Workflow Management Using Building Information Modeling (BIM) for Prefabrication in a Construction Retrofit Environment

by

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ABSTRACT

The semiconductor manufacturing business model provides unique challenges for the design and construction of supporting fabrication facilities. To accommodate the latest semiconductor processes and technologies, manufacturing facilities are constantly re-tooled and upgraded. Common to this sector of construction is the retrofit project environment. This type of construction project introduces a multitude of existing conditions constraints and functions entirely differently than traditional new-build projects. This facility conversion process is further constrained by owner needs for continuous manufacturing operations and a compressed design/construction schedule to meet first-to-market milestones.

To better control the variables within this project environment, Building Information Modeling (BIM) workflows are being explored and introduced into this project typology. The construction supply-chain has also increased their focus on offsite construction techniques to prefabricate components in a controlled environment. The goal is to overlap construction timelines and improve the productivity of workers to meet the increasingly demanding schedules and to reduce on-site congestion. Limited studies exist with regards to the manufacturing retrofit construction environment, particularly when focusing on the effectiveness of BIM and prefabrication workflows. This study fills the gap by studying labor time utilization rates for Building Information Modeling workflows for prefabrication of MEP (mechanical/electrical/plumbing) and process piping equipment in a retrofit construction environment.

A semiconductor manufacturing facility serves as a case-study for this research in which the current state process for utilizing BIM for prefabrication is mapped and analyzed. Labor time utilization is studied through direct observation in relation to the current state modeling process. Qualitative analysis of workflows and quantitative analysis of labor time utilization rates provide workflow interventions which are implemented and compared against the current state modeling process.

This research utilizes a mixed-method approach to explore the hypothesis that reliable/trusted geometry is the most important component for successful implementation of a BIM for prefabrication workflow in a retrofit environment. The end product of this research is the development of a prefaBIM framework for the introduction of a dynamic modeling process for retrofit prefabrication which forms the basis for a model-based delivery system for retrofit prefabrication.

DEDICATION

For my father who always taught me to “think backwards.”

For my mother whom I know shares my love of academia and research.

For my sister who is, and always will be, my best friend. Now it’s your turn!

For my family, near and far, I am grateful for your love and support.

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CHAPTER 1

OVERVIEW: FRAMING A DISSERTATION

The demand for the construction supply chain to improve productivity and to meet compacted schedules with decreased budgets has led to substantial industry focus in automated construction techniques and enabling workflows. Off-site prefabrication of construction components has become a key factor in the improvement of labor productivity and an increase in quality on construction projects (McGraw Hill Construction, 2011). Extensive research by the Construction Industry Institute (CII) (CII, 2002b), among others, has shown that schedule and budget constraints can often be met through the effective use of prefabrication introducing overlaps in schedules and offsetting labor into controlled environments. Much of these savings has shown to come from the introduction of economies of scale and repeatable tasks and assemblies. With advances in computerized representation of building components, the AEC industry is entering an era where the 'mass customization' of project systems and subsequent delivery processes needed in the construction realm can be met with offsite construction techniques (Kieran & Timberlake, 2004). It is within this realm that project teams must understand the importance of pre-planning for offsite construction techniques to properly harness and leverage the tools that are available for enabling this system of construction.

Often coupled with prefabrication is the use of advanced Building Information Modeling (BIM) workflows (Nawari, 2012). This is an attempt to respond to the overall decline in construction productivity as compared to other industries as illustrated by Teicholtz (2004, 2013) in an overall industry comparison study. Efforts made in the field of manufacturing to automate processes and workflows are being introduced into the field of construction through the use of LEAN theory and interjection of computer-aided manufacturing (CAM) techniques. The sheet metal industry has helped to pave the way for prefabrication, and now many specialty trades are beginning to follow suit. The expected skilled-labor shortage in coming years has helped to amplify the research in automated construction techniques through the utilization of Building Information Modeling tools and workflows (FMI, 2012).

While there is a heavy focus in improving the overall productivity of the construction industry, most research is narrowly focused on the new construction, or green-field, sector. The scalability of the available research to meet the stringent demands and varying constraints of renovation/retrofit projects has not been well defined. This research focused on the retrofit sector of construction and begins to define the productivity rates of the workforce utilizing Building Information Modeling tools and workflows to prefabricate construction components at the task-level, or workface.

This research is a direct attempt to identify the factors affecting successful Building Information Modeling use for prefabrication in retrofit environments. This chapter unfolds through an introduction of various definitions related to the overall research scope and subsequently utilized throughout the study. Next, a quick overview of the construction industry will reveal the motivation for this particular research. Once the motivation is defined, the problem statement and hypothesis are revealed leading to a discussion around research contributions. Finally, this chapter will introduce the overall organization of the dissertation.

1.1 Definition of Terms

1.1.1. List of Commonly Used Acronyms

AEC/O – Architect/Engineer/Contractor/Owner

AEC – Architecture Engineering & Construction

AIA – American Institute of Architects

ANSI – American National Standards Institute

BIM – Building Information Modeling

BPMN – Business Process Model and Notation

CAD – Computer-Aided Design

ETS – Early Tool Set

FM – Facilities Management

ICs – Integrated Chips

IPD – Integrated Project Delivery

LOD – Level of Development

mCx – Model Commissioning

NIBS – National Institute of Building Science

NNVAT – Necessary Non-Value Added Time

NVAT – Non-Value Added Time

POC – Point-of-Connection

QA – Quality Assurance

QC – Quality Control

RTS – Ramp Tool Set

SRC – Semiconductor Research Corporation

TOP-UP – Timing, Order, Proof – Unified, Propagation

VAT – Value Added Time

1.1.2. Green Field Projects

Green field projects are scenarios that offer a clean slate in which to begin the design process or simply a "project that is lacking constraints imposed by previous work" (Das & Ara, 2014, p. 16). While constraints are inherent within any AEC undertaking, green field projects can generally be seen as a project typology that offers the most freedom for design and construction operations. This allows for a clear delineation in which processes can be implemented. Often times, a simplified approach to design can be realized due to the freedom of approach. For this research, a green field project is a new construction project in which an owner's facility vision is translated to reality on a generally undisturbed and open site.

1.1.3. Retrofit Projects

In contrast, retrofit projects include existing obstructions and excess physical constraints at the beginning of the design process. This complicates a project's process from the outset and will inherently restrict the approaches taken by all parties involved. This approach to a project induces such technical constraints as: the need to analyze existing capacity and verify for introduction of designed measures, physical capabilities of the current facility, existing material properties analysis, and volumetric capacity capabilities. This type of project introduces additional steps into the traditional design-construct process such as the need to capture existing conditions prior to design start. Planning and assessment becomes a major point of emphasis for this type of undertaking (Sanvido & Riggs, 1993)

1.1.4. Integrated Project Delivery (IPD)

Integrated Project Delivery (IPD) and relational contracting is shifting the way projects are delivered. This type of contracting structure puts the project first and creates integrated teams of stakeholders aimed at one particular goal – successful delivery of an owner's project needs. As discussed by El Asmar et al. (2013), shared incentives are a main component of this contracting structure. Incentives can be introduced throughout the multi-party contract via integrated forms of agreement

(IFoA's) in order to negate adversarial relationships and promote innovation throughout the process. The main focus on this contracting structure at the present revolves around the owner-designer-contractor relationship. It is important to note that the contractor-supplier relationship is becoming as important due to the integration of BIM as an enabler for offsite prefabrication.

For purposes of this research, the definition of IPD developed by Asmar et al. (2012) is utilized and can be read as follows:

> "A delivery system distinguished by a multiparty agreement and the very early involvement of key participants."

Expanding upon this definition, the research notes that not all projects claiming IPD structures function to the full capacity of the definition provided. In this scenario, the research introduces the term "IPD-ish" as defined by Asmar et al. (2013) as an umbrella term for a contracting structure which is loosely based on the ideals of an IPD environment but do not contain both upfront collaboration or involvement of key stakeholders and a single, multiparty contract.

1.1.5. Building Information Modeling (BIM)

The National Institute of Building Sciences (NIBS) defines BIM as: "a digital representation of the physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable base for decisions during its life cycle from inception onwards." This definition is further clarified by Eastman et al. (2011) as "a verb or adjective phrase to describe tools, processes, and technologies that are facilitated by digital machine-readable documentation about a building, its performance, its planning, its construction, and later its operation." This process leads to the creation of a "Building Information Model." The model itself is a parametric, responsive visualization of a facility as it is designed or exists. As Ghosh (2015) points out, there is a distinct differentiation between drawings and models. This research utilizes this distinction and understanding of BIM, as well as the provided definition clarifying the differences between 2D and 3D wherein, “2d and 3d CAD drawings are the traditional methods of digital drafting and representation of design and construction information while 3d CAD models are the more advanced methods of representation and BIM is a process that combines the 3D CAD models with all information required for designing, building and maintaining a facility” (p.16).

1.1.6. Prefabrication/Offsite Fabrication

This research pulls from CII research regarding PPMOF, or Prefabrication, Preassembly, Modularization and Offsite Fabrication (CII, 2002b). The focus for this research is centered on the following two definitions:

- Prefabrication – “A manufacturing process, generally taking place at a specialized facility, in which various materials are joined to form a component part of a final installation.”
- Offsite Fabrication – “The practice of preassembly or fabrication of components at a location other than the installation location.”

These two terms will be used interchangeably throughout the research to denote the controlled manufacturing of construction components for delivery and installation at a live construction site.

1.2 Motivation for Research

1.2.1 Industry Conditions and Trends

The construction industry is entering a phase where a shortage of skilled labor is presenting a unique landscape for industry transformation. Industry trends identified by the McGraw Hill SmartMarket Report 2012, indicate that retirement of the baby boomer generation, the transition of the workforce out of the design and construction industry due to the recession and a lack of sufficient education for the incoming workforce are of concern for many in the industry. The findings indicate the areas expecting the greatest shortage in skilled labor are specialty trade contractors including (but not limited to) HVAC and electrical trades (McGraw-Hill, 2012). This research is furthered in the findings of the National Institute of Building Sciences where they estimate that by the year 2020 the United States will be short nearly one million engineers (ANSI, 2007).

An increased utilization of technology for manual labor automation, process enhancement and project complexity are shifting the traditional approaches to AEC supply-chain management. This dynamic shift from traditional means and methods of construction is challenging project teams to innovate and respond to criticisms of lacking productivity rates and excessive waste in traditional processes. As a shift in the workforce is occurring, the management techniques and methodologies are also beginning to shift.

As illustrated by Teicholtz (2004, 2013), productivity rates within the construction industry are in a state of decline. The economic downturn that occurred due to the financial market collapse in 2008 disrupted the AEC industry at large and amplified the need to reverse the identified productivity trends. This resulted in a bifurcation of project management approaches. The two main trends being: 1) a regression in innovation and subsequent relapse to basic design-bid-build / hard-bid / low-bid practices and methodologies to simply win projects and 2) an opposing era of innovative approaches to push the envelope in integrated knowledge based project delivery (FMI, 2012). The hope of the latter methodology is to recover handsome profit returns through the utilization of shared expertise and knowledge and ultimately recuperation of the shared profit pools from the successful delivery of a project under budget and on an expedited schedule.

With the emergence of integrated teams, delivery methods for the design and construction of facilities and supply-chain management techniques comes the utilization of more transparent design and construction documentation methods; one of which is the utilization of Building Information Modeling (BIM). This technology has been adopted at different rates throughout the AEC industry and building lifecycle (Giel & Issa, 2013). As with any technology, BIM is subject to the "hype cycle" of new technology. As described in Figure 1, Fenn (1999) classifies this curve into five distinct phases.

- Phase 1 – Technology Trigger: Excitement is prompted through the introduction and promise of a new technological solution.
- Phase 2 – Peak of Inflated Expectations: Over-zealous promises of the technological solution become the general consensus. Discussions around unrealistic expectations ensue and the promise of the new technology seems unlimited.
- Phase 3 – Trough of Disillusionment: Ultimately the technology fails to stand up against the unrealistic expectations generated by the masses. This is generally due to the false starts in development and/or the limitations in potential due to unforeseen issues in implementation.
- Phase 4 – The slope of enlightenment: Small steps are made towards improving the technological solution for global application. Benefits begin to be realized at a project level.
- Phase 5 – Plateau of Productivity: The technological solution has been accepted as a norm and application is widespread. Incremental

> benefits are seen and links with new technological solutions become viable (Fenn, 1999).

This notion of the "hype cycle" is an important component of this research. As various BIM-related software solutions and rates of adoption / implementation can be seen in the AEC, the use-case discussions and associated benefits become diluted. This research will explore various technology applications for use in the design/construction of complex facilities and ultimately identify areas where expectations and realities are not in alignment.

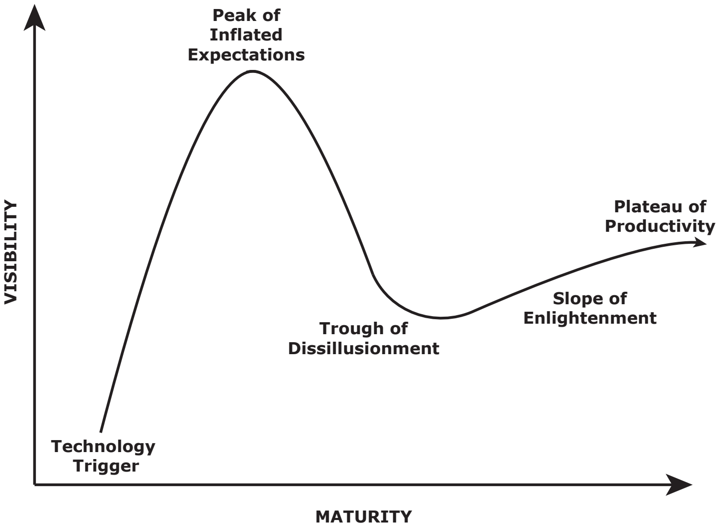


Figure 1: Technology Adoption Hype Curve (adapted from Fenn, 1999)

1.3 Framing the Problem

1.3.1 Problem Statement

Technology has recently become more available to construction teams. Interjection of technology solutions into the construction process has seen varied impacts on project delivery and overall project success. Most research regarding the utilization of new technologies such as Building Information Modeling (BIM) and workflows for prefabrication of construction components is focused on greenfield projects. There is a gap in this research, as well as in the industry, with regards to the implications of a retrofit environment on BIM and prefabrication workflows and resultant productivity of the construction supply-chain. This gap is furthered with respect to technical environments like semi-conductor manufacturing plants or "fabs." This research focusses on an extended case-study at a large semiconductor manufacturing facility in the southwestern United States. The timeline for research coincided with multiple ramps in construction operations wherein capital equipment (tool) conversions and upgrades were undertaken to enable the most recent processes for semiconductor wafer, or chip manufacturing. The owner of the semiconductor manufacturing facility allowed the research team to access the site as well as the individual fabs undergoing conversion. Access to project stakeholders representing the design team, construction team and owner's representative was also granted by the owner and individual management teams. This particular project provided an excellent environment to study the impacts of BIM and prefabrication on retrofit construction. Due to intellectual property (IP) concerns and overall confidentially provisions within the company and various teams involved, all names of individuals and organizations have been changed.

