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CONSTRUCTIBLE BIM ELEMENTS –A ROOT CAUSE ANALYSIS OF WORK PLAN FAILURES

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ABSTRACT

The project Building Information Model (BIM), made up of component trade models, can be used to coordinate and sequence building elements prior to construction. The model should serve as a surrogate for prototyping the actual construction process and can also be used to implement the lean practice of filtering work for constraints prior to assigning work. The term 'constructible BIM element', referring to an element that can be built exactly as it is modeled, is defined to focus on the use of the model for constraint removal and visual planning. Using an in-depth case study, incomplete assignments from Weekly Work Plans were identified and their root causes were mapped onto their associated BIM objects. This spatial analysis makes explicit and begins to quantify the connection between constructability of BIM elements and the variability of work execution in the field. Learning from the underlying patterns, the authors propose process changes for teams to more effectively identify constructability issues in BIM models, and thus leverage the BIM process to improve the reliability of field work planning.

KEYWORDS

Building information modeling (BIM),constructability, root cause analysis, weekly work plan

INTRODUCTION

Removal of constraints to reduce variability of production rates in a system is central to the concept of flow in construction. The Last Planner process removes constraints on activities through the make ready process. Missed tasks indicate that constraints were not removed. Through tracking missed tasks, the Weekly Work Plan serves as a barometer of flow on the project. To construction contractors, a Building Information Model is a virtual model of a project created prior to and during construction to facilitate understanding of how to design, plan, build and maintain the project.BIM is used to coordinate elements, visualize upcoming tasks and communicate information. Deviations between the digital information in the model and the physical assembly

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indicate that the digital elements or their context were not modeled with sufficient detail to execute in construction. If such deviations could be identified in advance, as part of the make-ready process, fewer immature tasks would be assigned.

To this end, the authors introduce and define the notion of a ‘constructible’ BIM element and explore the typologies of digital elements that are not constructible. The connections between missed tasks and the constructability of the BIM were reviewed using root cause analysis in a case study. A process for teams to proactively identify constructability issues in BIM and thus to leverage the BIM process to improve the reliability of field work planning is recommended.

LITERATURE REVIEW

The importance of flow on construction projects has been thoroughly established by Koskela (2000). Ballard (2000) asserts that the lookahead process has “the job of work flow control”. By identifying constraints through planning assignments 3-6 weeks out, teams begin to “make work ready” in the construction process (Ballard, 2000). In the same way, teams use the BIM to identify various constraints that may arise in the design and planning process, primarily by means of clash detection (Eastman, et al., 2011). Sacks, et al. (2010) proposed a framework for research of interconnections and synergies between BIM functionalities and Lean Principles. The framework shows that the Lean Principles with the highest number of interactions with BIM Functionalities are (A) getting quality right the first time (reduce product variability), (B) focus on improving upstream flow variability and (C) reduce production cycle variations.

Tommelein and Gholami (2012) investigated the root causes of clashes in BIM models and concluded unequivocally that clash detection relates directly to removing waste and improving flow, contributing to buildability. Bhatla and Leite (2012) presented the case for the use of BIM to support the Last Planner System™ (LPS) process for construction, hypothesizing that 4D visualization will lead to a better understanding of progress and that the collaboration involved in clash detection will reveal constraints. In addition, Khanzode (2010) demonstrated that the use of the LPS to set objectives and manage the process of BIM coordination leads to an increased rate of prefabrication and a reduction of construction RFIs. Together, these studies demonstrate an interesting reciprocity between BIM and LPS.

Egan (1998) claims that too much time is spent in construction on site trying to make design work in practice. This results from the separation of design from the rest of the project. Sacks, Treckmann and Rozenfeld (2009) expand on the silo mentalities (Jones and Saad, 2003) that obstruct sharing of information across project phases and teams. BIM coupled with Lean helps foster a collaborative culture in which personnel build on prior knowledge, leading to less information being lost from phase to phase of the project. BIM facilitates transfer of information and knowledge to the right people at the right time in the right place throughout the supply chain.

