THE EFFECT OF INTER-TEAM DYNAMICS ON THE CONSTRUCTABILITY OF THE BIM MODEL

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ABSTRACT

An abundance of research focuses on the collective performance and motivations of the TEAM in BIM coordination and execution. The team, however, consists of trade partners with different motivations and sophistication. Trade partners whose product is directly fabricated from 3D models, such as mechanical and steel contractors, are highly sophisticated in BIM. Their models tend to be accurate and vetted for constructability as their profitability depends on quick onsite assembly of prefabricated items. Trade partners whose work installation is not directly fabricated from 3D models tend to have less accurate models that are not vetted for constructability. Non-constructible elements included in BIM are waste as they do not bring value to the intermediate or end user. More perniciously, these models are a presentation of inaccurate information in a highly detailed form, leading to the perception of accuracy and the incorrect detailing of adjacent assemblies.

This paper uses case studies of BIM implementation in the San Francisco Bay Area to analyze model accuracy and implementation by trade and identify best practices in team alignment. This analysis is used to propose a framework for enforcing model constructability based on the basic tenets the Last Planner System™. Beyond project controls, this paper investigates natural alignment of trade interest in constructible models. Specifically, if a trade partner's profitability is increased through the use of model-based layout or increased off-site fabrication, the model will consequently be more accurate, benefiting the larger team. Therefore, this paper also discusses the advantages of intrinsic motivation to reduce variability of trade models between coordination and the field, and proposes methods to achieve this future state.

KEYWORDS

BIM, Constructability, Last Planner™, Buildability

INTRODUCTION

The intent of this research is to explore the relationship of BIM, constructability, and the Last Planner™ System. Short summaries of these concepts as they relate to the research are included to provide a basis for discussion.

Traditional project control models focus on pre-planning and monitoring variances from the master plan. This method of project control has been often critiqued as not sufficient to reduce variability or generate value for a project. (Ballard 2000, Huovila and Koskela 1997) The Last Planner™ System was developed

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as a conceptual shift of thinking from project control to production control. The root concept of the Last Planner™ System is almost deceptively simple – taking what CAN and SHOULD be done, committing to what WILL be done, and measuring what WAS done. The production units, called assignments, are designated by the last planners, the trade specialist who will execute the work. The planned percent complete (PPC) is a measurement of the actual completion of work committed by the last planners. In analyzing why work was not completed, continuous improvement is built into the system.

The second component of the Last Planner™ is Work Flow Control, which 'coordinates the flow of design, supply, and installation *through* the production units.' Pull scheduling is a common application of work flow control as 'pulling' to project milestones reduces variability in schedule as resource continuity is considered; constraints to release work are identified and removed; and interdependencies are discussed in advance of the field. (Ballard, 2000) In pull sessions, discussion of the Process and Step hierarchies[1] of a Lean Work breakdown are particularly helpful in elucidating the interaction between trades as each trade specialist is forced to think of her installation in relation to trades adjacent in location and sequence.

A Building Information Model is a model of a project created in virtual space prior to construction in order to facilitate a better understanding of how to design, build and maintain the project. In addition to modeling geometry of a building in three dimensions, information such as material and cost can be embedded. As building systems have become increasingly complex, employment of Building Information Modeling to coordinate building elements prior to construction has become prevalent in the building delivery process. Typically, Mechanical, Electrical, Plumbing, and Fire Protection (MEPF) contractors will engage in the process to ensure that elements of each trade can be installed without conflict in the field. This process eliminates rework in the field, allows for greater prefabrication, and has a positive impact on the schedule. While BIM can be used in all phases of project delivery, this research focuses on the use of BIM for coordination, detailing, and construction layout.

