reduces errors and uncertainties that could occur in subsequent stages. BIM also provides an efficient way to manage scheduling, cost estimating, design, communication and other important components in a construction project (Bryde et al., 2013).

BIM methods, at present, have not been used significantly for construction waste minimization (Liu et al, 2015). In the previous research, BIM has indicated the potential to aid contractors and designers to minimize the construction and demolition wastes by planning waste control strategies. A BIM based system can extract material and volume information through the BIM model, then integrate the information for detailed waste estimation and planning (Cheng and Ma, 2013). There are still many challenges that exist in the current application of BIM in minimizing construction waste. Investigation of the literature implies that current BIM implementation in construction waste minimization is limited, with many systems only analyzing some specific aspects. Combining BIM with other complementary analytical techniques has the potential to yield improved decision-making tools for C&D waste minimization.

3. RESEARCH OBJECTIVE AND APPROACH

University-related construction has many unique aspects compared to other construction applications. Public postsecondary construction has been decentralized since 1995, when most state universities and colleges have administrated their own construction program, with the direction provided by individual boards of trustees (BOT). Campus projects are funded from a variety of state and non-state sources, which dictate certain project aspects. Generally, all of the construction projects in a university need to be fitted within a predetermined campus master plan. Such campus master plans are based on assumptions about basic campus characteristics drawn from projections of long-range academic plans (Caruthers and Layzell, 1999). They outline building design and location, campus traffic patterns, utilities needed, and required land improvements or acquisitions.

Construction Administration (UACA), a department at the University of Alabama (UA), seeks to determine how to better support their responsibilities for construction in a public university environment. The objective of this research project is to develop a prototype DSS for quantification and reduction of construction material waste. UACA is aware of the total amount of construction material waste disposed of, and the associated disposal cost. However, they require more detailed visibility into the component volumes and costs, as a step toward material waste reduction.

"Decision support systems couple the intellectual resources of individuals with the capabilities of the computer to improve the quality of decisions. It is a computer-based system for management decision makers who deal with semi-structured problems" (Turban and Aronson, 2001). A DSS can effectively extend the decision makers' capacity for representing and processing information while reaching solutions faster and with more reliability. Quite often, the solutions will be optimal with supporting evidence provided. However, the use of DSS is limited by the underlying mathematical model selected, the hardware/software platform selected, and the design itself. As a result, it may be intended for a very specific range of problems (Moynihan et al, 2006). The components of a DSS can generally be classified into the following distinct parts: (1) the data management system; (2) the model management system; (3) the user interface; and (4) the user(s) (Moynihan et al, 2006). The model management system is particularly important for the success of a decision making system. The model is mathematical in nature, usually consisting of a management science/operations research (MS/OR) algorithm.

4. PROPOSED FRAMEWORK

Consistent with the traditional systems development life cycle (SDLC), accepted DSS development methodology identifies four primary phases: 1) data acquisition, 2) system design, 3) system construction, and 4) verification and validation (Turban and Aronson, 2001; Laudon and Laudon, 2013). According to the SDLC approach, the first step in DSS development consists of determining the key concepts and relationships with respect to algorithms, parameters and system constraints (Huscroft et al, 2013). It involves the understanding of the underlying data and algorithms and their merging into the modelbase. This research utilized existing models that were obtained through the review of the relevant literature. It did not aim at developing new models since extensive research has already been done in this field, and further exhaustive experimentation would be required for formulation and validation of any new model. Thus, the research focused on developing a DSS using only proven theories and models. Using accepted SDLC techniques (Laudon and Laudon, 2013; Jacyna-Golda, 2013), a generalized proof-of-concept system is being developed and evaluated, as a basis for further refinement.

As an initial step, the conceptual design envisioned an overall DSS framework that integrates BIM with advanced analytical methods encompassing a waste management cost metric within a decision-making tool. Figure 1 shows the components of this conceptual framework. After considering a variety of criteria, particularly software availability, Microsoft Excel was selected as the modelbase for this DSS project. Several studies have successfully used Excel as a DSS modelbase (Li et al, 2004).