CONSTRUCTIBLE MODEL ELEMENTS

The information in the coordinated BIM should aid the customers of the BIM, the last planners who install the work, in field planning and implementation. In the make ready process, BIM can be used to verify construction flows such as design, components, space, and connecting works (Koskela, 2000). In short, to be of value as a prototype, the BIM must be constructible as modeled. To be constructible, each element must be modeled with thought towards installation sequence and the characteristics of the physical fabrication. A BIM element may be considered constructible if four conditions of constructability are met:

- The form and location of the digital representation and physical fabrication meet the conditions of satisfaction.
- The form (geometry) of the digital representation accurately represents that of the physical fabrication.
- The paths through which the fabrications must move to their installation locations must be unobstructed. The sequence of installation as modelled must be free of time-space conflicts (which can be represented and checked using 4D (Akinci and Fischer, 1998).
- The physical fabrication can be placed in the location of the digital representation. The modeled assemblies surrounding the digital element must accurately represent that of the existing condition of the building.

If these conditions are not met the element is considered not constructible and the model element will not be a reliable tool in the make-ready process. In the process of realizing prototypical BIM elements as fabricated building objects in the field, there are two major hand-offs of information. The first is when the element is released for fabrication. As shown in Figure 1, information from the model can be directly fed into the machine fabricating the physical element (automated fabrication);the fabrication process can use information represented in shop drawings produced directly from the model (direct fabrication); or a more circuitous path is followed, typified by fabrication independent from the model and the use of the model as a reference (indirect fabrication).

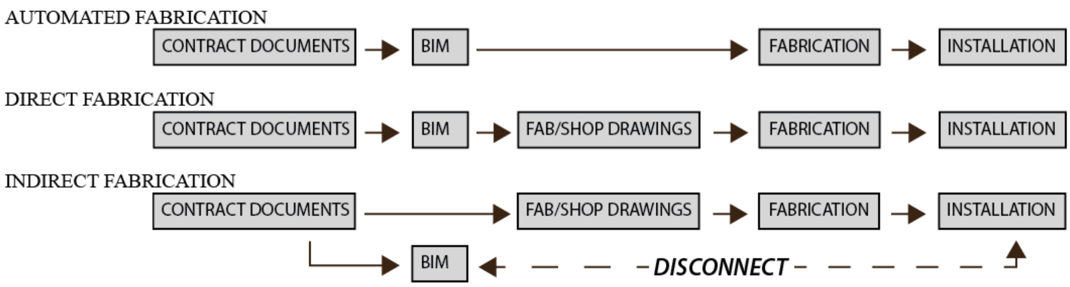


Figure 1: Automated, direct or indirect fabrication.

The second information hand off is between the model and the field. If the workers installing the physical fabrication do not have the correct information, the chances of deviation from the model are greater. It should be noted that this relationship is reciprocal. If installation needs are not communicated to the modelers, the chances of the digital elements being modeled in an unconstructible location or form are greater. In the field, the sequence of work installation is critical in determining outcomes. A fabrication often cannot be installed in the same location as the BIM due to another fabrication occupying that location. If the primary physical fabrication cannot be placed due to an adjacent fabrication, the analysis must be expanded to determine the installation logic of the secondary fabrication.

Thus by considering the technical limitations of the model, transfer of information, conditions of satisfaction, and the effect of adjacent physical fabrications, one can determine the root cause of the unconstructible element. Figure 2 shows a flow chart for this procedure. It should be noted that in certain conditions, multiple root causes will be present.