Semiconductor manufacturing is a unique business sector and one which puts additional constraints on traditional design/construction timelines for the delivery of supporting facilities. The persistent need to introduce new process technology related to demands from the marketplace causes continuous upgrades to the tools utilized to support the manufacturing process. Matching construction schedules with the expedited nature of 18-month timelines experienced by an understanding of Moore's law (Moore, 1965) and first-to-market demands by the owner create an environment in which traditional means-and-methods for construction become challenged. This first-to-market timeline constraint has also resulted in the realization that building a new facility from the ground up each time a new manufacturing process is identified is too time and cost intensive. Thus, retrofitting existing facilities has become the standard construction environment within this industry sector. Traditional on-site construction techniques also lead to worker congestion issues, life safety concerns and productivity constraints. Clean-room protocols also introduce timing issues for construction trades and can extend even the simplest of processes. In response to these various issues, techniques for offsite construction have been explored by many trades involved with the conversion projects.

The owner in this particular case, has mandated the use of Building Information Modeling for all tool demolition/conversion/installation work. This mandate initially came about as a way to reduce on-site workers during construction installation so as to decrease overall site congestion in the hopes of both enhanced safety and value-added productivity. Each scope of work identified: tool demolition, tool conversion and tool installation, varies in complexity. This scope of work and complexity is often identified at the trade level and dictates the level of BIM engagement. The main BIM uses identified as a value add for the team members on-site spans existing conditions capture through the use of laser scanning, conversion of point-cloud data to 3D models in various formats for use in routing design and archiving, creation of construction models for routing of electrical, mechanical and process piping systems and components, coordination of 3D information through on-site clash-detection and transfer of 3D information into prefabrication drawings, or spool drawings at the trade contractor level.

Previous research by Ghosh et al. (2015) conducted on the same case-study site, identified a schedule savings of 10%, change order savings of 1.95% of total cost, and total project cost savings of 2.17% through the utilization of 3D CAD modeling at the trade contractor level. However, productivity rates at the task-level for installation failed to meet the owner's projections or expectations. This introduced a source of conflict amongst internal owner's representatives regarding the value of BIM and prefabrication in this particular environment. The main source of contention being the initial investment spent on creating the platform for which BIM could be supported. The initial capital investment in creating usable BIM data for retrofit support is not being seen on a project level and the overall owner goal for increasing task-level productivity rates has been lost in translation.

This research extends the problem statement presented by Ghosh et al. (2015) which identified the variables related to construction labor workforce productivity and the evaluation of BIM impacts on labor productivity, but focusses on upfront content generation for effective prefabrication model creation. Exploring these additional variables will provide an understanding of the implications of owner invested BIM content and the value of 3D content on the prefabrication workflow process. In combining the identified gap in existing literature, and owner related concerns, the problem statement can be summarized as follows:

"While the owner has explored the use of BIM and prefabrication techniques to expedite on-site capital equipment conversions, many of the expected productivity benefits have not been realized. The transition from traditional construction processes to 3-dimensional design modeling has caused task-level process confusion and misalignment between team members wherein project success is not seen on a consistent and repeatable basis. Through exploration of the case study environment, this study will research the impact of reliable 3D information at the modeling task-level and evaluate the impact of workflows and processes on labor time utilization rates of the modeling workface."

1.3.2 Scope/Limitations/Assumptions

This research scope is limited to BIM use for prefabrication only. This is further defined as BIM use for prefabrication of process piping, mechanical and electrical systems within the sub-fab level of a semiconductor manufacturing facility. As the research is heavily based on a case-study, inherent limitations exist regarding sample size for data collection. Thus, overall sample size for initial data collection is restricted to on-site personnel. The unique and complex nature of the case-study environment also introduces a limitation regarding access to homogenous case-study samples for comparative and cross examination of conditions and findings.

1.3.3 Research Questions

Research questions were introduced throughout the study to help facilitate and guide overall efforts. The research questions utilized are as follows:

- **R1:** How does the initial process of modeling impact the number of workers on site during construction?
    - **R1.1:** What is the current work process for prefabrication and who are the stakeholders in the process?
    - **R1.2**: How does the Level of Quality in BIM correspond with the value added from prefabrication delivered and installed on site?
        - **R1.2.1:** How do trades currently measure/enforce the Level of Development (LOD) of BIM's used for prefabrication?
- **R2:** What is the effect(s) of a process intervention on BIM-for-prefabrication in a retrofit environment on modelers' time utilization rates during construction?
    - **R2.1:** What is the subsequent effect, or effects, of a process change on prefabrication supply-chain performance?

1.4 Research Methods, Data Collection & Data Analysis

This study utilized a case-study environment in which to conduct research. In order to guide the study, an on-site steering committee was provided. The steering committee consisted of owner's representatives from various facets of the construction and operations within the owner's company. Regular meetings with the steering committee occurred throughout the study in order to discuss milestone findings and next steps. The steering committee worked to provide access to site-wide data and team members as needed.

A second level of study guidance was provided by a research committee and dissertation advisor. Research committee meetings were engaged on a near quarterly basis for research alignment at a macro-level while weekly meetings with the dissertation advisor took place to guide the study at a micro-level.

This research utilized a mixed-method, case-study research approach. The results from both qualitative and quantitative studies were analyzed and combined into the final interpretations and discussions of findings. Multiple sources of data were collected over the course of the research study. The conduit providing much of the data came in the form of the case-study environment. The research methods and subsequent data collection methods are described in the following sections and are broken apart into larger categories of Participant Observation and Direct Observation. The two are distinctly different. Participant observation offers the researcher the ability to become a part of the study environment and subsequently have an effect on conditions within the environment in order to understand the complexity of the various relationships and variables. Direct observation is an outside, removed look at the relationships and happenings within the study environment with the intent of analyzing and measuring data without effecting the conditions being studied. These two categories are dissected further in the following sections.

Participant Observation is the assimilation of a researcher into the studied environment in order to further the understanding of complex relationships and other human factors. Schensul et al. (1999) describe this type of qualitative study as "the process of learning through exposure to or involvement in the day-to-day or routine activities of participants in the researcher setting (p. 91)." Bernard (1994) furthers the definition of participant observation to describe the ability to blend into the community/environment so as not to inhibit the existing members from acting naturally. Once a relationship amongst members is established, the researcher is able to disconnect from the environment and review/analyze data and ultimately better understand the connections and meaning behind the analysis. His definition encompasses observation, natural conversations, interviews (varying typologies), checklists, questionnaires, and any other unobtrusive method of data collection.

This type of research method was utilized to immerse the researcher in the site context and enhance the development of various research tools utilized in the case study for both qualitative and quantitative data. Figure 2 denotes how Participant Observation was engaged in the case study.

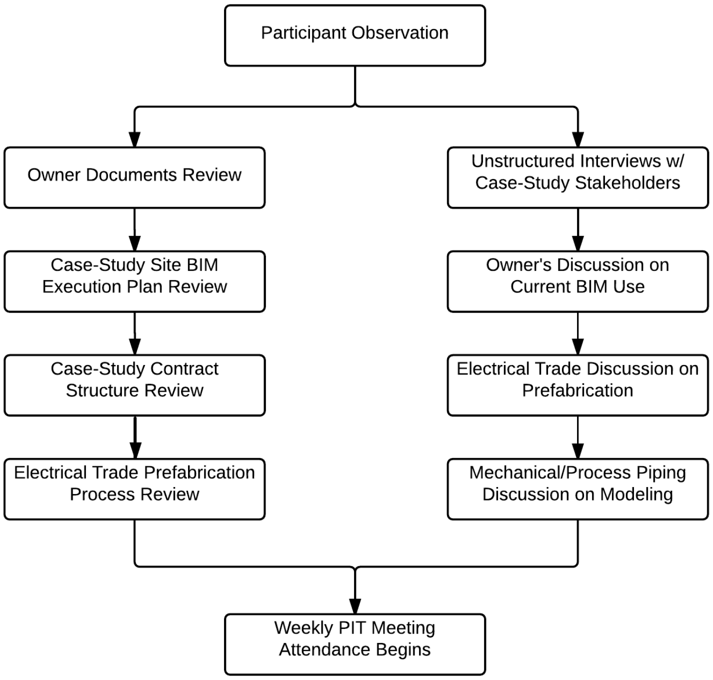


Figure 2: Stages of Participant Observation

<u>Internal Documents Review & Analysis</u> – Within the realm of participant observation, internal documents from various stakeholders were reviewed for a deeper understanding of varying processes and coordinated requirements across disciplines. As the owner provided access to the various design and construction teams on-site, the documents reviewed and analyzed varied in complexity and scope from fully comprehensive BIM execution plans, to deliverable requirements for various milestones, down to internal trade processes for QA/QC of model content or prefabrication components.

<u>Unstructured Interviews & Informal Discussions</u> – In order to explore broad topics related to BIM practices, or prefabrication techniques and workflows, unstructured interviews were utilized. While there was not a formal research instrument utilized

for questioning project stakeholders, this research method resulted in a more organic discussion ultimately aiding in greater exploration of how variables related to site context and internal/external relationships. Continued informal discussions resulting from unstructured interviews often lead to the coordination of more formal stakeholder meetings to discuss varying viewpoints and management techniques.

Surveys – Both qualitative and quantitative data was collected through the instrument of various surveys. Figure 3 graphically depicts the main surveys delivered on-site for collection of data. Each of these surveys was developed following internal documents review and a series of unstructured interviews & informal discussions as described in the above sections. The main purpose of the surveys was to illustrate the problem statement and visually represent the areas of BIM and prefabrication workflows which warranted more in depth focus. Each survey was structured differently. The survey instruments that were delivered for data collection were designed utilizing the following structures: open ended response, rank-order definition and Likert-scale.

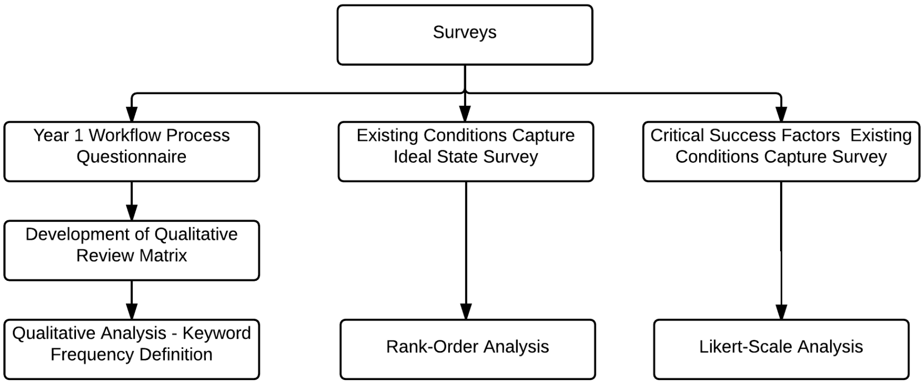


Figure 3: Research Survey Typologies

Process Mapping / Workflow Diagramming – A main component of the research method revolved around the creation of various process maps and workflow diagrams. During the initial internal documents review process, a series of workflow diagrams were identified. Conflicting information between trades and stakeholders was apparent. Initial research conducted by Ghosh et al. (2015) introduced a more streamlined process map for design-to-installation of prefabrication of modeled components utilizing the Business Process Modeling Notation (BPMN). This research built upon this process map in order to further understand the site workflow dynamics. It became apparent through collected survey data that re-visiting the process maps and refining the workflows was needed. This research method enabled a graphical representation of individual steps to be created for further analysis and discussion between stakeholders.

Direct Observation differs from participant observation in the realm of obtrusion. In direct observation, the researcher strives to be an outsider without participating in the context so as not to influence or add bias to any observations. While direct observation has the ability to utilize technology such as videotaping or audio recording for assistance in furthering detachment from the observed phenomena, the nature of the case study environment did not allow for this type of intervention. Therefore, the direct observations undertaken for this study relate to directly observing various phenomena while physically present on the case study site. Figure 4 denotes how direct observations were utilized for data collection in the case study and ultimately broken down into typological categories defined as Value-Added Time (VAT), Necessary Non-Value Added Time (NNVAT) and Non-Value Added Time (NVAT). Each of these categories can be defined as follows (definition adapted from Aziz 2013):

- ***Value Added Time (VAT):*** Time utilized to convert materials and/or information into a component or deliverable which ultimately meets client's requirements.
- ***Necessary Non-Value Added Time (NNVAT):*** Time utilized to support the transformation of materials and/or information into a component or deliverable which will ultimately meet the client's requirements.
- ***Non-Value Added Time (NVAT) or Waste:*** Any time which consumes a resource but does not ultimately add value to the client's requirements.

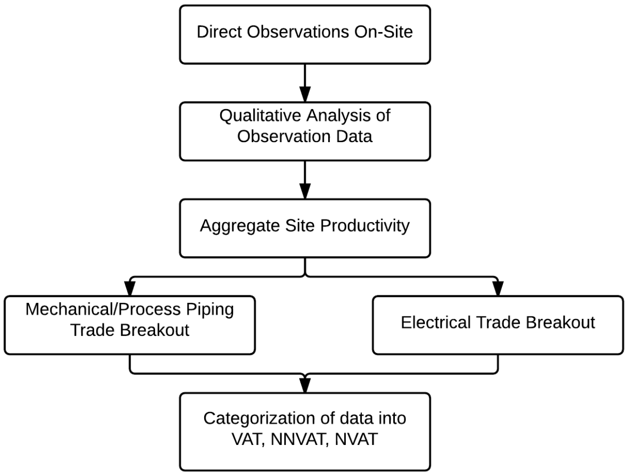


Figure 4: Stages of Direct Observation

1.4.1 Validation

The "prefaBIM" dynamic modeling workflow, which is the final outcome of this dissertation, underwent validation through multiple iterations of direct observation during various process interventions highlighted in the ideal state. The subsequent observations utilized identical observation matrices and logs. The conditions from which observations were gathered remained similar and access to the same resources remained unchanged throughout the duration of the case study. Chapter 5 introduces the interventions and discusses overall results and conclusions from the data collected.

1.5 Organization of Dissertation

Chapter 2 presents a comprehensive literature review. The literature review is approached from three main facets: Semiconductor manufacturing facilities and subsequent design/construction needs and constraints, Building Information Modeling and Integrated Project Delivery Methods. These three categories are further distilled to include offsite construction techniques where external industries are highlighted, ultimately culminating in BIM Content Generation.