Constructability in design can be defined as 'the optimum use of construction knowledge and experience in planning, design, procurements, and field operations to achieve overall project objectives' (Russell, et al, 1992) and further expanded upon as 'removing all the unnecessary in construction process which does not contribute to the quality of the building.' (Alarcon, 1997). Value is defined as 'what the customer wants from a process.' Waste is all that does not add value. (Liker 2004) The

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[1] Example of Hierarchies excerpted from Ballard and Howell (2004)
Project: Commercial office building
Phase: Site Preparation, Substructure, Superstructure, Skin, Building Systems, Fit Out
Operation (within the Substructure phase): Layout, Excavate, Shore, Place Drilled Caissons, Cap Piles, Place Underground Utilities, Build Foundations, Build Walls
Process (within the Place Drilled Caissons activity): Fabricate Cage, Drill Hole, Place Cage, Pour Concrete
Step (within the operation Fabricate Cage): Acquire Materials, Place straight bar in jig, Weld coiled bar helically around cylinder, Fit and tack lifting bands, Weld out lifting bands
Assignment (for today): Perform welding steps in the operation Fabricate Cage. Fabricate cages 101, 102, and 103 in that order.

customer of a constructible BIM is the group that is installing the work, and so the terms 'value' and 'constructability' become almost synonymous in this discussion.

LITERATURE REVIEW

Creating a BIM is inherently collaborative as several trade contractors, the design team, and the general contractor work together to create a coordinated model. In recent years, several researchers have investigated the natural alignment of BIM and Lean principles, recognizing that 'while the two are conceptually independent, there appear to be synergies between them.' Sacks et al (2009)

Sacks et al (2009) propose a framework for research of interconnections and synergies between BIM functionalities and Lean Principles. A review of the framework demonstrates that the Lean Principles that have the highest number of interactions with BIM Functionalities include (A) getting quality right the first time (reduce product variability), (B) focus on improving upstream flow variability and (C) reduce production cycle variations. (Sacks et al 2010)

Within the framework proposed by Sacks, several authors have contributed research exploring the interaction of BIM and Lean. Clemente and Cachadinha (2013) presented a case study in the use of BIM in managing the flow of operations on a daily level. Variability of work in the field was reduced through the use of BIM to coordinate and plan, visualize upcoming tasks, and communicate information to remote parties. Completed work was incorporated into model, providing the team a continually updated resource from which to plan.

Bhatla and Leite (2012) present the case for the use of BIM to support the Last Planning 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 contrast, Khanzode (2010) demonstrates that the use of Last Planner™ 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 Last Planner™.

Hamdi and Leite (2012) use the BIM Capability Maturity Model to measure a project's BIM maturity and hypothesize that a high level of maturity has a positive effect on how successfully lean processes are implemented.

The majority of the research summarized above demonstrates that the Project BIM functionalities positively interact with Lean Principles. This paper accepts the premise that the implementation ***of*** a Project BIM adds value and supports Lean Principles, and addresses the precedent question of 'How is value added ***to*** a project BIM'?

Value is achieved through the reduction of waste. A modeled element that is not physically constructible is waste, resulting in material waste, variability in schedule and product, and removing the value of coordination time put into that element. Conversely, if an assembly is modeled exactly as it will be built, all that does not add value has been removed from the process and it is, by definition, constructible. Project BIM are an assembly of trade specialist's BIMs, which are an assembly of modeled elements. To understand the value of a Project BIM, the component models must be understood. If value is added to the component BIMs, the project level BIM functionalities as defined by Sacks of (1) visualization of form, (9-10) collaboration in design and construction, and (14-17) electronic based object communication will consequently be enhanced.

METHODOLOGY AND CASE STUDIES

Four case studies were used as the basis of data for this paper. The projects studied ranged from 75 to 120 million dollars, utilized BIM to coordinate MEPF and structure, and selectively employed BIM to coordinate framing and finishes. All projects were contemporaneous with active construction phases from 2011 to 2014.

Quantitative information about the extent of trade participation in BIM was ascertained through surveys. Interviews were conducted to gain qualitative information on perceived successes and failures of the constructability of the BIM. Constructability issues, such as leaving out a portion of a wall to provide access to a non-accessible mechanical connection, are often dealt with in the field without documentation. Therefore, interviews were chosen over an evaluation of project RFIs to gain insight into constructability issues.

In order to understand how value can be added to BIM, the extent of the individual models that make up the BIM and the use of the models by each trade specialist must be understood. The BIM Participation Matrix was developed to give a quick visual read of the components that make up the BIM model. Squares are marked black if a trade consistently used the model in the manner indicated and grey if the trade selectively used the model in the manner indicated.

