4D BUILDING INFORMATION MODELING AND FIELD OPERATIONS: AN EXPLORATORY STUDY

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ABSTRACT

The value generating aspects of BIM technology on the virtual design and coordination sectors of construction have been well documented. However, a more thorough understanding of BIM's ability to assist in the sequencing and implementation of field operations is required in order to fully comprehend BIM's effect on overall project productivity. For this paper, a case study of a 500,000 ft^2 OSHPD hospital project in Southern California was performed in order to observe, identify, and analyze both the field operational activities which could potentially benefit from 4D BIM integration and the factors that could aid and/or deter successful 4D application in the field. Project data was aggregated over a three month period using a combination of observational studies and open ended interview questions. In order to analyze the data for interactions between field operational activities and 4D BIM applications, a relationship matrix was created. The resulting analysis confirmed that by adding transparency to production sequencing, visualizing trade and equipment movement, and understanding constraints in terms of the site and schedule, the use of 4D BIM could serve as a method through which increased value in field operational activities could be achieved.

KEYWORDS

Building Information Modeling, 4D, planning, field operations

INTRODUCTION

Since its inception nearly 25 years ago (van Nederveen and Tolman, 1992) the presence of building information modeling (BIM) technology in Architecture/Engineering/Construction has revolutionized the way structures are built. From conception and design, to coordination and construction, the use of these intelligent computer imaging tools has opened avenues of communication and clarity previously unavailable to the industry. Though BIM technology systems have seen an increase in adoption and implementation, the ways in which these principles have been applied has remained stagnant. A 2010 study of BIM use on construction projects indicated that the majority of surveyed participants used BIM for visualization, clash detection, and building design (Becerik-Gerber and Rice, 2010); relegating beneficial BIM capabilities to pre-construction and prefabrication activities

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with little to no regard for field applications. These limitations toward the use of BIM in the planning and completion of site work represent a knowledge gap in the AEC industry. In order to further the evolution of BIM in construction, research and analysis of this gap between the current uses of BIM and their potential to support trades in the field is needed. Our paper seeks to reduce this gap by investigating beneficial 4D BIM applications in field operations. It is our hope that through investigation of this knowledge gap, untapped opportunities for increased productivity and project flow improvement within the AEC industry can be found.

BASIS OF RESEARCH

In the seminal article by Sacks et al. (2010a), “4D visualization of construction schedules” was listed as one of the BIM functionalities with the highest concentration of unique interactions in relation to lean principles. In Ballard and Howell’s (1998) similarly significant study of process control in construction, it was stated that in regard to the effect of production shielding on field activities “a further stage of improvement can be reached by increasing the visibility of work flow”. From the results of these studies it can be hypothesized that due to the ability of 4D visualization to beneficially interact with lean principles and the potential for visualization to positively affect lean based production shielding methods, a synergistic relationship between 4D BIM and production control may exist. As such, the approach of interacting 4D BIM functionalities with shielding production criteria (Ballard and Howell, 1998) is a natural step in the researching of BIM applications on field operational processes.

The research performed for this study is broken into two parts. The first section involves the creation of an interaction matrix in order to determine potential synergies between trending 4D uses and quality assignment criteria and the second involves the performance of a case study in order to examine potential parallels between the theorized interactions and the observed field conditions.

BIM, LEAN, AND PRODUCTION MANAGEMENT

In this section, research from past studies regarding the relationships, benefits, and challenges of BIM, lean, and production control have been collected and are discussed to form the theoretical basis of the research presented.

BIM AND LEAN INTERACTIONS

Sacks et al (2010a) designed a matrix which aimed to juxtapose lean building principles against BIM functionalities in order to determine positive and negative interactions. From their research they determined that BIM and lean do exhibit a synergistic relationship in many applications; however those applications must be applied at the correct stages in the presence of compatible business processes in order to receive the full benefits.

Bhatta and Leite (2012) explored the integration of BIM and lean in their case study of the Lee and Joe Jamail swimming center at the University of Texas at Austin. They concluded that though this project was fairly successful in terms of BIM implementation, they struggled with the process flow of activities. In response, they devised an integration framework of BIM and the Last Planner System which helped to 1) establish milestone based master schedule, 2) use 4D CAD model used to track progress along milestones and allow participants to look for sequencing issues/possible activity alternatives, 3) develop a 4-week lookahead including scope for BIM coordination meetings, and 4) select weekly plans from quality assignments.