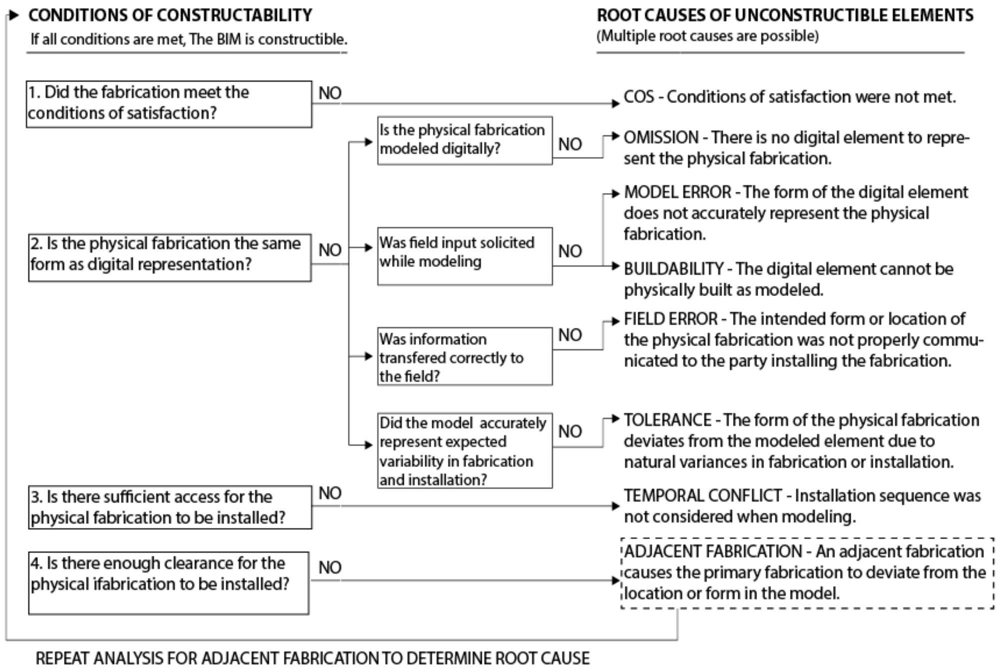


Figure 2: Model Constructability Analysis Flow Chart

METHOD

A core and shell downtown high-rise office building, currently under construction in San Francisco, was used as a case study for root cause analysis of constructability failures and identification of their relationships to elements in BIM. An industry standard BIM execution plan was implemented on this project. Steel, mechanical, electrical, plumbing, fire protection and framing trades contributed to the model. Clash detection was performed using Navisworks and coordination meetings were held for clash resolution. The architect's model was used as a proxy for trades who did not contribute models. The extent of BIM element detail and level of engagement by each trade is shown using the BIM Participation Matrix (Spitler, 2014) in Figure 3.

The Weekly Work Plan was used to track commitments and Planned Percent Complete results were recorded by trade. Commitments were tracked by trade contractor, description of work, and location. If a commitment failed, a reason code was recorded. Fifty two weekly work plans were analysed. Missed tasks from the weekly work plan were tracked by area, time, contractor, and reason code (see Figure 4). The density of the fill in the figure correlates with the number of missed tasks. These missed tasks were then spatially mapped to BIM elements to determine if the root cause of the task failure could be traced to an unconstructible BIM element. All missed tasks were plotted on a pivot table with location along the y axis and time along the x axis. Using the sorting filters assigned to each task, patterns, or clusters, of missed tasks were identified. Further analysis of these clusters was performed to determine the root cause of these systemic failures.

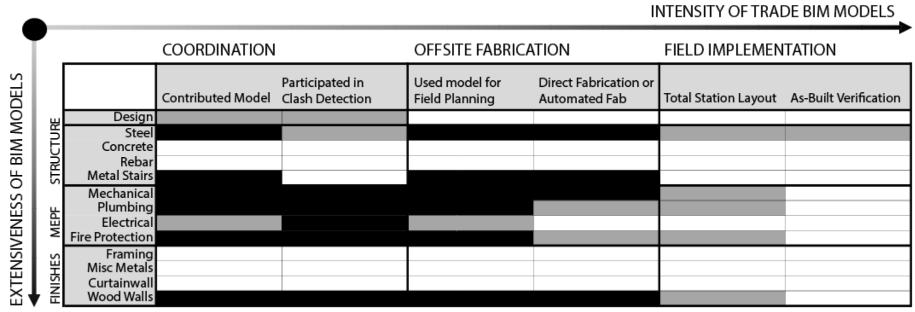


Figure 3: Case Study BIM Participation Matrix (refined from Spitler, 2014).