The number of darkened squares on the X axis indicates the number of trades contributing models, or the extensiveness of the Project BIM. The more trades that contribute, the more comprehensive the model becomes. The number of darkened squares on the Y axis shows the intensity of application of the BIM model from coordination to field implementation. The more a trade applies the model, the closer the installed product will be to the BIM model.

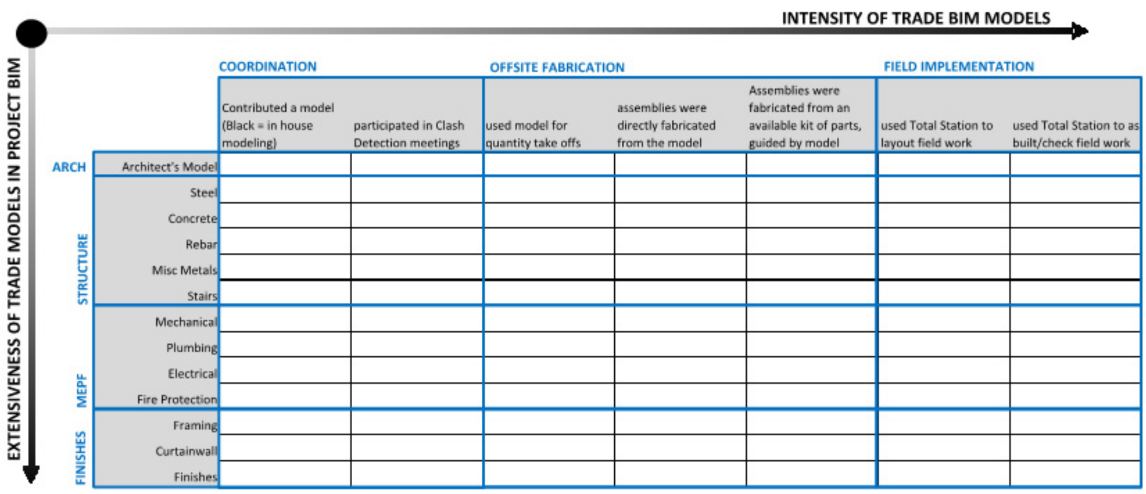

Figure 1: Sample BIM Participation Matrix

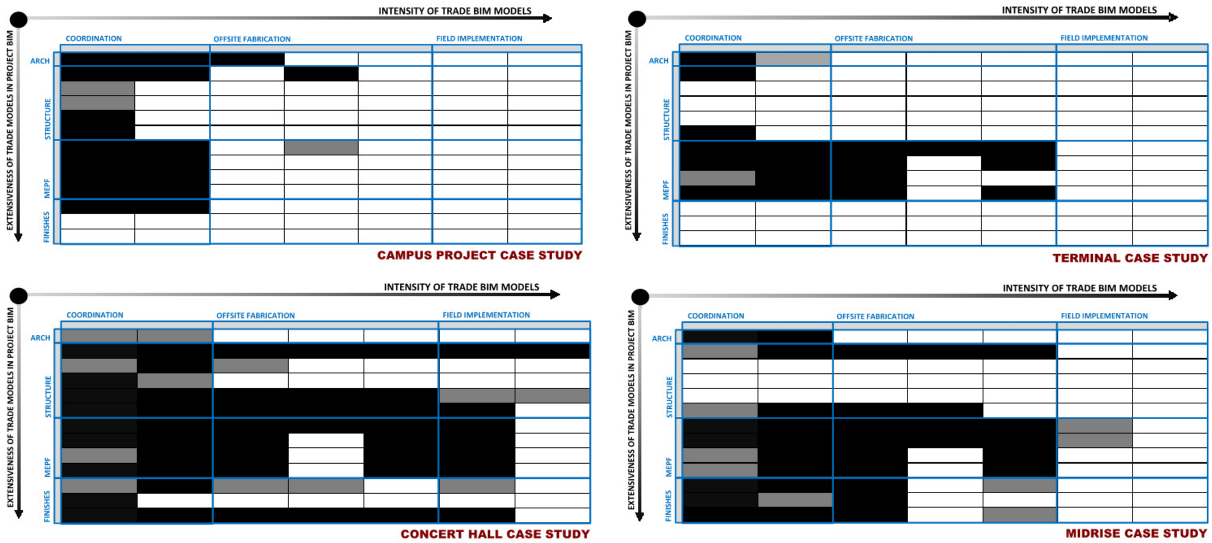

Figure 2: BIM Participation Matrices for the Case Studies

The matrix is divided into three vertical sections. The first section, 'Coordination' quantifies how many trades participated in BIM. The Campus and Terminal case studies show that MEPF coordination with structure was completed. The Midrise and Concert halls show successive levels of finish and curtain wall participation in BIM.

The second section quantifies the trades who engaged in offsite fabrication. Offsite fabrication reduces onsite labor hours and the variability of components coming to the field. Trades who participate in offsite fabrication have less flexibility to deal with unexpected field conditions as modifications to prefabricated components may not be possible.

The third section quantifies the trades who used BIM for field layout and verification of installed components. This application of BIM is an example of the "Check" in the PDCA (plan-do-check-adjust) process. It should be noted that the use of BIM for layout and verification is dependent on the use of BIM for coordination and also overwhelmingly occurs in conjunction with pre-fabrication.