Hamdi and Leite's paper (2012) explored the relationship between BIM as a process and Lean as management thinking through the performance of a case study on a 550,000 sqft health facility located in Tennessee. The case study results were measured and analyzed using the Sacks et al. (2010) Interaction Matrix and the National Building Information Modeling Standard (NBIMS) Capability Maturity Model. They determined that there was the potential to create an assessment tool which combined lean principles with BIM functionalities in order to help focus lean principle implementation based on the BIM maturity strengths/weaknesses.

BIM use in Production Planning/Management

The trends of 4D use for construction planning were investigated by Heesom and Mahdjoubi (2004). They uncovered that with 4D there were both inherent advantages and disadvantages to its application on construction projects. On the positive side, 4D BIM increased the ease of communication and dissemination of information to clients and contractors, and added visualization allowed for more intuitive comprehension of the construction process than 2D drawings and schedule information. These benefits however, were subject to labor intensive information input processes, dependence on the model's level of detail to drive possible applications within the planning and implementation process, and the requirement of high levels of interactivity of the model in order to test and analyze sequencing alternatives.

Similarly, Mourges et al. (2007) performed a test case on a multifamily housing unit project in order to evaluate the effect 3D and 4D daily huddles on jobsite communication. This line of study was derived from the observation that though 3D and 4D models are regularly used to improve the production analysis and management of design/construction, there was a disconnect between the information provided to the superintendent and foreman (via VDC models) and that seen by field labors (in 2D drawings and verbal instruction). This study discovered that 3D models were preferred to 4D models during the huddles due to 3D BIM's flexibility of use. It was also determined that successful VDC use requires a VDC engineer onsite, full buy in by all project participants, changes in the levels of communication, labor engagement and motivation, and better superintendent-labor communication.

In order to analyze the use of 4D technology in supply chain management, Porkka et al. (2010) performed a case study on a residential housing case in Finland. An application called 4D Live Linker was used to link the 3D model to the schedule and supply chain characteristics. This information was then animated and evaluated to investigate the effects of two different supply chain alternatives (on-site bathrooms or factory-made bathroom elements) on the cost effectiveness of the project. The use of 4D tools to assist in the selection of a supply chain method proved to be beneficial due to its ability to allow the project team to assess the alternatives visually.

To bridge the gaps between the Last Planner System (LPS™) and performed field operations, Sacks et al. (2010b) created the KanBIM program. KanBIM is an integrated system of Andons and Kanban style process flows compiled within the BIM platform which can be used by project managements, superintendents and field staff to manage field production in real time. The KanBIM interface was tested in three focus group workshops in the UK and Finland with CMs, trade managers and crew leaders. Overall the focus groups believed the inclusion of the KanBIM interface into construction projects could prove beneficial.

INTERACTION MATRIX FRAMEWORK

For the assembly of the interaction matrix, Heesom and Mahjoubi's trending 4D applications (2004) and Ballard and Howell's five criteria for quality assignments (1998) were arranged on the axes of the framework. A list of the BIM and quality assignment characteristics has been included below.

Trending 4D Applications

Heeson and Mahjoubi (2004) have identified the following major trends in 4D applications: product modeling and visualization and process modeling and analysis. These trends are described as follows. *Product modeling and visualization* is a broad trend that covers a wide range of applications. Its goal is to deliver product information to clients and contractors in a way that is easily accessible for those lacking in technical experience and quickly understandable for professionals attempting to glean information from the model. The use of 4D BIM for modeling and visualization provides a technological output through which many lean principles, including increased transparency and increased output value through customer consideration, can be realized.

Process modeling and analysis purpose is to aid in the decision process by providing a virtual playground through which project teams can test and evaluate multiple sequencing and scheduling alternatives for cost and/or feasibility. Through process modeling and analysis, projects can benefit from increased process transparency, increased sequence flexibility during the planning process, and the ability of all participants to visualize the entire process. *Collaboration and communication* are enhanced by 4D BIM models which assist in advancing these activities on project sites in various ways including: 1) allowing communication between different contractors on the construction site at various stages of production, 2) removing ambiguity of mental 4D models, removing potential communication problems and 3) using annotations on 4D models which can help explain prospective construction problems to planners making the model more supportive to decision making.

