Principal Component Analysis to Investigate the Effect of BIM Use on AEC Project Changes

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ABSTRACT

Building information modeling (BIM) is a process that has the potential to positively impact the performance of architecture, engineering, and construction (AEC) projects. Previous studies showed the quantitative performance benefits of BIM from a general perspective. This paper aims to build upon the previous studies and investigate the effect of BIM Uses on a specific key project performance metric: project change. BIM Uses include visualization, clash detection, code checking, early coordination between stakeholders, and others. The research methodology includes conducting a principal component analysis (PCA) on a dataset of 34 completed vertical construction projects. A new input, the BIM Use Score, was created through PCA and was used to test if increased BIM Use actually affects project change metrics. Interesting results emerged from the analysis, including the lack of relationship between BIM Use and the extent of project change, and a potential correlation between BIM Use and the project change initiators: increased BIM Use seems to result in less design changes but more owner changes. The findings of this study provide a more comprehensive understanding of the impact BIM Use can (or cannot) have on project performance, ultimately helping project stakeholders decide how to most effectively use BIM on their projects.

INTRODUCTION

The following definitions give a broad understanding of building information modeling (BIM) and some of the most common uses. Eastman et al. (2008) states a building information model contains precise geometry and relevant data needed to support the design, procurement, fabrication, and construction activities required to realize the building. Azhar (2011) builds upon this definition by stating a building information model is a model that characterizes the geometry, spatial relationships, geographic information, quantities, properties of building elements, cost estimates, material inventories, and project schedule. The use of BIM has grown rapidly over the past decade. Even though BIM has been around for nearly two decades, it often takes new technologies years to gain popularity and widespread use in a field, especially in the Architecture, Engineering, and Construction (AEC) industry. According to McGraw-Hill (2012), new technologies gain traction when their benefits are meaningful and sustainable for users. BIM users have realized many benefits stemming from BIM adoption and therefore, the AEC industry is investing in this technology. A different study by McGraw-Hill (2009) states that even as the design and construction industry confronted a slow economy, most BIM users were seeing positive payback from their use of the technology. Users gain bankable benefits that enhance productivity, improve their ability to integrate teams and had an edge over their competition. The combination of BIM having meaningful benefits and the fact that BIM users have seen positive payback even during a slow economy are two of the major drivers for the adoption of BIM for users in the AEC industry today. Many studies have shown qualitatively how BIM is being used in the AEC industry, but few studies have shown quantitative project data on how BIM Uses are impacting project performance, specifically when it comes to project changes. This paper aims to build upon previous studies and empirically investigate if BIM Uses have an effect on project changes. The paper will begin with a review of literature to analyze the current body of knowledge available regarding the uses of BIM and the benefits associated with these uses. Then, the methodology will be thoroughly explained and will be followed by a principal component analysis of recent project data.

PREVIOUS LITERATURE

A review of relevant literature was performed to analyze the current body of knowledge available regarding the uses of BIM and the performance benefits of BIM. The goals of the literature review were to compile BIM Uses and performance outputs to be used during the development of the survey and the collection of data. Issa and Suermann (2009) performed a survey across the AEC industry to evaluate the perceptions the impact that BIM has on six primary construction key performance indicators (KPIs) that are commonly used in the AEC industry: quality control (rework), on-time completion, cost, safety (lost-man hours), dollars/unit (square feet) performed, and units (square feet) per man-hour. Zuppa et al (2009) used a survey of 202 AEC professionals to gain an understanding of the prevalent definition of BIM and to identify BIM's perceived impact on the success measures of construction projects. Becerik-Gerber and Rice (2010) identified and benchmarked tangible benefits and costs associated with BIM use through a survey of 424 respondents. Giel and Issa (2011) analyzed data on the possible cost savings of implementing BIM on construction projects. Azhar (2011) illustrated the cost and time savings realized in developing and using a building information model for the project planning, design, preconstruction, and construction phases. Barlish and Sullivan (2012) developed a methodology to analyze the benefits of BIM, apply recent projects to this methodology to quantify outcomes, resulting in a holistic framework of BIM and its impacts on project efficiency. Bynum et al. (2013) investigated the perceptions among attendees at a design-build conference of the use of BIM for sustainable design and construction.