CONTRACTOR PROCESSES

Trade specialists typically fall into one of two process categories.

DIRECT FABRICATION FROM BIM - The BIM model is integral to these trade specialists' fabrication process. Generally, the trade specialists will use software unique to their disciplines and compatible with the fabrication process. These contractors utilize a high percentage of prefabricated components and offsite labor.

If Lean philosophy is applied to this process model, the trade specialists' fabrication shop would be considered the customer of the coordinated model handoff. Therefore these contractors invest in the accuracy and completeness of the BIM because their investment is returned with efficient fabrication and consequent reduction in onsite labor. Steel and mechanical contractors generally fabricate directly from the BIM model.

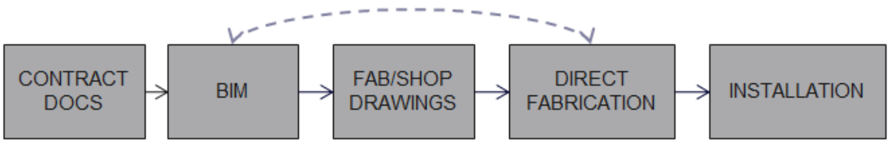

Figure 3: Sample Steel Direct Fabrication Process

INSTALLATION AS A PARALLEL PROCESS TO BIM - For certain trades, the fabrication and installation of work is independent from BIM. These trade contractors typically engage in BIM as a contractual requirement.

The customer in this scenario would be the general contractor. Because these contractors do not realize a direct savings if the model is more constructible, they are less incentivized to invest in the accuracy of the BIM.

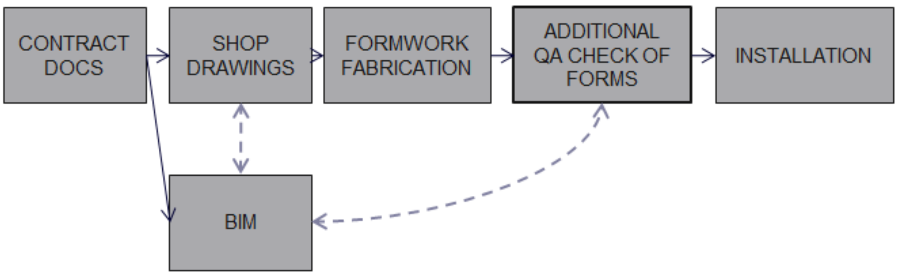

Figure 4: Sample Concrete Indirect Fabrication Process

TYPOLOGIES OF VARIABILITY BETWEEN BIM AND FIELD

The BIM is used as a basis for construction. Variability between the model and the BIM were discussed and typologies of constructability issues were established.