Five Criteria of Quality Assignments

The five criteria for developing quality assignments in the LPS™ environment are discussed by Ballard and Howell (1998). These criteria are used here to support the discussion on how 4D BIM can support the development of quality assignments, and to identify when/where assignments fail to be performed because these criteria were not observed. The five criteria are defined in the following paragraphs.

Definition refers to the level of specificity in activity descriptions. When definition is included as a production control requirement, ambiguity within activities is reduced. This allows all participants to clearly understand the nature, needs, and scope of the work to be performed and facilitates accurate tracking of the start and completion of activities. The *soundness* of an activity is directly related to the thoroughness of the Make Ready process. A sound activity is one that is free of all potentially avoidable constraints. Though there is always the potential that unforeseen circumstances can stall workflow, sound assignments ensure that trade crews will be able to perform the prescribed work packages free of foreseeable interruptions.

Activity *sequencing* refers to the logic of the chosen constructability order. When constructing a sequence, the chain of activities is considered from both the implementation/installation and customer requirements perspectives. The activities are then ordered accordingly ensuring that higher priority is given to specifically important, especially productive, and customer value adding activities over those that can be considered as secondary tasks. These additional secondary tasks can then be used as a workable backlog in the case of failed primary assignments or exceptional productivity. Assignment *sizing* is the requirement that all given tasks are appropriated portioned so that the intended crews are able to complete the tasks in the allotted timeframe. Suitable sizing requirements will also remain cognizant of established work flow production units in order to ensure the proper turnover of completed work from one trade to the next. Finally, the *learning* criteria promotes the analysis of percent plan complete and failure reasons log which are used to record reasons for assignments not completed. These failure reasons can be relayed to activity planning members for analysis and correction, allowing participants to learn from past mistakes and continually approve the planning and make ready processes.

INTERACTION MATRIX COMPILATION AND ANALYSIS

Once the blank framework was completed, potential interactions (formed as synergistic field operation applications) were hypothesized and added to the matrix (Table 1). 23 applied interactions in total were identified by the writers. In order to validate these findings, a case study was performed. This case study served three purposes: 1) to observe field conditions which exhibited either the presence or absence of an identified applied interaction in order to validate the hypothesized applications, 2) to identify factors which could potentially aid or deter the application of 4D BIM on field operations, and 3) to serve as a basis for future targeted 4D BIM implementation efforts.

CASE STUDY DESCRIPTION

This case study was performed on a 700 million dollar, 510,000 square foot healthcare project located in the Southern California area. The project consisted of the construction of a 10 story tower with a 161 bed-capacity, an attached central utility plant, and the renovation of an adjacent building. Though the project was not under an Integrated Project Delivery (IPD) contract, the job participants were collocated in a 20,000 sq foot trailer complex in the hopes that enhanced collaboration and information exchange efficiency could be attained. At the time of the study, 4D BIM was being investigated for use in production planning, but not yet implemented. 3D BIM was the primary platform used by the project team and its functionalities were mainly focused on clash detection, trade coordination, drawing creation (both shop and general use), and service as a visual aid during meetings. All meeting spaces within the complex were outfitted with digital technology tools. Though these technologies were regularly used during field operational meetings, printed plans and handouts were identified as the main focus, relegating electronic documents to a secondary informational supplement. 2-D digital plans were made available via iPad.

CASE STUDY METHODOLOGY

Data collection was conducted over a three month time period. The first author attended meetings (4-week lookahead, subcontractor meetings, BIM coordination), and subcontractor fabrication shop tours in order to investigate team dynamics in situ and fully understand the field activity planning/execution processes. Parties involved with the data collection for the case study included: (from the GC) superintendents, field engineers, the project scheduler, BIM engineers and the 4D scheduler, (from major subcontractors) project managers, project engineers, and foreman. Following observations and the collection of informal background information, open ended interview questions were conceived with the following goals: 1) to understand the current uses of BIM in the operational planning/production process, 2) to gather examples of activities the participants deemed successful and unsuccessful, 3) to determine the factors participants believe lead to those successful and unsuccessful activities, and 4) to gauge the participants attitudes regarding the increased inclusion of BIM in their activities. After data collection, field production examples were analyzed for interaction relevance, factors contributing to the failure activities, and ways in which identified interactions may have been able to help the situation.