Chapter 3 presents overall research methodologies and the basis for direct observation data collection. Integration within the case study environment is presented and site-wide team dynamics are explored. This chapter essentially discusses the conditions from which the research hypotheses were further developed. Ultimately research questions R1 through R1.2.1 are explored.

Chapter 4 presents the results of the data collected on-site regarding productivity rates at the modeling task-level. Overall results at both an aggregate site-wide level and individual trade-level are presented and compared. This chapter lays the foundation for the formulation of a theory and responds to research questions R2 and R2.1.

Chapter 5 introduces an overall framework for an ideal state workflow for modeling for prefabrication based on the data analysis presented in chapter 4. The theory is grounded in the literature review presented in chapter 2 as well as the informal and formal observations at the case study. While the theory is rooted in the case study, scalability of the process ideals is presented. This chapter also highlights the validation process wherein subsequent direct observations were engaged for measurement lending towards comparative analysis of process interventions.

Chapter 6 reiterates research goals and questions and summarizes overall study findings. This chapter opens the door for future research directions and topics based on data presented in this dissertation. In conclusion, this chapter presents contributions to the body of knowledge future directions of study.

CHAPTER 2

A Literature Review: Industry + Academic Conditions

This chapter presents the literature review completed through the duration of the study. Section 2.1 introduces the semiconductor manufacturing facility environment and related design and construction variables that make this a unique environment for design and construction projects. Section 2.2 presents literature regarding offsite construction techniques and the implications of utilizing these construction methods. Building Information Modeling (BIM) is introduced in Section 2.3 and topics related to workflows and challenges are presented. This discussion spans the industry at large and more importantly introduces the current gap that exists in the utilization of BIM in a retrofit construction environment. Section 2.4 introduces Lean Construction theory and presents the overlaps in BIM related tools and offsite construction techniques for improving construction productivity and reducing waste in its various forms during the execution of a project. Completing the literature review is Section 2.5 which presents gaps in existing literature and defines research opportunities, ultimately defining the basis for this study. Finally, Section 2.6 presents conclusions and summarizes the overall literature review.

2.1 Semiconductor Manufacturing Facilities

"Semiconductor manufacturing is an expensive, complex, and highly reentrant process" (Agrawal & Heragu, 2006, p. 119). The fabrication facilities themselves are commonly referred to as fabs and are complex environments that support the manufacturing process of Integrated Circuits (ICs), or chips, which are ultimately introduced as a component of various products in the realm of commercial electronics. This is, in essence, the process that enables the existence of computers and related products.

Manufacturing at its most basic form can be defined as “the process by which raw materials are converted into finished products” (May & Spanos, 2006, p. 01). The manufacturing process itself is supported by the utilization of sophisticated machines, known as tools, which require highly specialized conditions for proper operation. In light of the need for these specialized environmental conditions, modern fabs can run a total project cost exceeding 1 billion dollars. A 60%-40% split can be seen in total manufacturing equipment cost and other construction related expenses respectively (Bard, Srinivasan, & Tirupati, 1999).

As denoted by Brown & Linden (2009), the term “semiconductor” is a general term for a material with a conductive property. The ultimate goal of the semiconductor manufacturing process is to take silicon (sand) and transform it into a usable electronic component known collectively as integrated circuits (ICs). At an abstract level, the manufacturing process for chips can be seen graphically represented in Figure 2.1. It is important to note that the figure does not depict an exhaustive list of the processes and materials needed to generate ICs. In actuality, the semiconductor manufacturing process consists of hundreds of steps that must be executed in a specific order and at near perfect conditions (May & Spanos, 2006).

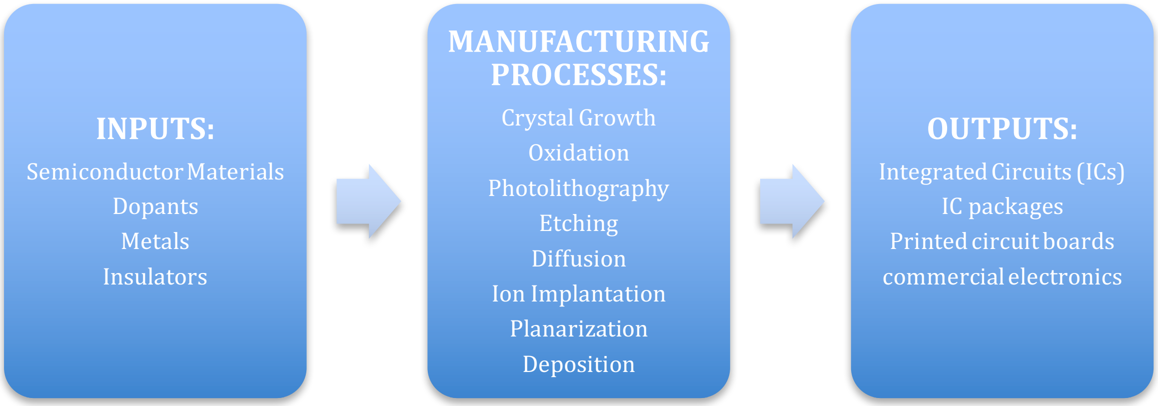


Figure 5: Manufacturing Process for Semiconductor Products (Adapted from May & Spanos, 2006)

Historically, semiconductor manufacturing has proved to be a highly competitive industry and one which holds enormous weight within the economic landscape. The industry is dependent on consumer demand, and as such, the output of manufacturing plants is directly related to future casting the demand of a specific technology. While manufacturing is taking place, new processes are constantly being introduced into the marketplace for development of the next technology. These processes are all predicated on the capital investment of a fabrication plant, “fab,” and the capacity which it was designed to manufacture. Figure 6 depicts a generalized look at the semiconductor supply chain and highlights the components which are concerned with the proper construction of the controlled fabrication facility environment. The variables within the semiconductor supply chain further the complexity found within the design and construction process of the fabrication facilities which support the ever changing internal manufacturing process for the next technology release.

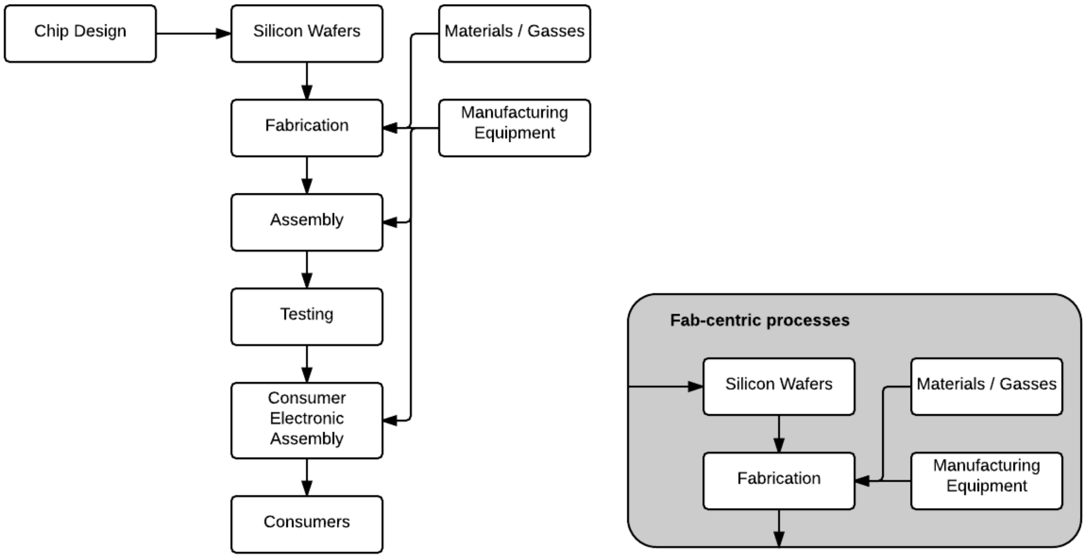


Figure 6: Generalized Semiconductor Supply-chain (Adapted from Brown and Linden, 2009)

Highlighting the metamorphosis of the semiconductor manufacturing industry from infancy to current manufacturing capacity and fab types, Brown & Linden (2009) have identified what they term the "Eight Crises" depicted in Table 1 (Brown & Linden, 2009). Each of these crises has led to adapting business models, emerging market sectors, changes in regional manufacturing focus and ultimately leaps in technology enabled by Moore's Law. All of these scenarios have led to transformation in fabrication facility designs, costs, complexity, size and location. Specialized R&D facilities will differ from that of high volume manufacturing facilities. The same goes for a facility located in the U.S. versus one in Asia. Each poses their own intricacies and difficulties when planning, designing and constructing.

Table 1:

Semiconductor Crises (Adapted from Brown & Linden, 2009)

Crisis	Description
Crisis 1	*Loss of competitive advantage*
Crisis 2	*Rising costs of fabrication*
Crisis 3	*Rising costs of design*
Crisis 4	*Consumer price squeeze*
Crisis 5	*Limits to Moore's Law*
Crisis 6	*Finding talent*
Crisis 7	*Low returns, high risk*
Crisis 8	*New global competition*

2.1.1. Fab Design Typology

Manufacturing factory layouts are becoming increasingly more complex problems to solve due to progressively more complicated processes, stringent tool specifications and subsequent requirements for operation and the increased space needs of tools (Huang, Kuo, Kao, Huang, & Lee, 2014). Ghosh (2015) maintains that a fab typically consists of 3 main components:

- **Cleanrooms –** These spaces are defined by ISO14644 as, "a room in which the concentration of airborne particles is controlled to specified limits" (Patel & Chasey, 2005, p. 11). These spaces are controlled environments where manufacturing processes take place. They house the capital equipment that ultimately transforms silica into ICs. As the manufacturing process is extremely sensitive to environmental conditions, this space requires stringent control over HVAC systems including airflow, filtration and humidity. The space is categorized based on sensitivity to external contaminants and is classified by ISO14644-1, which dictates the acceptable level of contaminated particles per cubic meter of air. Typically, within these spaces are raised metal flooring systems which are intended to serve two purposes: 1) They allow access to the tool tie-ins, or points-of-connection (POC's), for all support infrastructure and 2) They allow air to flow out of the cleanroom space to control filtration.

- **Sub-fab** – This space is dedicated to housing equipment, utility runs and ancillary tools that support the process equipment and tools found in the cleanroom environment. This space is where the major MEP routing highways can be found in a manufacturing facility. For a single tool placed in the cleanroom space, the possibility for dozens of supporting tools, ancillary equipment and specialty utility routes can be found residing somewhere in this space.
- **Utility level** – This level of a facility is less regulated as it pertains to overall contamination and houses any support systems for the equipment found in the sub-fab level. Most major utility tie-ins are found at this level and will be directed to the equipment found in the sub-fab

At a high-level, 5 phases can be identified in semiconductor factory design. Figure 2.1 depicts these phases. Encompassing all 5 phases of facility design is the programming process. Programming a semiconductor manufacturing facility revolves around matching systematic, manufacturing process needs with space constraints.

Figure 7: Phases of Layout Planning (Adapted from Huang et al., 2014)

Space constraints are related to both tool and equipment placement, as well as distances of travel for personnel and materials engaged in the manufacturing process, known as work-in-progress (WIP). Traditionally, material handling (MH) of a wafer was done through manual processes which had the potential to introduce contamination and product yield issues due to mishandling of material. As processes have become more advanced and enabled an increase in the size of the wafer produced, automated processes have been introduced into fab layouts for optimization of material movement. Modern layouts for 300-mm wafer facilities are traditionally centered on an overhead track which moves chips from tool-to-tool and various processes. This track and the vehicle operating on the track, a front-opening unified pod (FOUP), are known together as an Automated Material Handling System (AMHS) (Agrawal & Heragu, 2006). Chasey & Merchant (2000) identified five areas of importance which drive changes in fabs. Ultimately they discuss the automated material handling system as the driving force for changes in both technology and the design/construction process for fabs. While there are other components to the AMHS system, those of main focus throughout this research are the vehicle carrying the wafers and the guide-track leading from one process tool to the next.

In order to reduce overall distance travelled for each chip engaged with the AMHS, modern manufacturing facilities are programmed into functional areas. Each functional area consists of all tools/supporting equipment needed to complete a specific portion of the manufacturing process. This programming layout approach is diagrammatically presented in Figure 8. This programming layout intends to optimize the flow of WIP over the shortest spans of distance, in the hopes of reducing incidents of material mishandling, thus increasing product yields (May & Spanos, 2006). Existing literature identifies algorithms and prescriptive, or procedural, methods as the two main avenues for the development of a layout design. However, neither approach to layout design is able to successfully account for all variables involved with the design process (Yang & Kuo, 2003).

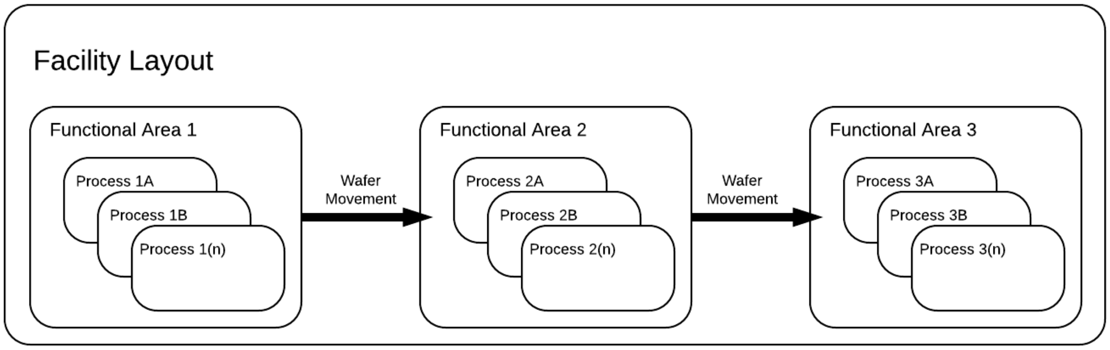


Figure 8: Process Programming Diagram (Adapted from May and Spanos, 2006)

While supporting the manufacturing process is the main goal of layout design for a facility, through the use of Analytical Hierarchy Process (AHP), Ngampak and Phruksaphanrat (Ngampak & Phruksaphanrat, 2011) identified layout flexibility, capacity and cost as the three critical factors involved in successful layout design. Utilizing these critical factors as a starting point, they applied AHP to a layout design and their findings indicate that initial investment cost and layout flexibility are the most highly valued areas of focus. Furthering the analysis of layout design, Huang et al. (2014) utilized the Analytical Hierarchy Process (AHP) to determine supplemental driving factors which add to the complication of the design process. They found that the "critical factors (Huang et al., 2014)" for fab layout at the macro layout design stage are "process flow, process time, contamination control and safety. (Huang et al., 2014, p. 101)"

The importance of this discussion for fab layout lies in the density of the design problem and time constraints for executing a layout and ultimately tooling a facility to meet production demands. As if there were not enough layers of complexity in the design process, overall layout design can significantly impact the performance of manufacturing processes (Yang & Kuo, 2003). It is also an important procedure in effectively designing a facility with acceptable operating costs, as operating costs are directly impacted by layout design and reductions in overall operating costs in the realm of 10%-30% are possible with efficient programming of layouts (Riedel, 2011).