ERRORS – Errors occur when the constructed component deviates from the modeled element in geometry or location. For example, if constructed stud framing has a different layout than the modeled stud framing, the model is considered erroneous. Errors are most likely to occur in the models of trade specialists who do not employ direct fabrication. In the School Campus case study, the plumbing contractor disregarded the modeled system and assembled a seemingly more efficient system in the field. Unfortunately, the Authority Having Jurisdiction (AHJ) did not allow deviations from the stamped plans and the plumber had to rework the system. In the Concert Hall Case study the concrete contractor used model-based layout for some, but not all edge of slab conditions. An interior edge of slab was incorrectly placed. The framing contractor followed the edge of slab rather than the design location. The error caused rework for both contractors.

OMISSIONS – If an object is not modeled or considered in BIM, it is an omission. In the Midrise case study, the miscellaneous steel was not shown above the toilet partitions. Though the need to leave space for such steel was discussed with the team at coordination inception, the absence of the visual reminder caused detailers not to account for steel location. The area was re-detailed prior to construction. The Terminal case study was constructed as a phased project consisting of core and shell construction and an interior build out. During the first phase mechanical equipment was installed. As the second phase was designed, the new layout failed to consider the location of the existing equipment and as a result, conflicts occurred in the field. The omission was the failure to consider the two systems in conjunction in the BIM.

TOLERANCES – Unlike other deviations between constructed and model elements, tolerance issues are inherent to the materiality of each element. For example, steel generally has a tolerance of a fraction of an inch. Spray on fire proofing is applied to each beam and also has a tolerance of a fraction of an inch. Due to a failure to account for accumulated tolerances, if a modeled element is located too closely to the beam, a clash may arise in the field despite the modeled element's correct location. In the Concert Hall case study panelized wood sections were attached to prefabricated stud sections. The wood sections had not fully acclimatized to the dehumidified environment and the connections were not aligned to the fractional tolerance. The resulting gaps had to be monitored and adjusted as the wood acclimated.

BUILDABILITY – If a modeled element cannot be physically built, a modification will have to be made in the field. Issues of buildability occurred when constraints of construction were not considered in the coordination process. Contractors who did not engage in direct fabrication and contractors who employed third party modelers tended to have these issues. In all case studies, modifications were made to stud framing in the field. In the Concert Hall case study and the Midrise Case study modeled electrical conduit deviated from the installed product because the model did not accurately represent the conduit bends achievable in the field.

MISSED OPPORTUNITIES – If the final or interim product does not produce the quality expected by the owner, the building delivery process was not successful. On the Midrise and School Campus case studies, the mechanical design model did not include insulation and therefore did not accurately represent the full depth of the element. When modeled accurately, the element was in conflict with ceiling heights, a condition established by the owner. Each case incurred major redesign of the systems, causing design iterations and detailing process to run concurrently. Collateral waste was created as other trades had to re-detail to coordinate with the revised mechanical systems. In the Terminal case study, an egress stair separated a major electrical room and the rest of the building. Chases and soffits were added for the electrical distribution system at the expense of the architectural functionality of the area.

The 'missed opportunity' typology highlights the role of design in constructability. Missed opportunities occur when the designers make a fundamental misassumption about the design of a downstream system. The early inclusion of trade specialists is intended to obviate such misunderstandings. At MEP engagement, especially in a design assist endeavor, a model review should occur to establish design constraints which much be reviewed prior to detailing.

DISCUSSION

Decreasing the variability between model elements and constructed components of the building increases the constructability of the model and therefore reduces waste. To increase the constructability of the BIM, typologies of error must be addressed and mitigated through process management. Additionally, the differing incentives and sophistication of specialty contractors must be acknowledged in management strategy. The BIM should become a simulacrum for construction; a virtual space to test construction methods, prefabrication, and sequencing. The key to the constructability of BIM is that team installing in the field must BELIEVE in the BIM.

When the team is broken down to the participant level, it is apparent that trade specialists occupy different ranges in the spectrum of Lean. In the current state, active controls must be set with the Last Planner™ framework to ensure that variability between the model and field is reduced for each trade BIM. The handoff of the BIM does not happen with a coordinated model, but with a constructible model.

INCREASING MODEL INTENSITY BY ESTABLISHING THE LAST PLANNER IN BIM

Increased **Trade Model Intensity of Application** Reduces	Errors	The use of model based layout ensures components are place as modeled.
	Tolerance Issues	Prefabricated elements have reduced tolerances due to production in a controlled environment.
	Buildability Issues	If models are used for installation, trades specialists will invest in accuracy of their model.