BIM USES DEFINITIONS

Kreider et al. (2010) focused on identifying perceived benefits and frequency of implementation of twenty-five BIM Uses, which are currently being implemented on projects in the industry. This was completed through the use of an online survey of industry members. The BIM Uses were listed as the most frequently used by the user and which had the most perceived benefit. The BIM Uses defined in this study, in order from most frequently used to least frequently used, were: 3D coordination, Design Reviews, Design Authoring, Construction Systems Design, Existing Conditions Modeling, 3D Control and Planning, Programming, Phase Planning (4D Modeling), Record Modeling, Site Utilization Planning, Site Analysis, Structural Analysis, Energy Analysis, Cost Estimation, Sustainability LEED Evaluation, Building System Analysis, Space Management/Tracking, Mechanical Analysis, Code Validation, Lighting Analysis, Other Engineering Analysis, Digital Fabrication, Asset Management, Building Maintenance Scheduling, and Disaster Planning. From the data collected, 3D Coordination and Design Reviews had the highest perceived benefit. Messner and Kreider (2013) recently developed a comprehensive system for the classification of the Uses of BIM. The authors defined a BIM Use as a method of applying Building Information Modeling during a facility's lifecycle to achieve one or more specific objectives. BIM Uses were categorized into five primary purposes: (1) Gathering, (2) Generating, (3) Analyzing, (4) Communicating, and (5) Realizing. The authors also added BIM Use Characteristics to precisely define the BIM Use beyond the purpose and objective alone, moving the BIM Use beyond answering "*why*" to a more distinct description, which could be used in procurement efforts.

OBJECTIVE AND METHODOLOGY

To implement BIM efficiently and effectively, owners, engineers, architects, and contractors must have a clear understanding of the possible ways in which BIM can be used and also how BIM Uses will affect project performance. The performance metrics that are often most important for these stakeholders are cost, schedule, quality, safety, and the amount of changes on a project. In this paper, one of these specific metrics will be studied: project changes. The total changes that occur on a project are measured and then these are divided based on the stakeholder that initiated the change.

Previous studies have shown benefits in using BIM (e.g. Azhar 2011; Eastman et al. 2008), but the specific effect that BIM uses have on the project quality and project changes have not been quantified previously. This paper uses an unsupervised statistical technique to reduce the dimension of BIM data to one variable, and then test how this summary variable contributes to project performance. The objective of this paper is to empirically analyze data regarding the uses of BIM on complex vertical construction projects. The methodology of this study consists of four major phases: 1) Literature Review, 2) Survey Development, 3) Data Collection and 4) Data Analysis.

A comprehensive literature review was conducted to analyze key BIM Uses, as well as major project performance metrics that are used in the AEC industry to assess project performance. The BIM Uses were collected from several studies (e.g. Kreider et al. 2010, Messner & Kreider 2013). Kunz and Fischer (2012) grouped the output or performance variables into six key performance areas. Since identifying the key BIM Uses and performance metrics provides guidance about the type of data that needs to be collected, the completion of the first phase serves as a solid basis for the survey development. The survey was designed to gather data on quantitative and qualitative performance metrics. It was shared with industry participants, specifically the general contractor or construction manager of each targeted project, to allow for the gathering of data in a consistent format. Data was received for 34 construction projects that have adopted BIM at various levels. The list of BIM Uses were compiled from the literature review (e.g.; Messner 2011) and includes variables such as:

- BIM Use for Visualization
- BIM Use for Space Validation
- BIM Use for Site Logistics
- BIM Use for Early Design Coordination
- BIM Use for Mechanical, Electrical, and Plumbing (MEP) Coordination
- BIM Use for Design Collaboration
- BIM Use for Clash Detection

After the BIM Uses were defined and the data was collected, the statistical analysis was completed. The data analysis for this study consisted of two steps: (1) exploratory statistical analysis and dimension reduction, and (2) regression analysis. The main method used in this study is Principal Component Analysis (PCA), a dimension reduction technique for quantitative data. The data used in this paper contained 35 BIM variables that gauge the extent of BIM use on a project. PCA was used to reduce the number of dimensions in the BIM dataset while keeping as much information as from the original data. PCA accomplishes this task by linearly combining the original variables into new variables that are uncorrelated with each other, such that a few of these new variables will explain most of the variation in the original dataset (El Asmar 2012). PCA was completed to reduce the many BIM inputs into a single new input that can be used to test the effect of BIM use on project performance. The outcome of PCA is a series of principal components (PC), each of which accounts for some of the variance in the dataset, with the first PC accounting for the majority of the variance and decreasing with each subsequent PC.

A sensitivity analysis was also conducted on the PCA results to ensure a true representation of the BIM inputs and to confirm missing data points did not affect the results. The sensitivity analysis used four different combinations of the BIM input data, the following describe the different data combinations used: (1) all missing values in the data were replaced with average values; (2) projects and BIM variables with more than four missing data points were removed from the analysis; (3) only BIM inputs with more than 4 missing data points were removed from the analysis, while keeping all projects in the dataset; and (4) all projects and BIM inputs with missing data were removed from the analysis. The sensitivity analysis resulted in 34 projects and 35 BIM inputs for the first analysis, 25 projects and 32 BIM inputs for the second analysis, 34 projects and 32 BIM inputs for the third analysis, and 20 projects and 30 BIM inputs for the fourth analysis.