2.1.2. Capacity Planning & Capital Equipment (Tool) Installation/Conversion

As the industry shifts towards the manufacture of larger wafers, new fabs will need to be built or existing fabs will need to be converted to accommodate new processes. "Unlike previous wafer diameter increases, the 300-mm transition is likely to generate an entirely new set of design criteria for the factory" (Chasey & Merchant, 2000, p. 454). Fab designs are becoming more complex due to the extensive needs of the manufacturing process. Couple this with a generally accepted 18-month timeline for the release of new technology, traditional methods of constructing a new fab pose an issue for time-to-market, as it takes over two years to design, construct and deliver a fab which is ready for production. This issue is further exacerbated by the need for reduced upfront costs in order to hold a competitive advantage, as well as the need to frontload the design process prior to development of the chip-manufacturing technology and ultimately construct the facility under changing design conditions (Gil, Tommelein, Stout, & Garrett, 2005). This introduces a scenario in which conversion projects of existing fabs are becoming a more prevalent means of company's approaching technology transition periods. Ghosh (2015) attributes this shift to the ability for equipment re-use and ultimately cost savings related to reduced workforce displacement and infrastructure build-out. This scenario comes with its own set of differing issues. When wafer size increases, so do tool size and capacity needs for process equipment. Relating back to the needs for automating more processes, new layouts for fabrication facilities will also become a topic of discussion as more internally controlled environments lend themselves towards a reduction in cleanroom requirements (Chasey & Ma, 2001).

Capacity planning is a scenario which adds another layer of complexity to effectively planning a semiconductor fabrication facility. Chen et al. (2008) identify the rapid progression of technology, increasingly high manufacturing cost and economics of supply and demand as areas of difficulty for effective capacity planning. While various categories of capacity planning exist, this research focusses on single-site capacity planning, which best represents the case-study site encountered. In this realm of capacity planning, the focus is on how to reallocate or expand capacity at an existing fab through tool conversion or replacement (Chen, Chen, & Liou, 2013). When a tool is converted, replaced or demolished from a fab, it is not a simple process. Tools varying in complexity and can have over 100 connection points to various supporting gasses, fluids, electric, mechanical, process and waste services. Table 2 denotes complexity of tools encountered during a study of tool installation.

Table 2:

Tool Complexity (Adapted from Chasey & Ma, 2001)

	Average	Maximum	Minimum
Points of Connection (POC)	26	126	1
Bulk Gas	6	37	0
Specialty Gas	2	25	0
Chemicals	1	8	0
Ultra Pure Water	1	10	0
Process Cooling Water	6	38	0
Drain / Waste Chemicals	2	26	0
Exhaust	5	19	0
Vacuum	3	14	0
Control	0	2	0

Tool installation/conversion is a standardized process outlined by the Semiconductor Equipment and Materials International (SEMI). Various documents released by SEMI drive tool installation and enable cost effective and expedited tool installation (Ghosh 2015). At an abstract level, four main phases can be identified for the tool installation/conversion process. Each of these processes comes with a specified set of deliverables and tasks to complete. Figure 9 denotes these phases in graphical format and breaks out the tool design and tool construction phases to explore the various stakeholders involved and standard deliverables for the phase.

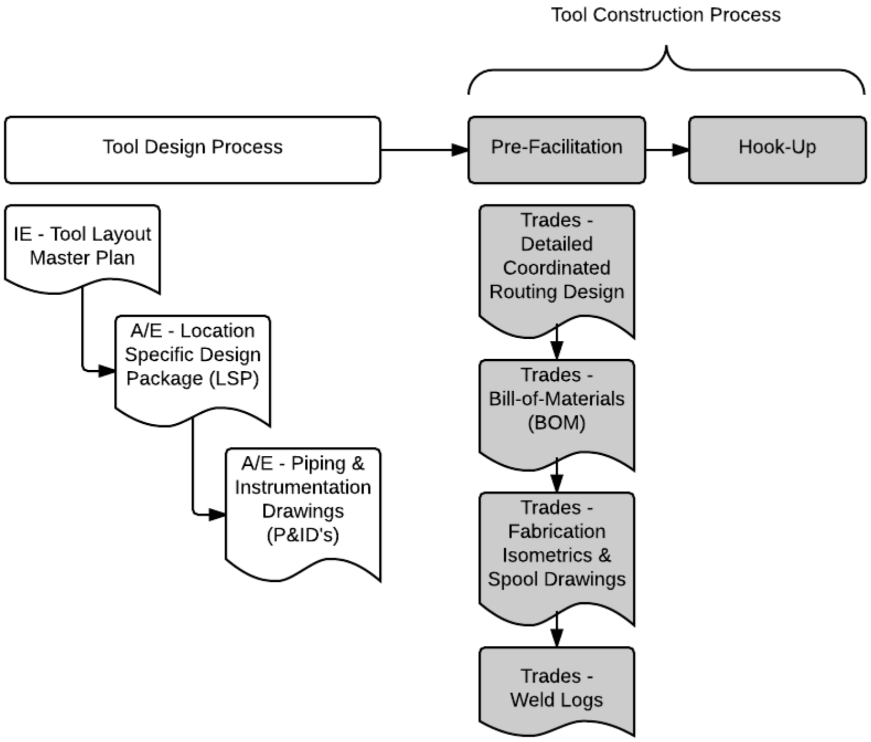


Figure 9: Tool Install Process (Adapted from Ghosh, 2015)

2.2. Offsite Construction Techniques

The Construction Industry Institute (CII) has done extensive research in off-site construction techniques and what they term as "prefabrication, preassembly, modularization, and offsite fabrication (PPMOF) (CII, 2002a, p. 01).” Table 3 presents the CII definition for each of these construction techniques. This is an area of current focus for construction research and industry execution. It is a technique which is meant to offer owner’s a way to improve overall project performance while curbing some of the issues resulting from schedule compression needs, adverse site conditions related to weather and congestion and ultimately an identified shortage of skilled labor (CII, 2002a).

Table 3:

PPMOF Definitions (Adapted from CII, 2002)

Term	Definition	Notes
Prefabrication	A manufacturing process, generally taking place at a specialized facility, in which various materials are joined to form a component part of a final installation	Common practice on industrial projects today
Preassembly	A process by which various materials, prefabricated components, and/or equipment are joined together by different crafts at a remote location for subsequent installation as a sub-unit. It is generally focused on a system	Common practice on industrial projects today
Modularization	A major section of a plant resulting from a series of remote assembly operations and may include portions of many systems	Typically the largest transportable unit or component
Offsite Fabrication	A practice of preassembly or fabrication of components both offsite and onsite at a a location other than the final point of installation	

According to a survey conducted by McGraw Hill (2011), 84% of contractors in business today utilize prefabrication/modularization to some degree. Their research found that specialty contractors are utilizing these techniques in order to stay relevant and competitive in the industry. Mechanical and electrical contractors have found significant improvements in project delivery efficiency and labor productivity through this approach to construction. A second survey conducted by FMI in 2013 states that 'on average, for mechanical and electrical contractors, 12% of their total annual labor hours were committed to prefabrication. In five years, they would like that number to rise to 32%' (Cowles & Warner, 2013, p. 4). Among the building sectors identified, the manufacturing sector was identified as third highest sector utilizing prefabrication/modularization, at a rate of 42%. The current drivers identified by the survey from a contractor's perspective are to improve productivity - 92% of respondents, gain competitive advantage - 85% of respondents, generate greater return-on-investment (ROI) - 70% of respondents, and finally demand from the owner/client – 31% of respondents (McGraw Hill Construction, 2011). Research has shown that off-site construction sectors are showing more rapid growth related to productivity than that of on-site endeavors and off-site construction is achieving higher rates of productivity that that of the global construction industry (Eastman & Sacks, 2008).

It is important to note that while many of the benefits related to cost or schedule are not seen in direct relation to the portion(s) of the project being prefabricated, they become apparent at the global scale of a project upon examination of the macro performance. It is imperative that "off-site fabrication is viewed from a project-wide perspective, and a suitable strategy is developed to optimize its use" (Gibb, 1999, p. 51).

Within semiconductor manufacturing, "the large capital investment required to bring a new fab on-line is driving semiconductor chip manufacturers to adopt strategies to minimize cost to maximize the return on investment" (Chasey & Merchant, 2000, p. 451). As SEMATECH has set a goal for 12-month delivery of a production ready fab, ultimately leaving a mere 9 months for the design and construction process (reduction in 9-months over delivery of a 200-mm fab), exploration and execution of various off-site construction techniques is needed (Chasey & Merchant, 2000). Gil et al., (2005) identified off-site fabrication as a project management process flexibility strategy which has the potential to save labor hours and installation time as well as possible cost savings and overall safety and quality improvements.

Table 4:

Areas of Needed Research for Fabs (Excerpt adapted from Chasey & Merchant, 2000)

Item	Research Needs
Layout	Modularization needs
	Impact of modularization on construction schedule
	Impact of AMHS on facility layout
Schedule	Impact of AMHS on cleanroom schedule
	Modularization technique to improve schedule
	Identify different construction approaches

As Table 4 showcases the needs for semiconductor specific research regarding off-site construction techniques, there is also a global scale need for research regarding the enablers of off-site construction. Process, technology and people are essential to the success of offsite construction endeavors. In other words, "… process in design, manufacturing, and construction have to be completely reengineered in order to harness maximum benefits from the manufactured construction" (Arif, Goulding, & Rahimian, 2012, p. 78). A fundamental re-thinking is needed to reap the benefits often cited in research regarding the utilization of off-site construction. This re-thinking is not necessarily needed in the highly technical realms of automation and interjection of advanced technology but in current "value-added activities such as visualization and simulation technologies" (Arif et al., 2012, p. 78). Table 5 presents this information in matrix format.

Table 5:

Priorities for Promoting Off-Site Construction (Adapted from Arif et al. (2012)

Areas			
Categories	Design	Manufacturing	Construction
Process	High Priority	High Priority	High Priority
Technology	Medium Priority	Low Priority	High Priority
People	High Priority	Medium Priority	High Priority

2.2.1. Critical Success Factors for PPMOF

As project teams transition into the utilization of more off-site construction techniques and PPMOF methods, important focus should be placed on the owner's responsibilities and resultant risks. This has become apparent through the study of critical success factors for executing PPMOF techniques and the enablers which accompany execution. A key finding of research completed by O'Connor et al. (2014) states that "more than half of the factors require leadership and implementation by project owners. For successful modularization to occur, the message is clear: substantial owner involvement must occur early" (O'Connor, O'Brien, & Choi, 2014, p. 10). Figure 10 introduces the Critical Success Factors (CSF's) identified by O'Connor et al. (2014) in hierarchical format. Various frequencies of success are seen with each CSF and they rang from very common on projects to very rare on projects. This research focusses on the CSF's at the top of the pyramid under the Occasional, Rare and Very Rare tiers. Within these three tiers, the CSF's identified in bold become the focus for this research.

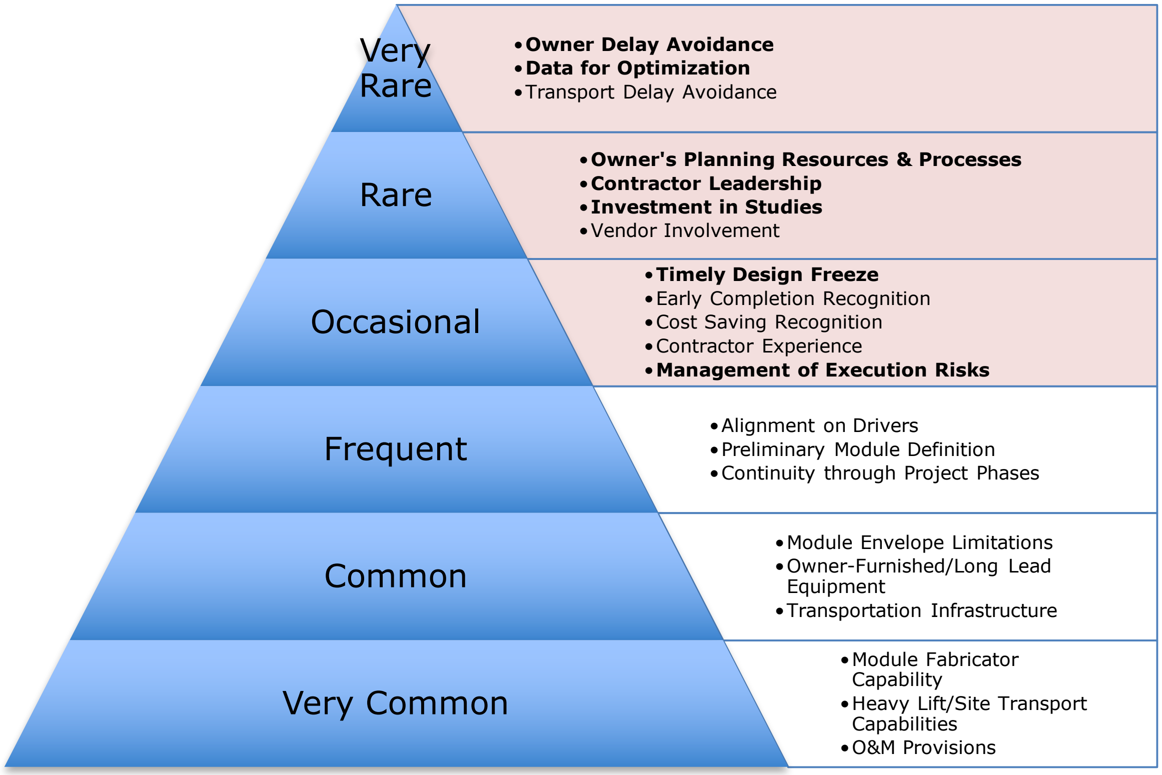


Figure 10: Focused CSF’s for Research Case-Study (Adapted from O’Connor et al., 2014)

2.3 Building Information Modeling

While productivity rates have been shown to be poor in the construction industry (Teicholtz 2004, 2013), one of the main contributing factors for diminishing rates has been identified as the consistent reliance on traditional design and fabrication information in the form of 2-dimensional drawings (Gallaher, O’Conor, Dettbarn, & Gilday, 2004). While various sectors of the manufacturing industry (automobile, airline & shipbuilding to be specific) have adopted the use of digital models for product design and fabrication, the construction industry is still heavily reliant on the human interface with physical or digital drawings rather than machine-to-machine reading of data. In response to this, the AEC industry is becoming more heavily focused on Building Information Modeling (BIM) (Eastman & Sacks, 2008).