RESULTS AND DISCUSSION

The analysis presented in Table 1 supports the following discussion on how 4D BIM can support the development of quality assignments, and identify when assignments fail to be performed because these criteria were not observed.

WASTE DUE TO IMPROPER ACTIVITY DESIGN – RELEVANT APPLIED INTERACTIONS: 5, 7, 11, 16, 17, 19, 20, 22

For the initial site to grade portion of the earthwork, a specific sequence of stair-step, cut and fill excavation activities was conceived during trade-contractor detail planning sessions. This sequencing required the earthwork subcontractor to work along a steeply-sloped side of a V-shaped canyon and use the cut materials from the hillsides as a fill material for the landing area where they would begin their next phase of work. Once beginning this work it became clear that the ability to perform this work was contingent on the existence of a containment wall (against which the first landing could be formed) that was not scheduled to be built until after the grading was complete. The lack of a progress tracking mechanism (like PPC) also concealed the extent of the delay from the team until well into the process. This improper design of earthwork activities and lack of progress tracking tool led to multiple weeks' worth of lost time. Recovery efforts involving Saturday shifts and overtime were implemented in order to mitigate the effects of the lost time.

Contributing Factors: The major contributing factor to this problem was the inability of the participants to collectively visualize the planned sequence of activities. This lack of activity visualization created a gap between the participants' individual understanding of the work to be performed and the realities of how the jobsite conditions would interact with scheduled activities over time.

Table 1. Interaction Matrix of Trending 4D BIM Applications and Five Criteria of Quality Assignments

		5 Criteria of Quality Assignments				
		Definition	Soundness	Sequence	Size	Learning
Trends in 4D application	Product Modeling and Visualization	1) Prefabrication of construction materials 2) Understanding of required materials for given activities	3) Visualization of materials on hand	4) Site layout management 5) Site safety considerations	6) Assist in work batch creation	7) Lessons learned
	Process Modeling and Anaylsis	8) Understanding of trade process dependancies	9) Abilitiy to determine if prerequisite work is complete	10) Assist in procurement schedule 11) Drive the production of building sequencing 12) Track equipment needs and movement 13) Track/organize material deliveries	14) Assist in TAKT time creation	15) Fosters in field ability to effectively improvise 16) Ability to revise 4D as needed, better understanding of effective sequencing
	Collaboration and Communication	17) Understanding of weekly trade responsibilities	18) Visability of potential/upcoming constraints (RFIs, COs, Permitting approvals, Inspections, etc)	19) Facilitate trade coordination 20) Assist with pre-task planning and weekly toolbox talks	21) Drive discussion on future work assignments	22) PPC reporting 23) Failure cause reporting

The secondary contributing factor was the lack of a progress tracking system. Without PPC to record activity progress or last planner to track commitments, plans to readjust the slowed activities were presented by the earthwork sub on non-committal terms, resulting in promised completion dates which were rarely met and lengthened activity durations.

How 4D BIM applications could have been used in this situation

The inclusion of earthwork activities in the BIM model and the use of 4D BIM walkthroughs in detail planning sessions and lookahead meetings could help avoid similar issues of this type from occurring. 4D BIM videos outlining the scheduled activities and their sequences would provide the team with a shared visual understanding of the work/trade flow in the upcoming weeks. This common understanding would then be used to help facilitate productive communication between the GC and subs regarding schedule logic, realistic assignment commitments, and potential real-time realignment of activities. BIM could also be used in conjunction with last planner to create a visual tracking system of commitments and completion progress. Each week, all participants would be able to reinforce their commitments through last planner sessions and view the week's sequence of events via 4D. Upon completion of the week's activities, progress could then be tracked in two ways: 1) reliability of commitment completion tracked through PPC and 2) visual understanding of progress made or amount of work remaining through comparing 4D video snapshots to present field conditions.