PCA was conducted on each of the four scenarios. While the number of statistically significant principle components (PC) differed between scenarios, Table 1 shows relatively similar loadings for the first principal component (PC1) across all four scenarios, indicating the missing values in the data did not have much effect on the results. The first principal component (PC1) in each of the analyses explained an average of 46% of the total variation in the dataset.

Table 1. Principal Component 1 Comparison Across All Four Scenarios

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**
BIM Inputs	**PC1**	**PC1**	**PC1**	**PC1**
BIM	0.67	0.77	0.67	0.59
BIMProtocol	0.57	0.64	0.57	0.53
BIMReliance	0.55	0.59	0.54	0.63
BIMJointSer	0.39	0.47	0.39	0.46
BIMuseVis	**0.88**	**0.89**	**0.88**	**0.85**
BIMuseValid	**0.74**	**0.77**	**0.74**	**0.66**
BIMuseLogis	**0.71**	**0.76**	**0.70**	**0.80**
BIMuseEnv	0.57	0.61	0.57	0.63
BIMuseCoorEarly	**0.75**	**0.75**	**0.75**	**0.75**
BIMuseCoorMEP	**0.79**	**0.83**	**0.79**	**0.69**
BIMuseCollab	**0.68**	**0.71**	**0.68**	**0.62**
BIMuseClash	**0.85**	**0.85**	**0.85**	**0.73**
BIMuseSubmit	0.52	0.51	0.51	0.64
BIMuseEstim	0.37	0.34	0.37	0.19
BIMuseSched	0.58	0.63	0.58	0.66
BIMuseFab	0.61	0.70	0.61	0.55
BIMuseSim	0.39	0.63	0.39	0.58
BIMuseTurn	0.54	0.59	0.54	0.72
BIMuseFM	0.47	0.49	0.47	0.56
BIMuseCode	0.47	0.49	0.47	0.48
BIMuseMarket	0.32			
BIMsysFoun	0.50	0.62	0.49	
BIMsysStruc	0.52	0.60	0.51	0.52
BIMsysFin	0.48	0.53	0.48	0.49
BIMsysEncl	0.51	0.56	0.50	0.46
BIMsysRoof	0.27	0.37	0.26	0.27
BIMsysMech	**0.74**	**0.80**	**0.74**	**0.65**
BIMsysElec	**0.65**	**0.66**	**0.65**	**0.55**
BIMsysSite	0.38	0.45	0.38	
BIMsysConv	0.38			
BIMsysSpe	0.31			
ExpBIMCMGC	**0.65**	**0.67**	**0.65**	**0.49**
ExpBIMSub	0.38	0.39	0.39	0.16
ExpBIMOw	0.59	0.59	0.59	0.54
ExpBIMAE	0.57	0.61	0.57	0.50

Relatively high loadings are shown as the darker shaded cells in Table 1. It is easy to see the darker colors for the more common BIM Uses, and to a certain extent for the modeling of mechanical/electrical systems and the experience of stakeholders with BIM. Using these loadings, PC1 can be calculated for each project and then used as a new BIM variable. Because this new input is heavily made up of BIM Uses it will be named the "BIM Use Score". However, this new created input also includes the extent of BIM use on mechanical/electrical systems and the experience with BIM of the major stakeholders in a project, specifically the construction manager or general contractors. The result from the new input is a single value (or score) to represent the level of BIM use on a project. The scores range from 0 for projects that used no BIM to a maximum value 90.78 in this dataset. More functions BIM is used for on a project will result in a higher BIM Use Score. The next section will use this new variable to explore the impact of BIM use on several project performance metrics.

ANALYSIS AND DISCUSSION OF RESULTS

After the aggregation of the many BIM inputs into a single input that represents nearly half the total variation in the data set, the BIM Score was analyzed against the project change metrics that were collected separately for each individual project. This analysis of the BIM Score and performance outputs yielded interesting trends in the effects that BIM Uses could have on project performance. Project change metrics included measuring the total percentage of changes on the project, as well as identifying the key initiators of these changes. Figure shows the total percentage of changes on a project plotted against the BIM Use Score. Although it might seem that the increased use of BIM increases the percentage of change on a project, the R^2 value is extremely low and shows that about 1% of the variation in changes is due to BIM Use. This finding potentially contradicts some of the literature that argues BIM will reduce changes on AEC projects.