Building Information Modeling has a wide range of definitions in both industry and academia. A literature review conducted by Ghosh (2015) discusses the two varying approaches to definitions of BIM: a process vs. a digital object model. Despite these two approaches to defining BIM, three distinct components are consistently addressed. The components defined are *geometric information*, *descriptive information* and associated *workflows*. There is distinct overlap between these three aspects but each must be addressed separately in the planning and understanding of proper execution/implementation on a live project. This research borrows from these finding and furthers the exploration of the geometric information component of BIM and associated interfaces in information and processes (Ghosh, 2015).

2.3.1. BIM Project Execution Planning (BIM PxP)

Properly leveraging BIM capabilities on a project requires extensive execution planning. Many frameworks for BIM Project Execution Planning (BIM PxP) exist in industry and they may vary based on project typology. These BIM PxP's are meant to identify reasons for the utilization of BIM on a project, relate the uses to project phases and identify various responsibilities and stakeholders responsible for completing components of the model. Ultimately the U.S. Department of Veterans Affairs has identified a BIM PxP as a document meant to streamline data handoff for use in the various phases of the design, construction, operations, repurposing and demolition lifecycle (U.S. Department of Veterans Affairs, 2010). This vision of a BIM PxP is shared amongst many players in industry and can be borrowed at a high-level for idealizing a document in assisting BIM implementation.

While there are a multitude of BIM Execution Plans in use industry wide, this research references the BIM PxP developed by Penn State University as a benchmark for BIM planning. This initial BIM PxP was developed through the buildingSMART alliance Project (ANSI, 2007). The main goal of the research was to create a document to assist in the standardization of BIM processes in the hopes of addressing efficiency and interoperability issues identified by industry. A BIM PxP can therefore be defined as a document that "should define the appropriate Uses for BIM on a project… along with a detailed design and documentation of the process for executing BIM throughout a facility's lifecycle" (Anumba et al., 2010, p. i). Figure 11 depicts the BIM PxP definitions procedure as taken from the Penn State PxP Planning Guide.

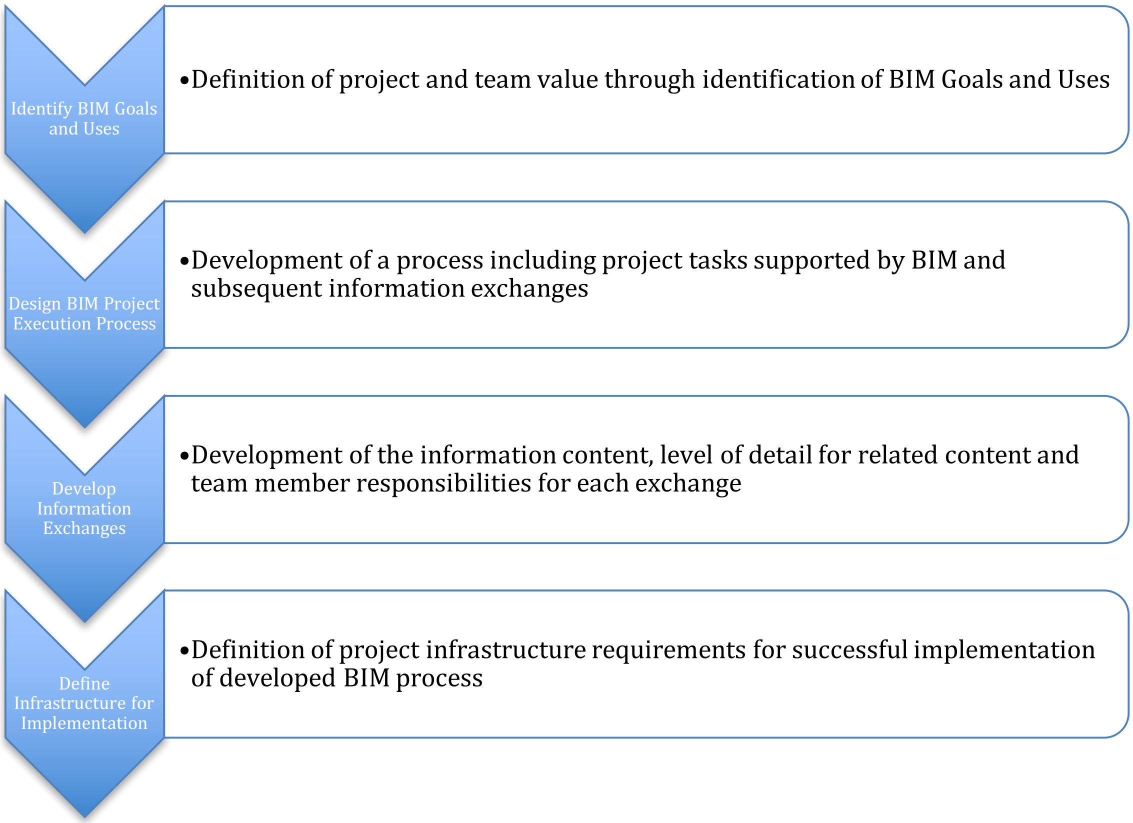


Figure 11: BIM PxP Procedure (adapted from Anumba et al., 2010)

2.3.2. BIM & Level of Detail/Development (LOD)

There are conflicting nomenclatures in the industry regarding the meaning of LOD from “Level of Detail” to “Level of Development.” James Vandezande of HOK sheds light on the differences of these two meanings within a presentation to the National Institute of Building Sciences (NIBS) and illustrates that the term “Development” means the “Reliability/Confidence” within use of a BIM, whereas the term “Detail” lends itself towards the actual “Input” of model parameters. Expanding on this notion, Vico Software originally defined the Level of Detail (LOD) as “descriptions of the steps through which a BIM element can logically progress from the lowest level of conceptual approximation to the highest level of representational precision,” in their 2004 release of a Model Progression Specification (MPS). Table 6 shows the various Levels of Detail as defined by Vico Software.

Table 6:

LOD Examples (Adapted from Vico Software Model Progression Specification)

Level of Detail	100	200	300	400	500
Element					
Interior Wall	Not modeled. Cost and other information can be included as an amount per s.f. of floor area.	A generic interior wall, modeled with an assumed nominal thickness. Properties such as cost, STC rating, or U-vale may be included as a range.	A specific wall type, modeled with the actual thickness of the assembly. Properties such as cost, ST rating, or U-value can be specified.	Fabrication details are modeled where needed.	The actual installed wall is modeled.
Duct Run	Not modeled. Cost and other information can be included as an amont per s.f. of floor area.	A 3-dimensional duct with approximate dimensions	A 3-dimensional duct with precise engineered dimensions.	A 3-dimensional duct with precise engineered dimensions and fabrication details.	A 3-dimensional representation of the installed duct.

The idea of Level of Detail is further expanded to define specific uses of a model at each subsequent phase from 100-500 and anywhere in between. This discussion has led to the development of the BIMForum LOD Specification. LOD in the eyes of the BIMForum stands for Level of Development and the LOD Specification can be defined as "a reference that enables practitioners in the AEC Industry to specify and articulate with a high degree of clarity the content and reliability of Building Information Models (BIMs) at various stages in the design and construction process" (BIMForum, 2015, p. 10). This expands on the granular level presented by Vico Software regarding specific detail of model elements and moves into a realm where model uses for various phases of the design/construction/operations lifecycle can be defined.

For sake of clarity, this research utilizes the concept of Level of Development as defined within the BIMForum LOD Specification (2015). Level of Development therefore means:

> "…the degree to which the element's geometry and attached information has been thought through – the degree to which project team members may rely on the information when using the model… Level of Development is reliable output."

2.3.3. BIM and Interoperability

A study conducted by the National Institute of Standards and Technology (NIST) estimates that $15.8 billion per year is lost in the construction industry due to interoperability issues (Gallaher et al., 2004). The findings from this report have led to extensive research efforts in the realm of standardizing data structures for transfer between software packages/authoring tools and disciplines. While the main goal of utilizing a single model for lifecycle decision making of a building or facility has existed for over three decades, it has proven difficult to reliably access data at varying points in a facility lifecycle. Interoperability issues are a key component to realizing this goal. This goal has also proven to be more complex than theory states and a more focused approach to utilizing a BIM and standardizing the BIM-use is warranted. (Howard & Björk, 2008).

Open standards for formatting information contained in a BIM have been presented and explored by both industry and academia alike. One of the most widely known open standard formats is known as the industry foundation class and it was originally conceived and distributed in 1997. The IFC format has been noted as "necessarily large and complex, as it includes all common concepts used in building industry projects, from feasibility analysis, through design ,construction, and operation of a built facility" (See, Karlshoej, & Davis, 2011, p. 3). While it has been nearly two decades since the introduction and furthered development of the IFC format, it is not widely utilized in practice (Howard & Björk, 2008). Ongoing research efforts are focused on the continued development of open standards for BIM data to ensure interoperability.

2.3.4. BIM in Retrofit Construction

Retrofit projects pose significant challenges for the utilization of a BIM workflow. Conditions are constantly changing and must be captured and reflected in a central location for all parties to utilize in the design and construction process. Through research conducted on the utilization of BIM's for operations and maintenance of facilities, it has been noted that changes during construction are not always updated in a BIM and or digital format and subsequently not provided to the owner in a true as-built format (Akcamete, Akinci, & Garrett, Jr., 2009).

To assist in highlighting the differences in retrofit construction as opposed to new construction projects, Ghosh et al. (2015) introduced a tri-tiered approach to reviewing existing literature regarding retrofit construction where three categories of papers were reviewed. The findings of the first type of paper which focuses on highlighting the difference in process models and management strategies between various project typologies show that a gap exists in the study of BIM implementation in retrofit construction and depicts various changes needed in process implementation for BIM use in retrofits. Table 7 provides an outline of some identified constraints related to retrofit projects:

Table 7:

Retrofit Constraints (adapted from Ghosh et al. 2015)

Source	Constraints
(Sanvido & Riggs, 1991)	Information (lack and uncertainty of existing data) Time (pressure for time to market) Space (congestion, access and work sequencing) Environment (hazardous/toxic materials, noise/vibration)
(Loughran, 2003)	Maintaining optimum production levels Demolition/disposal of hazardous materials Maintenance of Environmental/Health/Safety (EHS) requirements Access for workers Removal or protection of existing equipment
(Ben-Guang, Fang-Yu, Kraslawski, & Nyström, 2000)	Reuse of existing equipment Experimental studies of uncertainties in design Late changes in retrofit design

2.3.5. As-Built BIM & BIM for Retrofit Construction: Existing Conditions Capture

Traditionally, BIM is seen as a tool in which design information is translated into a 3-dimensional format and ultimately documented for construction. A recent utilization of BIM has been introduced to projects and can be termed “as-built BIM” (Hichri, Stefani, Luca, & Veron, 2013). The creation of an “as-built BIM” can be described as a reverse engineering process in which the facility data is matched to survey data to provide near exact conditions of a facility at a specific point in time (Dore & Murphy, 2014). Many tools exist to map existing conditions of facilities from traditional survey methods to more advanced laser scanning and photogrammetric techniques which ultimately expedite the process of data collection. As with any technology, there are limitations to implementation. This research pays particularly close attention to the application of laser scanning techniques for existing conditions capture in congested, manufacturing environments.

While laser scanning allows for expedited capture of existing facility conditions at a specific point in time, post-processing and manipulation of data is still a large component of the process. Properly registering scans for use in modeling and the human interface against understanding the ‘dumb’ data-points captured (point cloud) introduce a lag time in process and the possibility for error in replicating or understanding of field conditions. These concerns, among others, have led research teams to identify ways of automating data from a point-cloud structure to a BIM format. This technology exists in a Scan to BIM scenario but are currently limited in the complexity and accuracy of recreated geometry (Thomson & Boehm, 2014).

2.4. Lean Construction Theory

Lean construction is an emerging theory in the construction industry. The manifestation is a translation of lean manufacturing theory, also known as the Toyota Production System (TPS), which can be traced back to origins at the Toyota Motor Company (Liker, 2004). The main ideas behind TPS can be globally summarized as a process focused on eliminating waste, reducing excess inventory, improving throughput, and encouraging a grass-roots movement towards continuous improvement (Womack & Jones, 2003). These ideologies directly relate to adding value to a process at the product level. The main goal of lean manufacturing is to reduce waste in the manufacturing system and provide greater value to the next customer downstream in the production system.

Ultimately this idea has translated into the construction industry and Rahman, et al. (2012) have summarized the result in the formation of three distinct, main features: "a) lean construction focuses on reducing wastes that may exist in any format in the construction process, such as inspection, transportation, waiting, and motion; b) lean construction aims to reduce variability and irregularity so that material and information can flow in the system without interruptions; and c) construction material is expected to be on site only when it is needed" (Rahman, Wang, & Lim, 2012, p. 9). These components of lean construction have ultimately led to a greater focus on a "(1) **T**ransformation; (2) **F**low; and (3) **V**alue generation (TFV) theory of production" (Aziz & Hafez, 2013, p. 680). This boils down to a project planning and project controls approach throughout the duration of a project in a cyclical nature (Aziz & Hafez, 2013).

While BIM and lean were developed separately, a great overlap exists between the two realms. Research by Gerber et al. (2010) successfully demonstrates this overlap and ultimately concludes that Lean and BIM need to be developed together with integration in mind. BIM has been identified as a tool which can reduce the inherent waste in the construction industry and one which can directly interact and influence core beliefs of the Lean Construction methodology (Gerber, Becerik-Gerber, & Kunz, 2010).

A lean tool which has been adopted for use in the construction industry is Value-Stream Mapping (VSM). This is a tool which aims to create a visual representation of a process in its entirety so that waste in the system can be identified. This has been a tool which is proven to be successful in the construction industry (Rajenthirakumar, Mohanram, & Harikarthik, 2011). A major component of VSM is making sense of a process and identifying where value-added and non-value added activities are taking place. Ghosh (2015) begins a discussion regarding the terms Value-added Time (VAT) and Non-Value Added Time (NVAT). This research continues the understanding of these terms adapted from Hines & Rich (1997) as follows:

1) Value-added Time (VAT) – a component of time spent adding value to an end product
2) Non-Value Added Time (NVAT) – a component of time which does not ultimately add value to a product (from the perspective of the customer) (Ghosh, 2015). This is ultimately waste in the system involving unnecessary activity and should be eliminated (Hines & Rich, 1997).

This research furthers the discussion around time components to include a third category of time:

3) Necessary Non-Value Added Time (NNVAT) – this is a component of time which may not ultimately add value to a product but are needed for current operations to proceed (Hines & Rich, 1997). Borrowing from the realm of Information Technology (IT), this component of a process can be defined as "non-value-adding activities that are necessary under the present operating system or equipment. They are likely to be difficult to remove in the short term but may be possible to eliminate in the medium term by changing equipment or processes" (Gartner, 2016).