Figure 5: The Effect of Increased Model Intensity

Of the trades analyzed, those that directly fabricate from BIM have the highest intensity of model application. They have fewer instances of errors, tolerance issues, and buildability issues because they detail their model to enable fabrication. Essentially, they have created an intrinsic customer who sets the conditions for approval for the handoff of the model. The reliability of these models adds value to the project BIM as other trades can coordinate with a high degree of confidence in the accuracy of fabrication model.

The key to increasing the intensity of model application for all trades is establishing each trade as its own customer; in short, applying the Last Planner™ philosophy. The basis of the Last Planner™ system is to only hand off work that CAN and SHOULD be done. Additionally, the customer sets the conditions for approval of the handoff. (Ballard and Howell, 2004) If the detailers have to deliver a model to their field team for installation, they will detail exactly what the field needs to install. As a result, the model will be more accurate and contribute positively to the value of the project BIM.

Active management by the BIM lead may be needed to encourage the application of Last Planner™ philosophy. Trades that do not fabricate from BIM are not intrinsically motivated to invest in the constructability of the BIM. For these trades, coordination and construction are completely delinked – the person who makes the commitment to the coordination of the model is different than the person who makes the commitment to execute in the field.

For example, the concrete contractor on the Concert Hall expressed a disinterest in engaging in coordination of finishes. The design detail showed cast-in-place radiused slabs meeting a pre-fabricated conic wood wall. The half inch tolerance demanded by the detail was less than the field tolerance of concrete. The General Contractor worked with the concrete contractor to understand that conventional 2D detailing would not meet the needs of the field layout team. Instead, detailed 3D models of slab edges and wood walls were developed. The model was used for wall fabrication and model based layout of forms. The forms and the slabs were surveyed and reincorporated into the model for verification. The wood wall contractor had a zero conflict installation. In this case, the general contractor helped the concrete contractor identify that the layout crew was the customer of the BIM, and the intensity of application of the model was increased to meet the customer's needs.

Project thinking and terminology should also be reviewed. Current BIM practice dictates that when an area is coordinated, each trade specialist indicates acceptance by 'signing off.' The term 'sign off' reinforces the categorization of the BIM as a product, the end result of the conversion process from design intent to a detailed model. Instead, the term 'handoff' should be used to emphasize that the completion of the model is a process step towards the installation of work in the field. The customer for the BIM handoff should be the person or group who has committed to execute the work in the field, the last planners, as they are best able to identify constraints.

Pre-handoff, it would be advantageous to have a construction pull session to review sequencing of that portion of the building. At that time, constraints such as priority walls and atypical conditions could be identified and the trade specialists can be aligned in their understanding of the BIM.

MODEL EXTENSIVENESS

Increased **Extensiveness of Trade Models** Reduces	Buildability Issues	More fabrication level models allow more opportunity for coordination and work planning.
	Omissions	If all trades are modeled, the BIM becomes a near complete representation of the building.
	Missed Opportunities	A complete model will allow better visualization for the owner and design team.

Figure 6: The Effect of Increased Model Extensiveness

The BIM process must be viewed according to Lean breakdown structure; essentially a project within a project. As with any project, an essential early step is to create the correct work breakdown structure. The milestones for BIM must recognize both design and construction milestones and mediate between iterative design and linear construction. If detailing starts before design is set, waste through re-work of model is necessary. If detailing starts too late, handoffs of information to the field needed for construction will be missed.

It may be appropriate to set a design review pass as a milestone and specifically include the owner and designers in the pull. In the Midrise case study, specialty contractors engaged in coordination and pulled a schedule to meet the steel fabrication release dates, neglecting to consider the level of completeness in the mechanical design. By nature, design has positive and negative iterations (Hamzeh, et al 2009) while detailing is linear. If the mechanical system lags behind others in design, the iterations in that system will cause rework of adjacent systems. Additionally the flow through the building will be disrupted, as more areas are released to maintain a continuity of work for the contractors not immediately involved in design coordination. If a design assist, or 'pre-detailing' milestone is recognized, appropriate resources can be allocated to validating and resolving the design prior to producing a fabrication level model of the building.