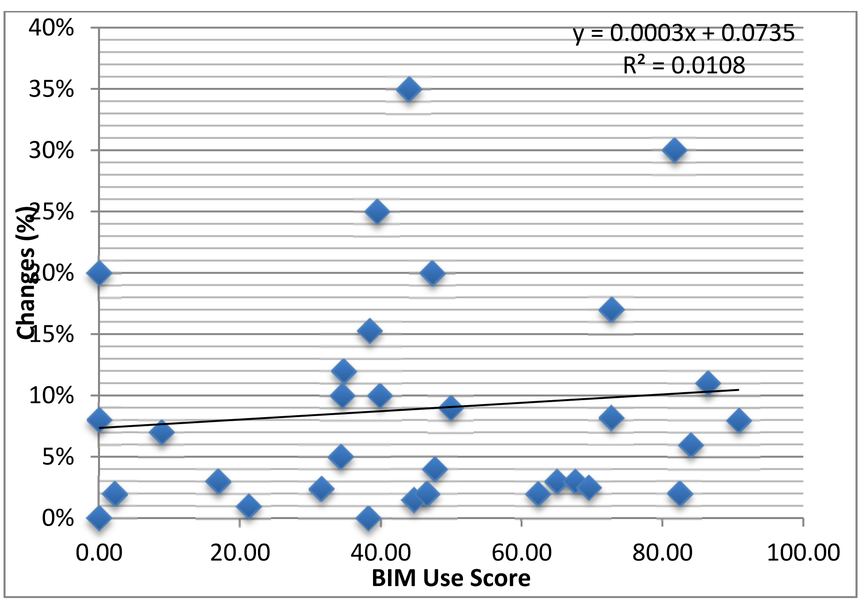

Figure 1. Changes vs. BIM Use Score

Even more interestingly, Figure looks at the change data on a more detailed level to investigate the initiators of these changes. The figure shows the percentage of owner changes versus the percentage of design changes on the project, both plotted against the BIM Use Score. The R^2 values are again low, but the trend is interesting nevertheless and could help put the results from previous literature in the right context by showing design changes could indeed be decreasing. When BIM is not used or used lightly, a large portion of changes are design changes; whereas when BIM is heavily used, a dramatic reduction of design changes is seen and a transition to a majority of owner-initiated changes. This transition may be attributed to the owner being able to visualize the facility virtually prior to construction being completed, which could lead to more changes that potentially increase the quality or the value of the facility for the owner.

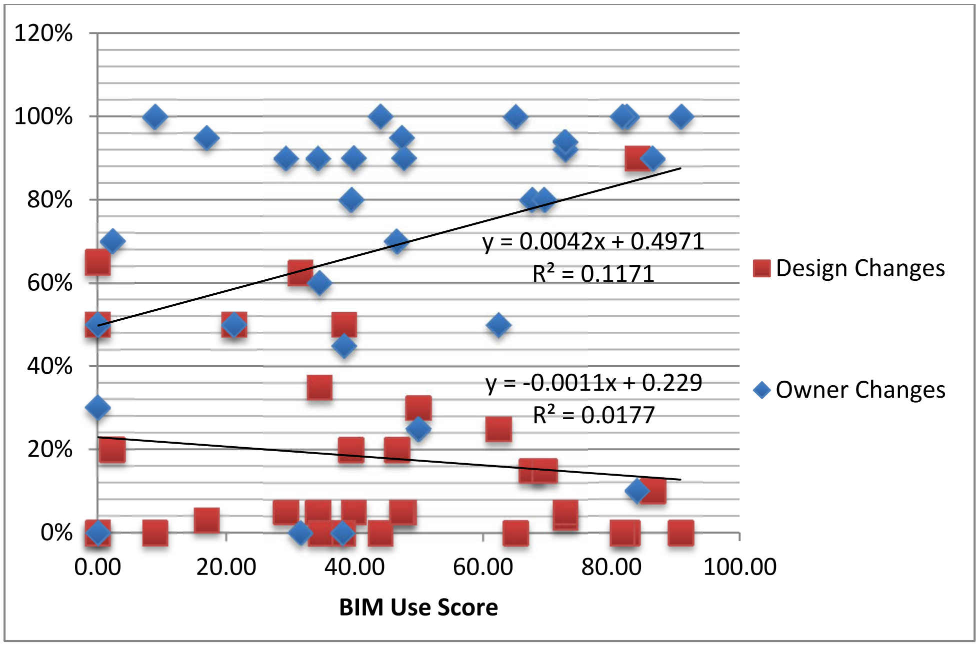

Figure 2. Owner Changes and Design Changes vs. BIM Use Score

CONCLUSIONS

BIM use has been rapidly increasing in the AEC industry due to the meaningful benefits that it provides. Quantitative proof of these impacts will keep users efficiently and effectively using BIM. This study builds on the current BIM literature by providing a more quantitative understanding of BIM impact on project change through the collection of project data and exploratory statistical analysis. The use of BIM was shown to increase the amount of owner changes and decrease the amount of design changes, while not influencing overall project change. However, these results are merely based on trends in the data that does not show high R^2 values and only explain a small portion of the variation in the data. With a larger dataset and more comprehensive data collection these trends have the potential to be statistically proven. The results presented in this paper are part of an ongoing research effort, which will expand the analysis to cover a larger dataset and include a wider variety of projects.

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