2.5. Research Opportunities

This section presents opportunities for research as identified through the lens of the literature review presented above in Section 2.1 through Section 2.4.

2.5.1. Utilizing Building Information Modeling (BIM) for Offsite Construction Techniques, in a Retrofit Environment

As discussed in section 2.2., Offsite construction has become an increased area of focus in the construction industry. While this type of construction method is not new, it is becoming a highlight for improvement in productivity and an enabler of successful project delivery with highly constrained schedules and site conditions. Each of the PPMOF approaches identified by the CII offers unique benefits and challenges and must be analyzed and planned for appropriately prior to deployment on a project; particularly retrofit scenarios, which are not heavily analyzed and/or understood in terms of the introduction of prefabrication processes (Volk et al. 2014).

2.5.2. Building Information Modeling (BIM) & Labor Time Utilization -

Building Information Modeling (BIM) is redefining the way construction projects are undertaken. This visualization process helps teams understand the intricacies of assemblies and construction sequences prior to any site-work being initiated. BIM, as a set of tools and processes (Eastman et al. 2011), is highly involved and requires proper technical and managerial expertise, as well as a set of defined processes and procedures tailored to project specific elements and workflows. BIM crosses all boundaries of a project delivery method and must be properly planned prior to execution on any project or task within a project. While BIM can help expedite the construction process, a shift in project schedule is needed to accommodate the necessary construction planning and design analysis that must be completed during the front-end of a project. Recognition of new processes, deliverables, and information handoffs must be identified and reflected in a new type of schedule, in order to successfully introduce a fluid, model-based delivery system for semi-automated and automated construction. This schedule must properly allocate for the modeling process to various Levels of Development (LOD's) and project teams must realize that further development and detail within a model (higher LOD) does not necessarily correlate with more modeling time (Leite, Akcamete, Akinci, Atasoy, & Kiziltas, 2011).

2.6. Conclusions

This chapter explored current literature and studies regarding the intersection of advanced technology workflows for improving construction project delivery and the unique scenarios introduced by a semiconductor manufacturing facility environment. The dichotomy between the structured and standardized approach to the manufacturing process and the implications of the construction of fabs in support of the manufacturing process present unique challenges and opportunities for the exploration of Building Information Modeling and off-site construction techniques for improvement of project delivery.

CHAPTER 3

CASE STUDY DEFINITION: TELLING THE STORY OF BIM FOR PREFABRICATION

This chapter juxtaposes the owner mandated BIM uses and expected outcomes against current state practices in BIM management and implementation and the expectations and capabilities of each player. Section 3.1 – Backdrop, Context and Case-Study Conditions provides an overview of the initial research problem and resultant investigative questions. It sets the stage for research by identifying the various components inherent in BIM project scope. An immersive understanding of team dynamics and stakeholder's perspective is introduced in Section 3.2 – Participant Observation and Team Dynamics. Following, Section 3.3 – Current State Process Definition, is the presentation of various layered diagrams highlighting the current state workflow for prefab modeling, project management and multi-dimensional visualization. Section 3.4 – Development of Observation Matrix discusses the trade level approach to modeling at the work-face and the resultant tasks inherent in all workflows. Section 3.5 – Furthering a Hypothesis presents the culmination of initial on-site observations, in which a hypothesis is formed and a plan for theory validation is created. Finally, Section 3.6 – Conclusions reviews the research methodologies and sets the stage for subsequent chapter discussions. This chapter utilizes research methods highlighted in Figure 12 to answer research question R1 and subsets therein. Those questions are:

R1: How does the initial process of modeling impact the number of workers on site during construction?

R1.1: What is the current work process for prefabrication and who are the stakeholders in the process?

R1.2: How does the Level of Quality in BIM correspond to the value added from prefabrication delivered and installed on site?

R1.2.1: How do trades currently measure/enforce the Level of Development (LOD) of BIM's used for prefabrication?

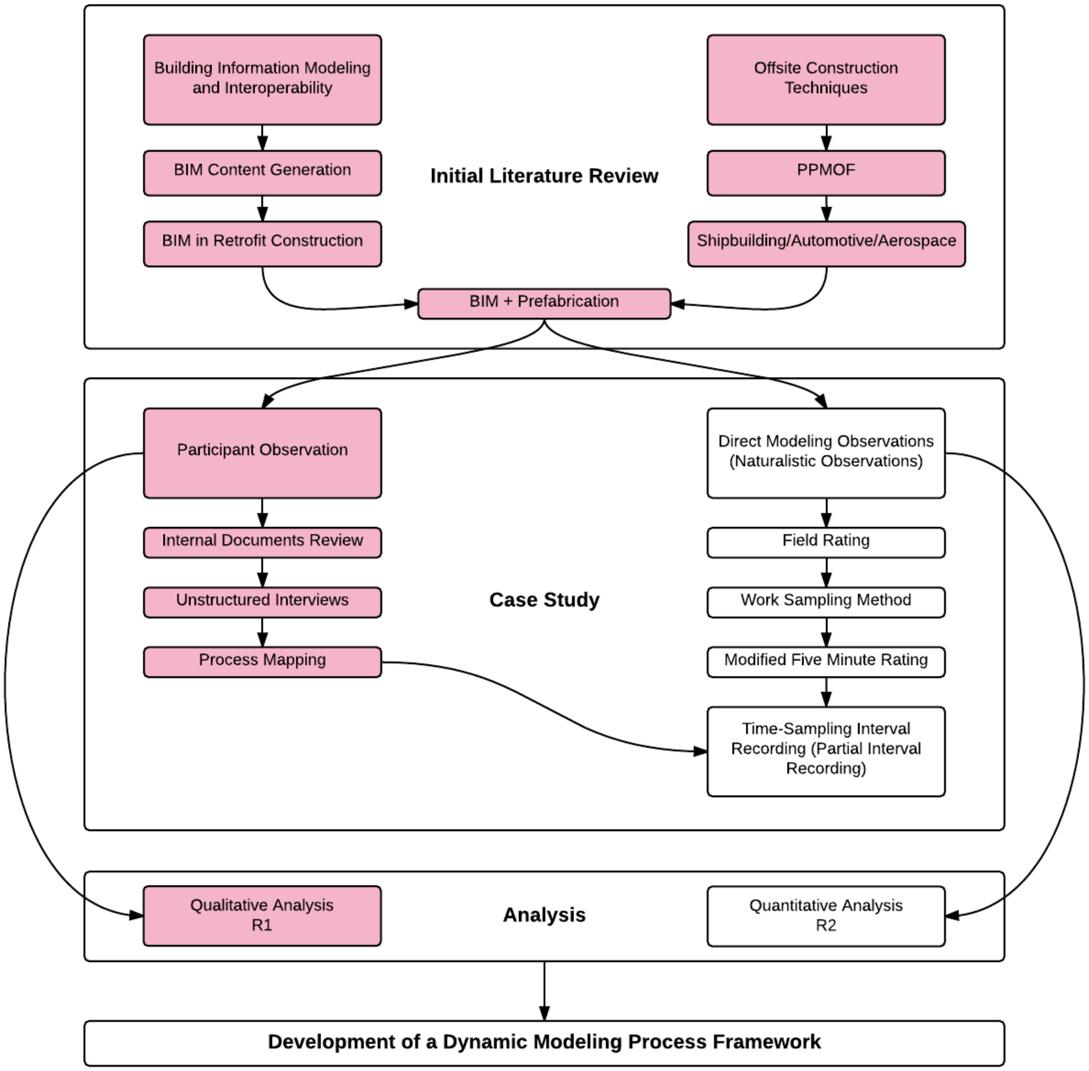


Figure 12: R1 Research Methods

Section 3.1 - Backdrop, Context and Case-Study Conditions

The semiconductor business model is unique compared to other industries and the facilities needed to support the manufacturing process to function properly are just as intricate. To accommodate the latest processes and technologies, facilities are re-tooled and upgraded with the expectation of continuing operations. Project teams are working in consistently more physically constrained environments while trying to meet increasingly stringent deadlines for first to market milestones. Capital equipment can reach in excess of $5 million/tool and cost an owner exponentially more if not ready when expected for rotation in the manufacturing process.

This case study is an extension of previous doctoral studies that served as part of ongoing dissertation work. The extended case study took place in the same semiconductor manufacturing as described by Ghosh et al. (2015). To recap, the facility is located in the Southwest Region of the United States on an expansive site, consisting of roughly four million square feet of conditioned space. The facility itself consists of high-volume wafer fabrication plants and subsequent support and utility spaces, as well as office and administrative buildings for business operations. The base-build components of the manufacturing facility have remained relatively static since originally constructed in 1996 and 2007. While the shell of the facilities have remained similar to that of 20 years ago, the interior core of the facilities, particularly the fabrication plants (fab) and sub-fabrication support and utility spaces (sub-fab) have undergone multiple phases of conversion, redesign, and retrofit. This series of retrofits has created a very complex environment for the introduction of a construction project and provides a rare setting in which to conduct research on innovative construction project management techniques.

As described in section 2.1.3, Retrofit scenarios are commonplace in the semiconductor industry for facility upgrades. These types of projects function differently than a standard new-build (greenfield) project. A diversion in construction means-and-methods and management techniques is necessary. New workflows and processes must be put in place and managed correctly for success.

While retrofit scenarios invite even more project constraints than a traditional new build project, the cyclical nature and uncertainty of the timeline supporting design of wafer manufacturing processes adds even more pressure to construction teams.

In light of the many recent study releases regarding productivity increases in project delivery due to prefabrication and the utilization of Building Information Modeling, the owner of the semiconductor manufacturing facility at which the case study is focused has mandated that prefabrication construction techniques and Building Information Modeling technologies be utilized in tandem for all capital equipment related installation or conversion projects. This mandate and response to construction techniques can also be attributed to the findings of internal (to the company) productivity studies on previous conversion projects in which site wide productivity rate losses were identified as a possible result of the increasingly physically constrained environments within which project teams are working to install equipment and related services. During a ramp in construction, there can be as many as 300 tools in an active install state requiring nearly 2,000 laborers and team members on-site, simultaneously working in a ballroom sized space, in order to meet schedule constraints.

The inherent congestion and owner concerns regarding site safety and lack of installation productivity (due to historical data) led to the research team being posed the following question at the outset of the case study:

> ***Owner's Problem Statement:*** "How do we reduce on-site headcount during an Early Tool Set (ETS) / Ramp Tool Set (RTS) ramp in construction operations while maintaining operational facilities?"

It is important to note the difference between an ETS and RTS scenario in on-site construction operations, as there is a major complexity difference. During an ETS ramp, capital equipment is undergoing a prototype scenario regarding any upfront demolition work for capital equipment conversion and/or design and construction work for new tool installation. That is to say, the piece of equipment and supporting services that are planned for install are seen for the first time by the design, construction and installation teams. In an RTS scenario, tools that have already undergone the prototype state defined in the ETS ramp become repeat installation designs that then must meet the varying locale specific constraints as they are replicated in the subfab and fab levels of the facility. Even though RTS tools are similar in nature, the routing and popout accessibility can differ as location changes within the subfab.

To begin responding to this question, further focus was placed on off-site fabrication techniques to highlight the labor productivity savings that could be realized through proper management of the "ideal" fabrication facility. This process allows for offsetting man-hours and displacement of physical bodies to a controlled, offsite environment and introduces repeatable tasks (globalized economies of scale and standardization). This initial objective was intended to further address the construction supply-chain pressures to:

- Meet rapid ramp schedules on new technologies.
- Effectively identify, contract and utilize construction resource headcount.
- Accommodate within-schedule changes, while maintaining change control.
- Minimize cost impacts to maintain affordability.

This research is an extension of previous SRC research completed under research grant task #2463.001, by the original principal investigator, and was therefore initially limited to semiconductor capital equipment, or tool install only. As an extension to initial findings, the research scope has been expanded to also consider capital equipment conversions, demolitions and swaps. The extension of this research has expanded upon initial findings regarding the differing values of BIM at the levels of Business Operations, Project Management, and the Modeling Workface. While this research engages all stakeholders identified in the BIM^2 Value Framework defined in the initial research outcomes by Ghosh (2015), the focus for the extended research resides in further defining the importance of reliable geometrical information at the Modeling Workface, as seen in Figure 13, which was originally identified as the most important value at that level of BIM utilization. Essentially, prior work suggested benefits related to reliable geometry from a theoretical standpoint, but this extension of research aimed to empirically quantify the impacts associated with different levels of model geometry and associated reliability of the geometrical information. This BIM-centric research extension utilizes information collected from the project owner and individual subcontractors on the case study project site from August 2014 to May 2016 and references material collected during the initial project time-period of November 2013 to June 2014.

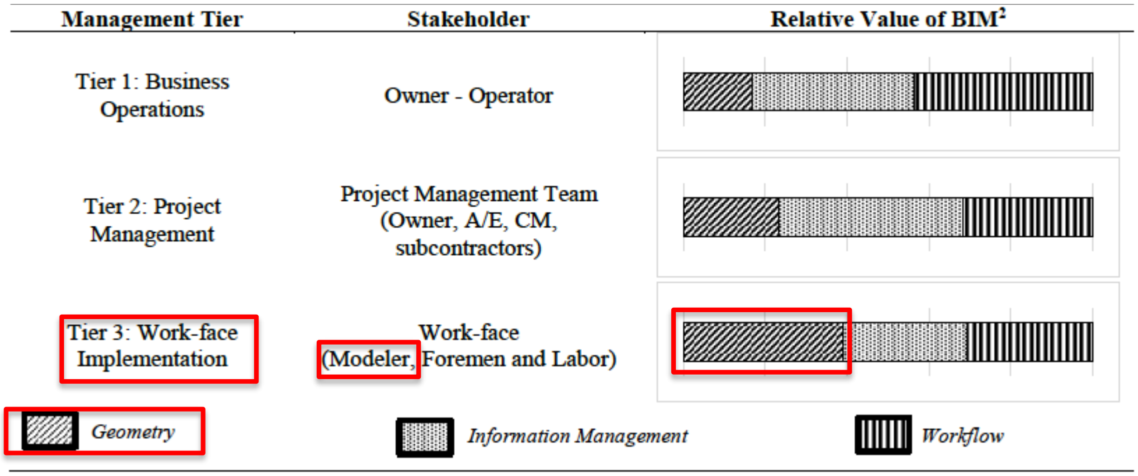


Figure 13: Relative Value of BIM^2 (adapted from Ghosh, 2015)

During the extent of the case-study research, the owner engaged in an integrated project delivery (IPD) method of contracting through the utilization of an integrated form of agreement (IFoA); in hopes of reducing costs, encouraging innovation through collaboration and ensuring timely delivery of capital equipment installation. While this method of contracting is said to be utilized by the project owner, through participant observation and document review, it must be noted that the contractual organization of parties engaged in this case study should continue to be classified as IPD-ish, as defined by Asmar et al. (2013) and Ghosh (2015) as it pertains to the case-study site. It should also be noted that throughout the duration of the case study the contractual environment remained the same but the level of participation and engagement of each of the stakeholders fluctuated against requirements and expected outcomes. This can also be seen detailed in an excerpt of an observation meeting dated May 12,2015, in Appendix C.

