Automation in Construction 93 (2018) 91–111

Contents lists available at ScienceDirect

Automation in Construction

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

Automated performance measurement for 3D building modeling decisions

Saman Yarmohammadi*, Daniel Castro-Lacouture

School of Building Construction, Georgia Institute of Technology, USA

ARTICLE INFO

Keywords:
BIM
Data analytics
Application programming interface
Modeling team
Performance measurement

ABSTRACT

Building information modeling (BIM) is instrumental in documenting design, enhancing customer experience, and improving product functionality in capital projects. However, high-quality building models do not happen by accident, but rather because of a managed process that involves several participants from different disciplines and backgrounds. Throughout this process, the different priorities of design modelers often result in conflicts that can negatively impact project outcomes. To prevent such unwanted outcomes from occurring, the modeling process needs to be effectively managed. This effective management requires an ability to closely monitor the modeling process and correctly measure the modelers' performance. Nevertheless, existing methods of performance monitoring in building design practices lack an objective measurement system to quantify modeling progress. The widespread utilization of BIM tools presents a unique opportunity to retrieve granular design process data and conduct accurate performance measurements. This research improves upon previous efforts by presenting a novel application programming interface (API)-enabled approach to (a) automatically collect detailed model development data directly from BIM software packages in real-time, and (b) efficiently calculate several modeling performance measures during schematic and design development phases of building projects. These indicators can be used to properly arrange modeling teams in the quest for high-quality building models. The specific objectives of this study to examine the feasibility of a proposed automated design performance measurement framework, and to identify optimal modeling team configurations using empirical performance information. A passive data recording approach allows for the real-time capture of comprehensive user interface (UI) interaction and model element modification events. The proposed framework is implemented as an Autodesk Revit plugin. Next, an experiment is conducted to capture data using the developed Revit plugin. Experiment participants' individual production rates are estimated to establish the validity of the proposed approach to identify the optimal design team configuration. The presented approach uses the earliest due date (EDD) sequencing rule in combination with the critical path method (CPM) to calculate the maximum lateness for different design team arrangements.

1. Introduction

The goal of design is to specify a product that best satisfies the client, ensures safe construction and operations, and achieves minimum overall costs [1]. As capital projects are becoming more complex, the design process increasingly requires substantial interactions among a wide range of designers from various architectural, engineering, and construction (AEC) disciplines [2]. Throughout this evolutionary process, multidisciplinary teams of architects and engineers need to make difficult decisions to design buildings that are functional, safe, and reliable, and that meet clients' expectations [3]. Given the specific requirements of different disciplines, each specialist has a unique approach to design. The existing variations in the understanding of design problems result in conflicts that negatively impact the concurrent design efforts as well as the downstream construction activities [4]. While design processes account for approximately 5%–10% of the total cost of a typical capital project [5,6], rectifying conflicts that result from faulty design decisions accounts for an additional 5%–8% of total project costs [7]. Given the value of the U.S. construction industry [8], approximately $70 billion will be spent annually to resolve design-related issues in capital projects alone.

The poor management of design processes is the primary cause of costly errors in construction projects [9–11]. Effective design progress monitoring is instrumental in preventing potential errors, and it results in both lower overall project costs and productivity improvements across the industry [12–15]. Any performance monitoring system depends on metrics to determine the performance of project participants. Calculating performance metrics enables managers to identify where team members are falling short, make corrective adjustments, and track outcomes across different projects [16,17].

* Corresponding author.
E-mail addresses: saman.yar@gatech.edu (S. Yarmohammadi), dcastro@gatech.edu (D. Castro-Lacouture).

https://doi.org/10.1016/j.autcon.2018.05.011
Received 3 January 2018; Received in revised form 24 March 2018; Accepted 7 May 2018
0926-5805/

1.1. Current performance monitoring methods for building design projects

Design performance is traditionally measured by tracking a designer's or engineer's production rate as the relationship between physical inputs and outputs. The current design or engineering performance metrics can be classified as follows [18]:

- **Design Hours per Construction Document**—in this approach, design hours and construction documents (e.g., drawings, specifications, contract forms) are considered to be process input and output respectively. In a study to measure engineering productivity, Thomas et al. [19] proposed using design work hours per drawing sheet, design work hours per specification section, and design work hours per contract document to measure design progress. Chang and Ibbs [20] measured production rate using design work hours per drawing sheet to identify the major factors that affect design productivity. These metrics regard project documents as tangible outputs of design, which makes output estimation relatively less burdensome. The number of billable hours that designers spend can also be measured using company payroll information. However, this method does not account for the differing complexity and unique characteristics of construction projects. Therefore, the proposed metrics are better suited for comparing design performance across similar projects.
- **Design Hours per Installed/Build Quantities**—this approach considers design hours and installed or built quantities (e.g., amount of installed equipment, concrete volume, building floor area) as the input and output of design processes respectively. In an effort to measure performance in 10 engineering disciplines, the Construction Industry Institute (CII) [14] proposed several trade-specific metrics based on the number of equipment pieces designed. Kim [21] later used these metrics in another CII-supported project to benchmark engineering performance. Sacks and Barack [22] and Sacks et al. [23] are other examples of utilizing installed or build quantities to estimate design output, where the authors investigated the impact of 3D parametric modeling on structural engineering productivity. The methodologies proposed in these studies incorporate project characteristics and design quality in the evaluation of design performance; therefore, they can be used to compare projects that are different in nature.
- **Normalized Design Hours**—in this approach, design hours are normalized using a basis for design hours. The CII [13] developed multiple regression models to calculate the basic hours in different engineering disciplines, and design performance in each discipline is measured by normalizing the actual design hours against the calculated basis hours. A normalized metric of less than one indicates a performance that is better than the benchmark. Liao et al. [24] and Liao et al. [25] proposed modifications to the CII's methodology to convert and aggregate unit-less design metrics into project-, portfolio-, and company-level measures. This allows managers to compare performance not only across different projects but also across different disciplines.

1.2. Performance monitoring in collaborative computer-aided design

In the context of this study, BIM is seen as a software platform enabling different project stakeholders to combine and coordinate their work into one building model. A building model, is a three-dimensional parametric model with embedded information [26]. The model consists of digital objects representing elements that compose the building. These objects have global unique identifiers, include information about their geometry and other properties, and are connected to each other [27]. Building modeling is also defined as the activity carried out by modelers when generating such 3D models of a building. This task is normally accomplished by using BIM software packages such as Autodesk Revit® Architecture and Structure, Bentley Architecture and its associated set of products, the Graphisoft ArchiCAD® family, and Gehry Technology's Digital Project™.

The capabilities of virtual design technologies have eased collaboration in typical design teams that involve a wide array of disciplines, such as architecture and structural, seismic, hydraulic, and pipeline engineering, working together for a relatively short period of time [28]. To facilitate virtual design efforts, different sequential and parallel collaboration strategies have been proposed for implementation [29,30]. A number of studies have been conducted to measure the success of these strategies to improve performance. Lee and Kim [31] conducted a case study of a seven-story office building to investigate the impact of parallel versus sequential approaches on a design coordination team's production rate. Their findings indicated that a sequential design strategy is faster than the parallel strategy in terms of design productivity. A further examination of these two approaches identified deficient information sharing among design team members as the main factor that negatively impacts performance. Other case studies, such as those conducted by Staub-French and Khanzode [32] and Manning and Messner [33], also investigated collaborative strategies with a focus on evaluating the impact of virtual design and construction (VDC) solutions on design performance. Together, these studies demonstrated that information transfer bottlenecks are the primary challenges for design progress monitoring in collaborative computer-aided design.

An important observation is that the data accumulated in building models largely consist of information about different building systems (e.g., structural, mechanical, electrical, architectural), and they exclude model progress data [34]. In fact, AEC companies still use conventional manual practices, such meeting minutes reports and Gantt charts, to document design modeling progress data [35]. In larger projects, those reports consist of several pages of emails, charts, descriptions, and spreadsheets that are difficult to read and analyze [36]. These unstructured documents lack the organization necessary for machine readability—i.e., inclusion in a relational database that search engine algorithms can readily search [37]. Structured data are understandable in machine language, and computers can automatically read and analyze them. In contrast, unstructured data are only understandable to humans, who do not interact with information in strict, database formats [38]. The manual compilation of unstructured progress reports to measure design modeling performance is a time- and energy-consuming task.

1.3. Shortcomings of the existing performance monitoring methodologies

1.3.1. Delays

The existing design modeling performance approaches are either backward-focused or trailing. This is due to the fact that these methods mainly rely on information collected after a project is complete [39]. In traditional design-bid-build (DBB) projects, there is a significant lag between the time at which the measures are calculated and the time at which design happens [40]. Similarly, in contemporary methods of project delivery such as design-build (DB) and integrated project delivery (IPD), performance measurement is done using information extracted from databases of past projects [41–43] or questionnaire surveys and interviews conducted after the end of projects [44–46]. Such delays prevent design managers from taking corrective actions to rectify issues in a timely manner.

The lagging measurements of design performance metrics can provide information about a project after the fact. However, the value of these metrics as future predictors for design-related conflicts remains questionable [47]. Moreover, an unbalanced focus on lagging after-the-fact-based approaches may discourage conflict prevention [48]. Therefore, organizations have also adopted proactive leading measures to predict future levels of performance. For such systems to function properly, it is necessary to collect accurate data in real time [49].