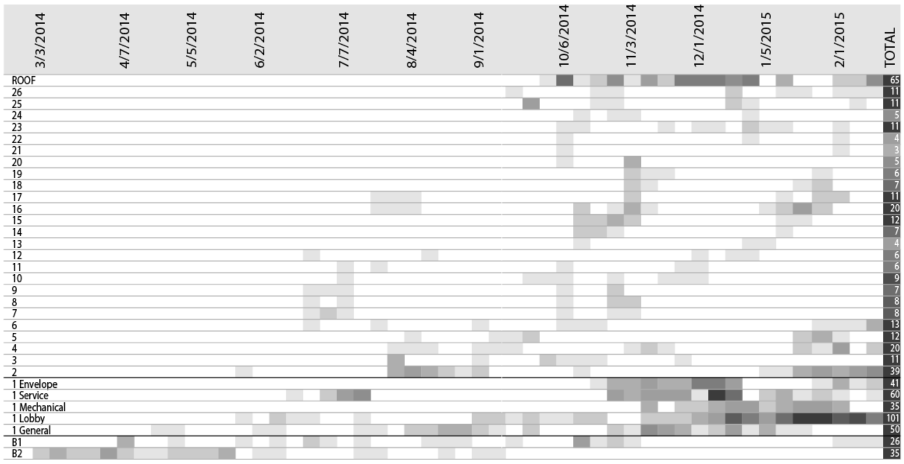


Figure 4: Missed activities sorted by location and schedule (darkness of the squares represents the density of missed tasks)

In this analysis, potential biases in data must be considered. While the WWP tracking on the case study was comprehensive and detailed, the data tracked in the WWP is subjectively entered by the project team. Work that is not essential to meeting that deadline may not be tracked accurately in the WWP. Rework and delayed areas may not be distinguishable from base work. In some isolated cases, the root causes cannot be determined with complete confidence because only eight reason codes were assigned. However, despite these limitations, given the amount of data, this case study is considered to be sufficiently rich and accurate to support identification of general trends and patterns.

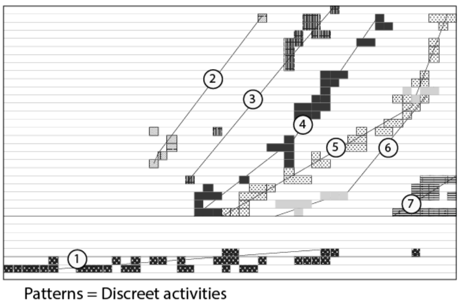
RESULTS

The project planning record included 2,228 tasks overall with a total planned percent complete of 71%. Of the 637 missed tasks, 24% can be attributed to factors unrelated to the BIM such as material, labor, or weather. At least 23% (146 tasks) have root causes that are represented in the BIM. The inability to identify the root causes in the BIM of the remaining 53% of missed tasks is due to the fact that some 90% of their work scope was not modeled at all. Two types of patterns were identified in the data:

trade clusters and location clusters. Of the 146 missed tasks whose root cause was visible in BIM, 83% could be attributed to one of these two types.

TRADE CLUSTERS

Trade clusters are characterized by having a root cause that repeatedly causes task failure across multiple locations. Seven trade clusters were identified and numbered in Figure 5(a) and can be seen to repeat on several floors. The root cause of three of these is visible as unconstructible elements in the BIM model. Clusters4&6in the figure represent a repeated task failure due to wall detail that did not match the field condition due to a model error. The model error, in this case, is in the handoff between the architects' design and its digital representation in BIM by the drywall subcontractor. When the shaft wall layout was changed by the architect, the requirements did not flow down to the drywall detailer to update the model. Had this been done, the drywall detailer would have noticed a new detail was required. Identifying this constructability issue earlier in BIM could have allowed greater flexibility of alternatives to choose from and ample time to adjust the plan for impact in flow. Instead, the issue was identified by the last planner in the field. The new detail required steps that had not been factored in the look ahead plan. This task failure accounted for over 10% of missed tasks on the project in the period of study.