While time is seen as a critical component of the overall project success, the research focus was placed on understanding the accuracy of time-to-completion in order to meet the owner's first-to-market goals. In other words, the importance for duration in a project, from an owner's standpoint, relates to time-to-market issues wherein a specific manufacturing start date determines the construction timeline. If a project team completes construction early, the capital equipment/tools are not necessarily going to be on-site and ready for installation. Therefore, an early finish is not perceived as valuable of a proposition as an on-time finish from an owner's standpoint. In essence, reliability in scheduling is more important than early completion when dealing with a manufacturing process. This understanding of project schedule importance was discovered during initial steering committee meetings and un-structured interviews with owner's representative team members.

This viewpoint for project turnover is taken instead of a more traditional approach to scheduling and project duration wherein early completion has the power to dictate success for a project team. This is important to note in that the reframing of time in this project environment can allow for a restructuring of management processes and introduce new and more rigorous planning phases to the overall schedule. This ensures accuracy in the delivery timeline of the facility. This viewpoint also challenges the notion of the standard IPD contract where shared profit pools from early project turnover become incentive for innovation and cooperation amongst project team members.

Contracting, technology and integrated processes are tools that are utilized by the owner to structure and allocate risk to the project stakeholder best able to control the risk and provide the most value to the project. This idea also expands upon the IPD-like nature of the contractual relationships between the parties. As no party is fully capable of bearing all the project risks, the total risk must be divided amongst the stakeholders in manageable components with overlap for buffer. The various tools and processes that were mandated by the owner and observed by the research team are seen as a response to lessons learned on past projects and the continued congestion within the subfab environment during each subsequent renovation phase of their facility. Ultimately, the owner is concerned with safety and productivity for timely project turnover, which lends towards the originally posed question of “How do we reduce on-site headcount?” In response to this inquiry, the research restructures what was asked to more holistically relate to the owner’s total project goals. After a series of initial observations and unstructured interviews, the following problem statement was developed:

Research Team's Problem Statement: "How can we begin to optimize on-site headcount through the utilization of BIM and prefabrication techniques?"

Section 3.2 - Participant Observation and Team Dynamics

Site integration through regularly scheduled observations. Initial observations were undertaken utilizing weekly BIM PIT meetings on-site as a forum for open conversations regarding ongoing installation and conversion projects and innovation. Representatives of each trade on site attended the weekly meetings: mechanical, process piping, electrical, and structural (base-build), as well as an owner's representative and the site-wide BIM coordinator. Notes were consistently taken by the researcher while attending these meetings and supplemented by owner's meeting minutes, which were sent to the entire team. These notes can be found in Appendix B. The meeting notes were used to identify trends in discussions as they coincided with the timing for various ramps in construction operations.

Initial Year 1 follow-up questionnaires. After attending weekly BIM PIT meetings for several months and prior to engaging in modeling workface shadowing for direct observations, a series of surveys were administered to the project team. Full versions of these surveys can be found in Appendix C. The intent of the surveys was to begin formulating a study platform for data gathering. The distributed surveys enabled the collection of baseline data from different project participants related to their previous experience with BIM and semiconductor manufacturing facility construction. The responses to the surveys served as a baseline from which responses from subsequent surveys could be compared and analyzed. This comparison enabled conclusions to be drawn related to the impacts of various processes on participant's perception. One of the surveys that was given was a process validation survey intended to present the final year one process map to all project team members (including the prefabrication modeling workface) simultaneously. Its purpose was to gain further validation of processes in place or begin to identify discontinuity with the actual modeling for prefabrication process. After 6 months of observation of the initial workflow, it was crucial to understand if the new process had taken hold on site or if there were still embedded issues within the workflow. The overall process map was provided to 16 on-site team members in hardcopy, print format. While a sample size of 16 is not seen as statistically significant for a traditional population, this sample size related to a large component of the case-study site and therefore is able to be analyzed with local accuracy and later interpolated for scalability. The researcher explained the overall notation for process mapping and answered specific questions regarding process map interpretation prior to allowing the team members to engage in a review and comment period for the provided process map.

This initial survey became the vehicle from which more pointed questions were designed regarding the use of various tools for existing conditions capture and use cases for possible automation processes which could be interjected into the workflow downstream from information creation. The process map can be seen in Figure 14. This was the process map that resulted from year one studies. It was revisited by the project team and ultimately commented on by four trade modelers, four BIM-coordinators and three management level personnel equating to a 68% response rate within the sample group. A larger version of the process map can be seen in Appendix A. Specific comments on the existing process map, by respondent type, can be seen in Appendix B.

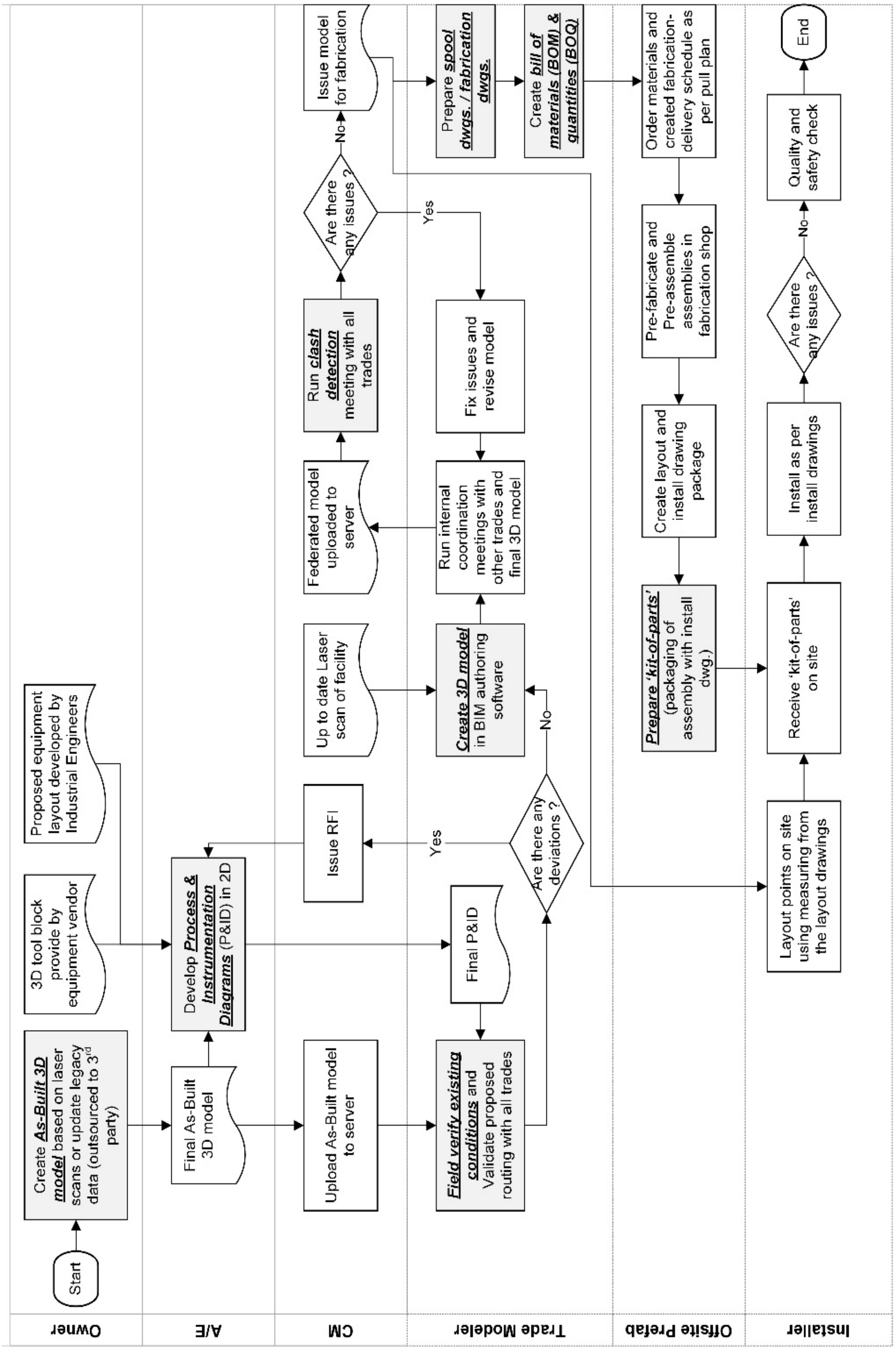


Figure 14: Current-State Process Diagram (adapted from Ghosh, 2015)

Following the initial process-mapping survey exercise, the author engaged in a qualitative study of the notes and markups provided by the respondents on each hardcopy of the process map survey. In order to make sense of the responses and comments on the process map survey without directly engaging in a conversation with each respondent, the researcher broke apart the hardcopy surveys into components and engaged in distilling the provided information into themes via a qualitative study matrix. This resulted in the creation of a research matrix which broke apart the overall process map into five categories of information:

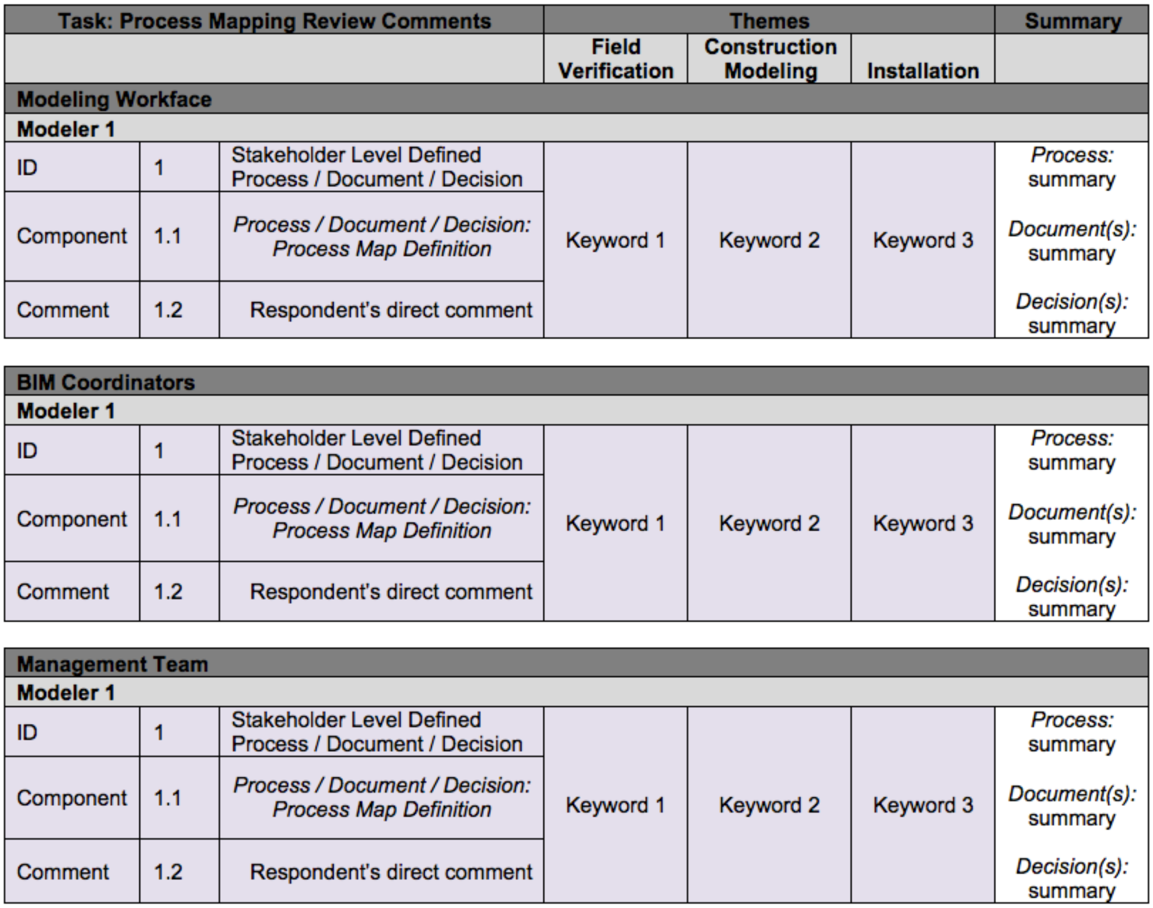
1. Respective stakeholder categories identified within the various swim lanes of the process diagram (Owner, A/E, CM Trade Modeler, Offsite Prefab and Installer)
2. Process-mapping notational elements defined within the current state process map (Process, Document and Decision)
3. Themes relating to the simplified components of the modeling for prefabrication project lifecycle (Field Verification, Construction Modeling and Installation)
4. Keywords which were identified by the author (keywords were pulled from BIM PIT Meeting themes/topics and notes). These are words that were recognized as repeat words in more than one BIM PIT Meeting. A sample can be seen in notes found in Appendix C. Bolded words in the notes represent a word or theme that has repetition in two meetings. Highlighted words in the notes represent a word or theme that has repetition in more than two BIM PIT Meetings. Words in red denote topics or categories of discussion which were highlighted in more than 3 instances during meetings. Words in italics denote an important discussion regarding existing processes (a sample of these notes from which keywords were pulled can be found in Appendix C).

5. An overall summary of findings simplified into descriptors relating to a particular process, document or decision in the current state process map.

Each survey was reviewed systematically as follows:

- Step One: Identify area of markup or comment by respondent and identify the stakeholder swim lane wherein the comment is located
- Step Two: Identify the component of the process map which has been commented on and define the element as a process, document or decision
- Step Three: Identify the verbiage and comment/response from the respondent and directly insert the comment verbiage into the research matrix without interpretation or paraphrasing
- Step Four: Identify the comment theme(s) (Field Verification, Construction Modeling, Installation)
- Step Five: Identify keyword(s) relationships within the respondent comment and place the keyword(s) in the corresponding theme category
- Step Six: Summarize the comment utilizing keyword(s) and component definition (Process, document or decision)

Ultimately, this matrix was utilized to systematically distill various forms of participant comments related to the current state process survey into a simple summary. The raw, matrix format can be seen in Figure 15 and the final qualitative review matrix can be seen in Appendix B.