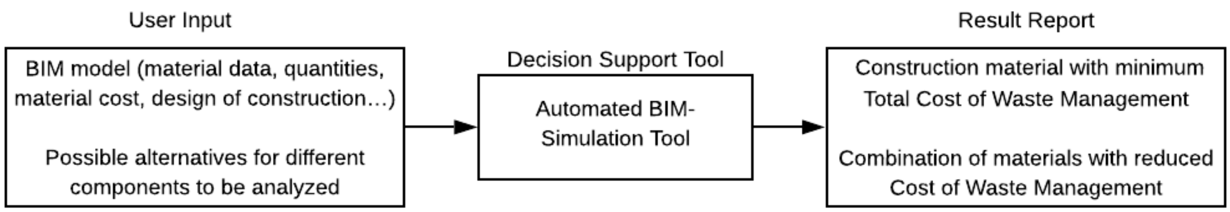

Figure 1. Components of conceptual design

4.1. Current Status

The methodology used in the research was to create a linkage between the BIM software model and the decision-making model. There are a number of commercially-available software packages for BIM, such as Autodesk, Bentley Systems, Nemtschek and Graphisoft (Ashokkumar and Varghese, 2018). For this research, Autodesk Revit was used to create the BIM models, which were provided by UACA. Autodesk Revit is capable of modeling building components, analyzing and simulating systems and structures, and iterating designs (Autodest, 2018). Different material options and quantities of each component can be obtained from Revit. Revit then exports the data regarding different materials used in the projects by UA Construction Administration, such as concrete, wood, steel, and bricks. This data will be used to determine the forecast usage value for each type of material.

The methodology employed in this research is to move the data from a BIM software model to the decision tool by creating a linkage between AutoDesk's Revit and Microsoft Excel. This one-way BIM – Decision-making link automatically populates the variables in the Excel spreadsheet with data from the Revit model, as depicted in Figure 2, and is accomplished through Java and Visual Basic applications. The data is output from the BIM model via its API into a Visual Basic or C++ external application. Shen (2017) used a similar process to create and customize a near-miss data visualization tool for enhancing construction safety. In his study, an algorithm was used to compute the optimized tower crane location through Revit, the text file and MATLAB (Shen, 2017).

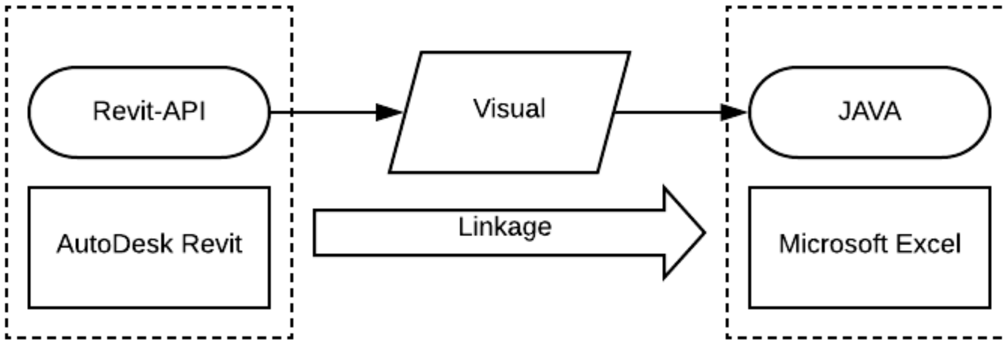

Figure 2. Linkage between BIM and decision support tool

A Revit model of a recent construction project was provided by UACA. The construction components were analyzed by using the Pareto Analysis statistical technique. Pareto Analysis is a method of ranking categorical names by the relative frequency of the categories in some data. The most frequent category appears first, followed by the second most frequent, and so on. Review of Pareto bar charts indicated the Pareto Principle "(80-20 Rule") at work: in general, about 20% of the categories are responsible for 80% of the material volume. Pareto Analysis is a decision-making type statistical tool which can help select the few categories producing the most significant overall effect (Aibinu & Odeyinka, 2006). Applying Pareto Analysis to construction material usage of a project determined the component types (here, masonry, metal, and other) with the relatively highest usage. A second iteration of Pareto Analysis within these three general categories, and with guidance from UACA, indicated subsequent focus should be directed to the following subcategories: bricks, blocks and other masonry; metal studs for walls; acoustic ceiling tiles, and drywall.