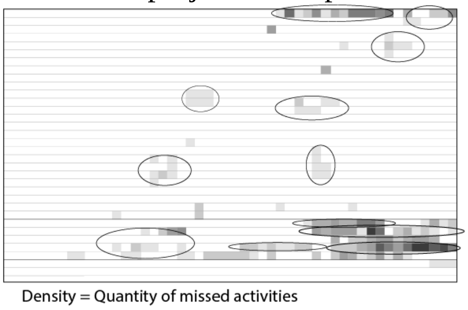


Figure 5(a): Trade Clusters *Figure 5(b): Location Clusters*

Cluster 7 represents the restroom build. The location of walls with regards to code required clearance dimensions was not fully worked out in the model. The model was not used for layout in the field, resulting in rework in plumbing to match the new location of the walls. Of the BIM constructability issues in this cluster, 87% were information transfer issues (Root causes = field errors, model errors, and buildability).

LOCATION CLUSTERS

The second type, the location cluster, is characterized by multiple trades in a concentrated location and time period (see Figure 5b). The high interdependency between trades causes small errors by earlier trades to compound with subsequent trades. It logically follows, and this is shown in the data, that these clusters occur where the design calls for a high level of interaction between trades. Of the twelve clusters identified in the data, nine occur in areas which have a high degree of interaction between trades. Nineteen percent of the missed tasks had root causes visible as unconstructible elements in the BIM.

One such area occurred at the generator exhaust riser (see Figure 6). Table 1 lists the scopes involved, sequence of installation, and root cause(s) identified by the model constructability flow chart.

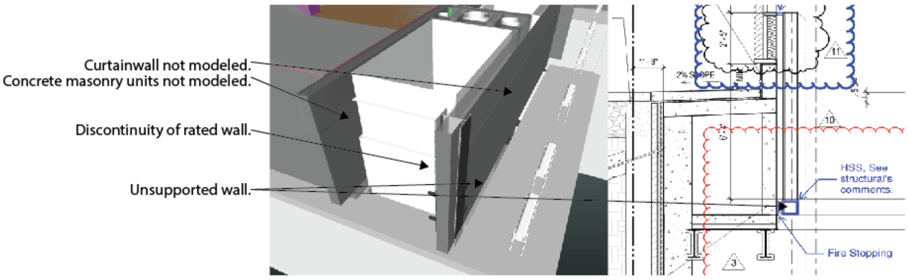


Figure 6: Constructability issues at Generator Duct Riser

Table 1: BIM Constructability analysis - Generator riser location cluster

Scope of Work Sorted by Installation Sequence	Modeled	Conditions of Constructability (See Figure 2)				Missed Tasks	Reason
		1. Conditions of satisfaction	2. Accurate Form?	3. Access?	4. Clearance		
1.Concrete Slab	Yes	Yes	No	Yes	Yes	0	Omission
2.Concrete Block Wall	No	Yes	No	Yes	No	0	Omission
3.Curtain Wall	No	Yes	No	Yes	No	5	Omission
4.Drywall Framing	Yes	No	Yes	Yes	No	16	Buildability, model error
5.HVAC Ductwork	Yes	Yes	Yes	Yes	Yes	0	Adjacent element

The result of the root cause analysis, as is typical with location clusters, is multiple failures. The omission of the structural trades caused a discontinuous rating issue to not be identified until work was in place. The model error (placing wall in an incorrect location) caused the team to miss additional support needed to install walls. Reliable flow depends on a level of confidence that the adjacent trades have installed their work per BIM. Indeed, the lack of a model for concrete and CMU block negatively impacted subsequent trades' installation, but not the structural installation. Basic modelling of structure and curtain wall scopes in conjunction with visual planning would have allowed the last planners to visualize and mitigate issues. This failure cluster accounted for over 6% of missed tasks in the entire project in the period of study and caused delay in a critical area of the project.

DISCUSSION

The general trends shown in the project level analysis are illustrative of the approach of contractors to design, fabrication and installation of product. When plotted in order of sequence (figure 7), trends emerge. First, it can be seen that the rate of missed tasks increases in later trades. This is intuitive, as trades who install first only have to coordinate within their scope to have an on-schedule installation. Trades who follow have to navigate work in place as well as internal coordination when installing work. When the team is considering who should contribute to the BIM, the value of the contribution to subsequent trades should be considered.