TRADE STACKING AND DECREASED PRODUCTIVITY – RELEVANT APPLIED INTERACTIONS: 5, 19, 20

The original schedule called for the completion of the earthwork grading activities prior to the concrete subcontractors start date, due to the compact space in which the planned activities were set to be performed. In practice, the improper sequencing mentioned in the previous example resulted in the earthwork duration extending into the start date of the concrete subcontractor's rebar setting activities. In order to try and mitigate the effects of the earthwork delay, the rebar work was performed alongside the continued excavation. Though the remaining activities in these sequences were performed without incident, the safety concerns arising from the close proximity of the two trades resulted in a general slow-down of both subcontractors.

Contributing factors: The main contributing factor of the decreased productivity was the close stacking of trades in the small work space. This on-site congestion had not only had a negative effect on trade productivity due to the lack of adequate space within which to function, but also created specific safety concerns due to the increased presence of heavy machinery in an area. In addition to the decision to stack trades, the initial poor sequencing of the preceding activities played a role in this issue. The effects of the sequencing snowballed into negative consequences for the following trade, ultimately leading to decreased productivity for both participants.

How 4D BIM applications could have been used in this situation

The use of 4D animation during the field operational planning stages could have helped this situation in multiple ways. The most prominent would be through the elimination of the improper sequencing which led to the need for trade stacking. As was discussed in the first example, the inclusion of a 4D sequencing illustration during the field operational planning stage could have helped the team collectively visualize and assess the planned activities. BIM could also be used in conjunction with the formation and review of site maps to facilitate increased communication between the trades. This enhanced level of communication could lead to better understanding of trade spacing needs and enhanced coordination between trade contractors. Moreover, the trade spacing and site map information could be combined with 4D BIM in order to create not only site specific, but activity specific, safety plans.

WASTE DUE TO INCOMPLETE ACCESS WAY – RELEVANT APPLIED INTERACTIONS 4, 12, 19, 20

During the underground utility phase for the project's central utility plant, the electrical, plumbing and concrete/rebar subcontractors were working on the trenching and installation of utility lines. The area where this work was occurring was bordered by an incomplete access road which ended in an open canyon space on the south end of the site. During the course of activity progression it was discovered that the incomplete access road left the contractors with limited amount of space for equipment access and laydown space (both for materials to be installed and excavated spoils piles). The resulting amount of useable area was only large enough to allow one trade access at a time, creating a large productivity slowdown for the three subs and waste due to inactivity. This issue ultimately resulted in a three week delay to the completion of the underground utility activities.

Contributing factors: This problem likely occurred due to a lack of visualization of the current site layout and a communication breakdown between the subcontractors and general contractor regarding the subs equipment movement, equipment access, and material laydown needs. The inability to depict the impacts the given site conditions had on sequenced activities negatively affected the group's ability to accurately re-sequence activities and coordinate their work processes around the site's capabilities.

How 4D BIM applications could have been used in this situation

The inclusion of 4D BIM in preplanning sessions could have likely prevented this incident from happening. The use of an animated model or 4D day-by-day work progression snapshots in conjunction with a project specific site plan could help give the participants a clearer understanding how the site's current characteristics would affect their operational logistics. This understanding of the spatial requirements could then be used to allow them to update the sequence in a way that will allow all participants to remain productive in the given conditions.

CONCLUSION

The creation of a matrix interacting 4D BIM treading applications and the five criteria for quality assignments resulted in 23 potentially beneficial interactions between the use of 4D BIM and shielding production methods in field operations. Performance of a case study displayed the existence of several situations/activities which could potentially benefit from positive interactions identified in the matrix. From these results it can be surmised that when applied correctly, 4D BIM has the capability to add value to field operational activities. Through 4D BIM, transparency within information exchanges and increased onsite collaboration can be attained. This allows for improved planning and scheduling for subcontractors, assists with delivery of people, equipment, and materials, and enhances the pull flow mechanism to reduce variability. Finally, a limitation of this study is that it has not quantified the benefits of 4D BIM when actually applied to field operations and the authors recognize that this represents an important area that merits further investigation.

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