4.2. Path Forward

Microsoft Excel can calculate the total quantities required for each of the targeted subcategories. This represents a deterministic forecast of material requirements. In practice, material usage may vary somewhat (e.g. due to worker skill/experience, and conditions at the jobsite).The application of Monte Carlo simulation is planned to take into consideration this uncertainty in material usage. Monte Carlo simulation is a statistical analysis tool which is based on the use of random sampling and probability statistics to investigate problems (Marzouk et al, 2018). Marzouk et al (2018) used it to evaluate the life cycle cost for alternative materials taking into consideration uncertainty in costs for sustainable buildings. In this research, an Excel-based Monte-Carlo simulation will be used to calculate a probabilistic forecast of material required.

Actual material quantities purchased for the construction project, and their respective costs, are available from project historical records. A gap analysis will be conducted by comparing the two data sets. The difference between the forecast and actual volumes represents the material waste by category. A functional flow diagram of the DSS processing logic is portrayed in Figure 3.

The total waste charging fee for each of the different types of construction materials will also be calculated. Based on the research of Yuan et al. (2010), *the total cost of waste management consists of cost of collecting, cost of sorting, cost of reuse, cost of recycling, cost of disposal and transportation cost*. These six costs will be used to calculate the total construction waste management cost for each material type. The supporting data for the waste management cost of different C&D waste components will be obtained from past University projects to the extent possible. Alternatively, sources from the existing literature (e.g. RS Means) or official statistics reported by the EPA will be investigated. A survey may also be conducted to collect the data of six cost variables.

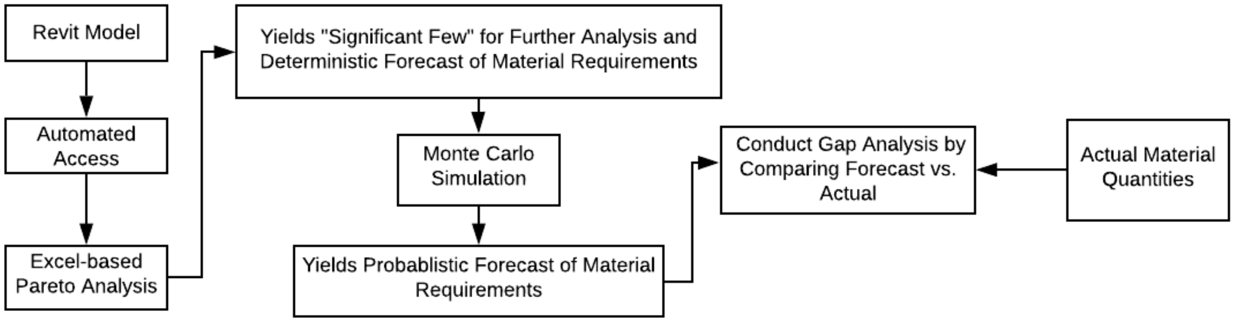

Figure 3. Functional flow diagram of DSS processing logic

Verification and validation are important steps in ensuring the quality and reliability of the DSS (Turban and Aronson, 2001). Verification confirms that the system is robust and error-free. Consistent with the procedure discussed by Laudon and Laudon (2013), unit tests will be conducted on the individual components of the DSS. System tests will then be executed to verify the correctness of overall system functionalities. Every test case and the corresponding result will be recorded in a test case form. When a result indicates a failure, the case will be analyzed and the system redesigned to correct the problem. After any modification, the system will be retested using the same test case. Such procedures will be continued until all test cases yield positive results.

As suggested by the International Standards Committee (2005), in their ISO 12207 document, validation denotes checking whether the final product fulfills specific intended use. Validation techniques can be broadly classified into two categories: qualitative validation and quantitative validation (Turban and Aronson, 2001). Qualitative validation, which is further classified into face validation and predictive validation, will be the validation technique to be utilized for this project. Face validation is a simple, qualitative fairly informal validation technique. The system will be evaluated at face value by experts from the problem domain, project members and users familiar with university construction projects. The prototype DSS will also be validated through their review of the system documentation and functionality. Suggestions for later enhancement will be noted.

5. CONCLUSIONS AND FUTURE RESEARCH

A clear quantification of the constituents of construction waste is the first step toward their reduction. Further research is envisioned to link the Revit model to the construction project's Work Breakdown Structure (WBS). The WBS identifies individual tasks within the project, as well as the relationship between them. Subsequent application of Pareto Analysis and Monte Carlo simulation, by the Excel decision tool, will identify those tasks responsible for the largest share of construction waste, and where management attention should be focused for waste reduction.

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