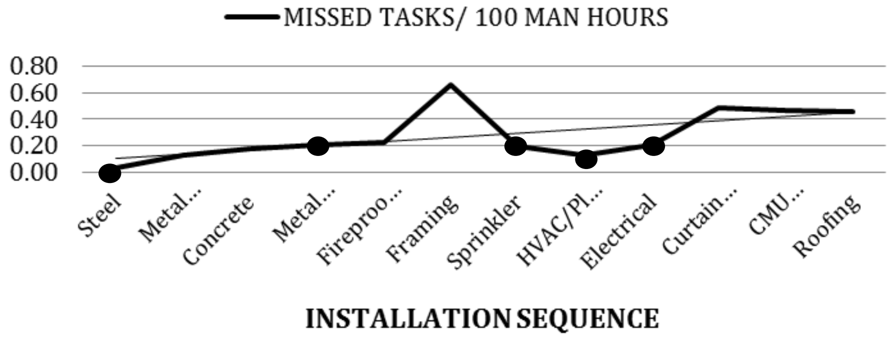


Figure 7: Missed Task Rate by Trade and Sequence

Second, it can be observed that trades who directly fabricate from the model have fewer missed tasks. This can be attributed to the amount of preplanning achieved through coordination and on the confidence and validation that the digital representation matched the physical. Confidence is gained when direct digital fabrication and placement is utilized. For example, MEP scopes can achieve the highest level of confidence due to the process of direct fabrication, robotic total station layout, and installation of the prefabricated pieces. When the coordination and planning is complete prior to construction, installation equates to assembling a kit of parts rather than figuring out atypical details in the field.

RECOMMENDATIONS

The data show that the majority of missed activities are not random, but predictable and clustered by trade or area. It follows that the most efficient mitigation of these issues requires a process solution. Addressing constructability and installation sequence in BIM coordination and execution in a rigorous way would remove constraints that could otherwise be missed until installation. The benefits would include reduced schedule variability, smoother workflow and increased productivity.

With hindsight, it is simple to identify areas of the models that should have been better resolved. The question becomes how teams can deploy BIM more effectively to resolve constructability issues prior to construction. Traditional BIM execution plans rely on prescriptively defining Level of Development by trade and applying clash detection, essentially a push approach that does not consider where value lies. Instead, BIM execution should be tailored to the needs of the building and the abilities of the participating trades. On the basis of these conclusions, four recommendations are made to help teams prioritize and focus their BIM efforts:

- **IDENTIFY POTENTIAL CLUSTERS OF UNCONSTRUCTIBLE ELEMENTS.**To identify potential clusters, teams must rely on trade partners to contribute experience on past issues and delays which are applicable to the current project.Areas of the building design that are atypical or new to trade partners and areas that require a high level of coordination between trades should also be considered. Rather than specifying a level of detail by trade alone, the BIM execution plan should define locations (areas) to be modelled to greater detail.
- **CLASSIFY CHARACTERISTICS OF UNCONSTRUCTIBLE ELEMENTS.** Clash detection is simply an algorithm that identifies if an element physically intersects

with other elements. Similarly, it would be desirable to develop BIM functions capable of rigorously identifying the four types of constructability issues identified in Figure 2. For example, as seen in the trade cluster example, buildability and field errors occur at the shaft walls due to the specificity of the detail and the indirect fabrication method of the sub. Abstracting this example, it can be stated that there is a potential for buildability and field errors at elements indirect fabrication method and a precise location. Areas that meet these characteristics, such as edge of slab, walls defined by required clearances, can then be identified and mitigated.

- **REALIZATION METHOD.** How well a model is coordinated becomes irrelevant if it is not built as modeled. Individual trade's BIM to field translation methods should be reviewed and understood so that appropriate 'as-builting' and model verification strategies can be built into the execution plan. To ensure success, trades should be engaged in the planning process to fully realize the extent of participation required.
- **RETURN ON INVESTMENT OF BIM COORDINATION AND TRANSLATION**. Project teams should consider the investments proposed during the early stages to maintain confidence that BIM accurately models reality. Contractors who directly fabricate from BIM are intrinsically motivated to contribute accurate models. Contractors who do not fabricate from BIM are not. Therefore, it is important to align the requirements with the beneficiaries where possible.