The Midrise case study utilized an inappropriate Work Breakdown Structure. The team was correct in recognizing that impacts to steel needed to be identified prior to steel fabrication, but the team did not identify that the key systems to coordinate with steel were the vertical risers while the major redesign occurred in the horizontal ducts. A more appropriate work breakdown would have been to have concurrent phase milestones of design assist and riser coordination followed by milestones of above-ceiling horizontal coordination by trades.

In the School Campus case study, the MEPF and framing contractors were engaged prior to submission of plans to the Authority Having Jurisdiction (AHJ). The specialty contractors reviewed the model for constructability and preferred installation details. All modeling was completed by the design team. A 'design review' milestone is an effective tool to prevent 'missed opportunities' because it provides an opportunity for a structured review and a forum for designers and owners to impart their values to the detailing team. Additional, focusing on removing major constraints will reduce variability and create a more predictable work flow for the detailing effort.

CONCLUSIONS AND RECOMMENDATIONS

If contractors establish an intrinsic customer for BIM, the constructability of each component BIM will increase. However, the sum of the BIM is greater than its parts. As confidence the constructability of each model increases, greater levels of coordination are possible between the component models, and the value of the Project BIM functionalities are enhanced. The project BIM then positively impacts Lean principles implemented on the project. This cycle demonstrates the positive reciprocal interactions between BIM functionalities and Lean principles.

CURRENT STATE: ALIGNMENT THROUGH MANAGEMENT

It is tempting to view BIM coordination as a linear conversion process to develop design drawings/models into detailed fabrication models. In this view, a traditional management of BIM execution would be applicable. The schedule would be set and the product delivered to each contractor's shop for fabrication. Deviations from the schedule could be addressed through increased resources. This model of BIM execution, however, does not account for the dynamics of trade interaction or encourage adding value to the model by improving constructability as explored in the case studies. The Last Planner™ System was developed to address variability by placing the responsibility for handoffs in the hands of those executing the work. This process model should also be used to enhance the constructability of the BIM.

To gain the maximum value out of BIM, Last Planner™ concepts must be applied to BIM execution.

- The Trade Foremen must be included in BIM coordination as the last planners. The completion of coordination is not a product. It is a handoff to the trade specialists that implement the model. The customer in a handoff defines the conditions of satisfaction, so it follows that the model is not complete until it is accepted by the field. At this time, a virtual pull session should be held to review constructability.
- Pull sessions should be held to pull to project detailing milestones. Detailers should discuss challenges of particular area, constraints identified, and flow established.
- The BIM milestone schedule must be set to the construction schedule. This will result detailed coordination starting later in a project.
- The Customer conditions for satisfaction must be established at inception.

FUTURE STATE: INHERENT ALIGNMENT

This paper reviews the current state of BIM coordination and proposes active controls to ensure constructability. The ideal future state is that all contractors are intrinsically incentivized to produce a constructible model. Trade specialists' models improve in accuracy if the accuracy of the model reduces waste in the field. The accuracy of each model contributes to the constructability of the project model.

Trade specialists who employ direct fabrication from BIM utilize a high degree of prefabrication and are therefore incentivized to detail a highly accurate model. Therefore, it follows that if contractors who traditionally stick build are encouraged to prefabricate they will correspondingly be incentivized to improve the accuracy of their model. The concert hall had several complexly curved walls. The trade specialist had to use specially fabricated curved studs. To define the radius, the contractor created a model from which the studs were fabricated. The adjacent contractors then had a high degree of confidence in coordinating to that model.

Model based layout is another technique which incentives model accuracy. If all parties are confident that the installed component will be the same as the model element then tolerances can be reduced and quality improved.

Collaborative contracts, such as Integrated Forms of Agreement, incentivize Trade specialists to prioritize the constructability of the entire building over the constructability of their trade.

A central tenant of lean and BIM is collaboration. It is the team's job to work together towards continual improvement and waste reduction in the field. Aligning the team to create a constructible model is integral to this journey.

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