While implementing this framework, the importance of having the right people in the room at the right time cannot be overstated. For each area of focus, the team should check in periodically during model development to review the conditions of constructability. In the early phases of the process, the right people to address constructability may be the procurement and management team. Once coordination starts, these questions need to be answered by the field team, the Last Planners. As each predefined point is met, the team's knowledge should effectively transfer downstream and confidence in the constructability of the BIM should increase.

Missed tasks in the weekly work plan indicate that the make ready process was not complete for those tasks. Often, the root causes of those missed tasks can be seen as unconstructible elements in BIM, indicating that the BIM process was not effective in removing constraints. Therefore, the framework proposed above is designed to pull BIM execution directly to the make ready process for construction. By explicitly focusing on areas whose field execution benefits most from BIM, the team will eliminate waste in the BIM process. By implementing coordination processes designed to address all types of constructability and understand translation methods, the team will ensure that the model will be a useful tool for building. Most importantly, using the four conditions of constructability to measure confidence in, and maturity of, the model, the team can ensure that the preconditions of construction tasks have been effectively met with the aid of BIM.

CONCLUSION

This case study demonstrates that the root causes of missed tasks are often visible as constructability issues in the BIM and that the project BIM is a useful medium for the spatial analysis of root causes.The explicit definition of the term 'constructible BIM object' is useful for project teams who leverage BIM for constraint removal. Although the recommendations are based specifically on the analysis of a single case study, the method of analysis in this paper provides a foundation for future research as well as practical metrics to measure the constructability of the BIM in construction practice.

REFERENCES

Akinci, B. and Fischer, M., 1998. Time-Space Conflict Analysis Based on 4D Production Models. In: *Proc. ASCE Congress on Computing in Civil Engineering.* Boston, Massachusetts, Oct. 18-21.

Ballard, G., 2000. *The Last Planner System of Production Control.* Ph.D. School of Civil Engineering, University of Birmingham, UK.

Bhatla, A. and Leite, F., 2012. Integration Framework of BIM with the Last Planner System. In: *Proc. 20th Ann. Conf. of the Int'l. Group for Lean Construction*. San Diego, CA, Jul. 17-22.

Eastman, C. M., Teicholz, P., Sacks, R., and Liston, K., 2011. *BIM Handbook: A Guide to Building Information Modelling for Owners, Managers, Architects, Engineers, Contractors and Fabricators 2nd Ed*. Hoboken, NJ: John Wiley & Sons, Inc.

Egan, J., 1998. *Rethinking Construction.* UK Government Department of Trade and Industry. Available at: <http://constructingexcellence.org.uk/wp-content/uploads/2014/10/rethinking_construction_report.pdf> [Accessed 1 March 2015]

Hamdi, O., and Leite, F., 2012. BIM and Lean Interactions from the BIM Capability Maturity Model Perspective. In: *Proc. 21st Ann. Conf. of the Int'l. Group for Lean Construction*. San Diego, CA, Jul.17-22

Jones, M., and Saad, M., 2003. *Managing Innovation in Construction*. London: Thomas Telford.

Khanzode, A., 2010. *An Integrated, Virtual Design and Construction and Lean (IVL) Method for Coordination of MEP*. CIFE Technical Report #TR187, Stanford University.

Koskela, L., 2000. *An exploration towards a production theory and its application to construction.* Ph.D. VTT Technical Research Centre of Finland.

Sacks, R., Koskela, L., Dave, B., and Owen, R.L., 2010. The Interaction of Lean and Building Information Modeling in Construction. *Journal of Construction Engineering and Management*, 136(9), pp. 968-980.

Sacks, R., Treckmann, M., and Rozenfeld, O., 2009. Visualization of Work Flow to Support Lean Construction. *Journal of Construction Engineering and Management*, 135(12), pp. 1307–1315.

Spitler, L., 2014. The Effect of Inter-team Dynamics on the Constructability of the BIM model. In: *Proc. 22nd Ann. Conf. of the Int'l. Group for Lean Construction*. Oslo, Norway, Jun. 23-27

Tommelein, I. D., and Gholami, S., 2012. Root Causes of Clashes in Building Information Models. In: *Proc. 20th Ann. Conf. of the Int'l. Group for Lean Construction*. San Diego, CA, Jul 17-22