Task: Process Mapping Review Comments			**Themes**			**Summary**
			Field Verification	**Construction Modeling**	**Installation**	
Modeling Workface						
Modeler 1						
ID	1	Stakeholder Level Defined Process / Document / Decision	Keyword 1	Keyword 2	Keyword 3	*Process:* summary *Document(s):* summary *Decision(s):* summary
Component	1.1	*Process / Document / Decision: Process Map Definition*				
Comment	1.2	Respondent's direct comment				
BIM Coordinators						
Modeler 1						
ID	1	Stakeholder Level Defined Process / Document / Decision	Keyword 1	Keyword 2	Keyword 3	*Process:* summary *Document(s):* summary *Decision(s):* summary
Component	1.1	*Process / Document / Decision: Process Map Definition*				
Comment	1.2	Respondent's direct comment				
Management Team						
Modeler 1						
ID	1	Stakeholder Level Defined Process / Document / Decision	Keyword 1	Keyword 2	Keyword 3	*Process:* summary *Document(s):* summary *Decision(s):* summary
Component	1.1	*Process / Document / Decision: Process Map Definition*				
Comment	1.2	Respondent's direct comment				

Figure 15: Qualitative Review Matrix

Final analysis of the qualitative study led to the creation of a Keyword Frequency graph that enabled a quick visual basis for understanding of problem areas within the current process. This understanding enabled further research questions to be formulated and more deliberate questions to be framed for research tools such as surveys, structured/unstructured interviews and PIT meeting discussions. Figure 16 depicts the final keyword frequency results of the qualitative study related to the process mapping survey.

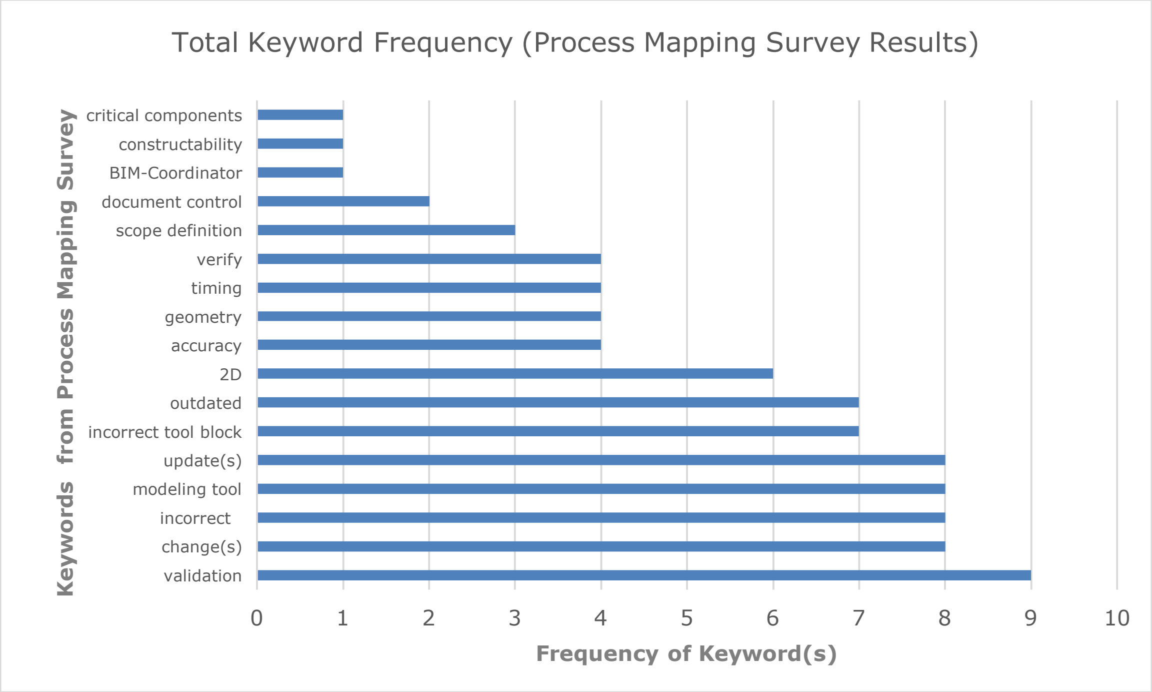


Figure 16: Process Mapping Survey - Keyword Frequencies

The keywords that are shown above were spread across three different themes: Field Verification, Construction Modeling and Installation. These themes encompass the three main categories of processes that take place in order to successfully model for prefabrication with field accuracy. Each of these keywords was defined by the researcher through examination of internal notes and PIT Meeting minutes. The keywords identified directly relate to subjects and conversational topics at various points in the research. A breakout of keywords by theme category can be seen in Figure 17. The initial process-mapping survey was broken down further into respective respondent group types and can be seen in Figure 18.

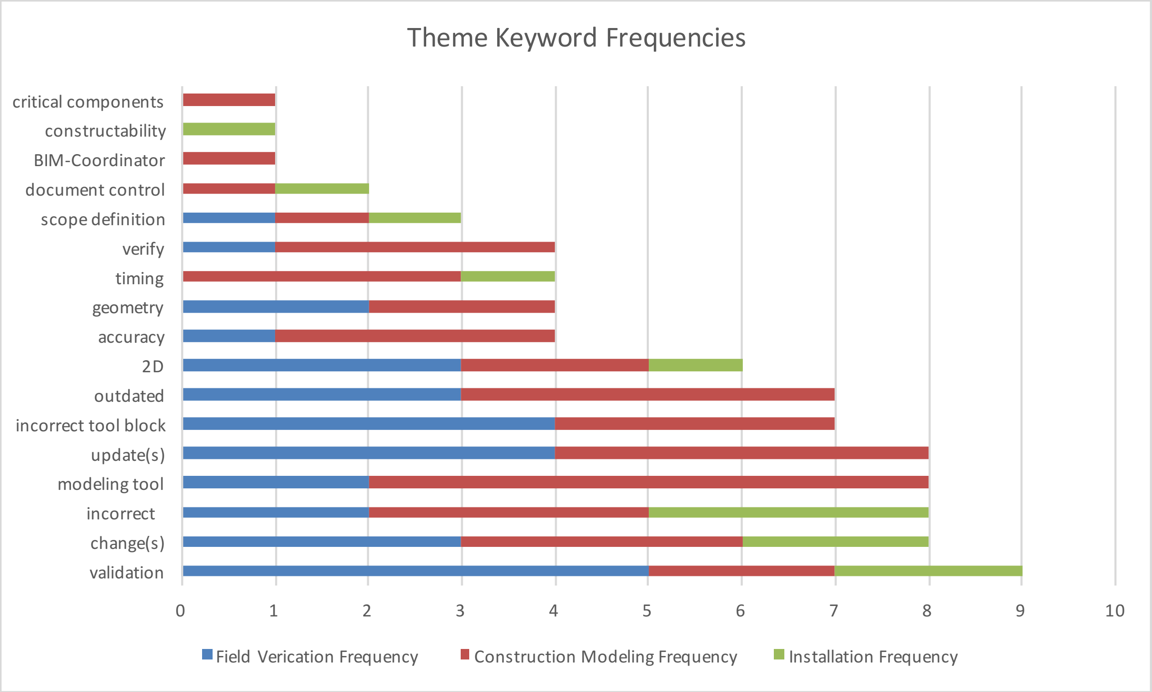


Figure 17: Process Mapping Survey - Theme Keyword Frequencies

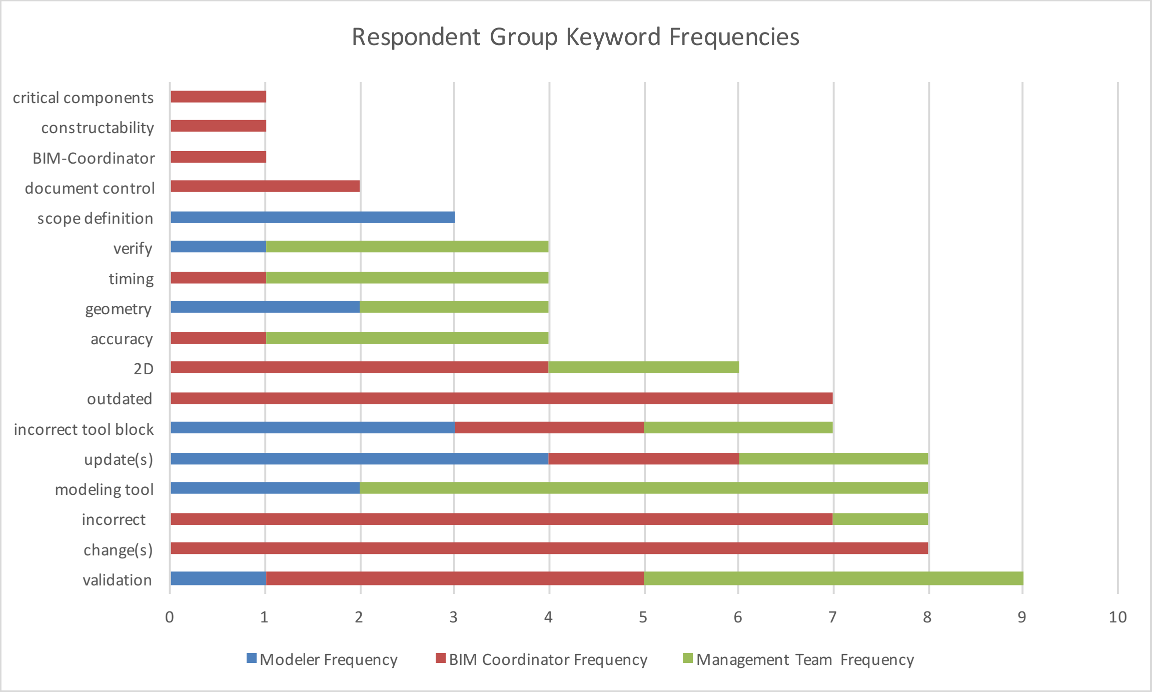
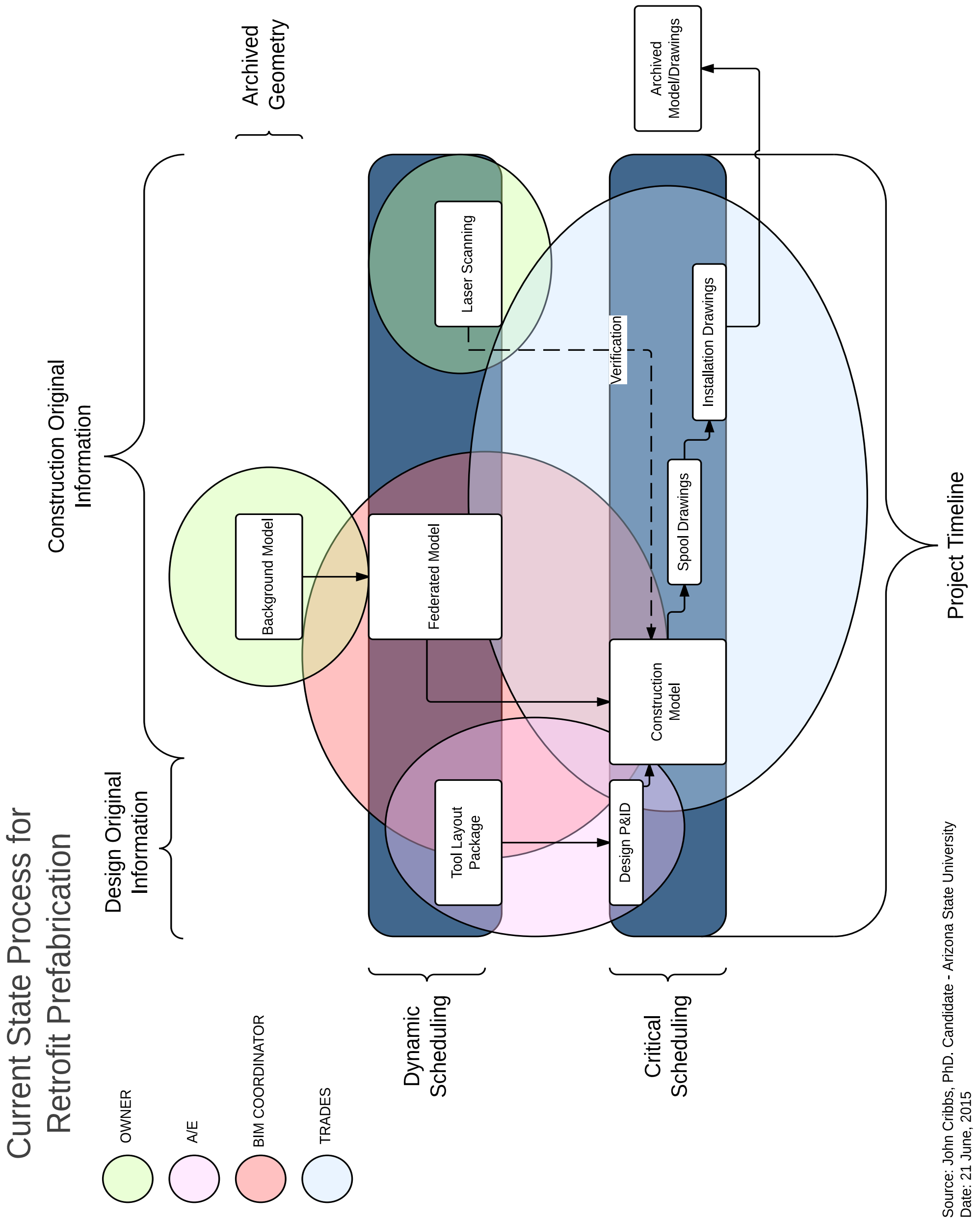


Figure 18: Process Mapping Survey - Respondent Group Keyword Frequencies

Section 3.3 - Current State Process Definition

Upon completion of the first year research by Ghosh (2015), a validation period ensued regarding the proposed workflow developed as an outcome of her research. The next steps for continuing the research efforts were to understand deviations from the proposed/validated workflow as defined in the original research presented by Ghosh (2015) to further message the waste in the system. Following analysis of the initial survey results, a revised current state workflow process diagram for Building Information Modeling as a construction tool for prefabrication efforts was developed. The revised current state workflow (Figure 19) was determined through direct observation of the modeling workforce and BIM management teams for the various trades. This was the first step to gaining an understanding of the implications of work-face planning on modeling productivity for prefabrication and the opportunities for advancing the current state of BIM use on site. This workflow diagram is a revised version of the year-one process map presented by Ghosh (2015) and intends to focus more on geometry and identifying the breaks in the process as identified in the original site survey and site observations.



Source: John Cribbs, PhD. Candidate - Arizona State University
Date: 21 June, 2015

Figure 19: Current State Process for Retrofit Prefabrication

The current state diagram can be broken into 3 components, which are then overlaid against the total project timeline:

1) Scheduling
    a. Critical Scheduling is currently identified as the modeling schedule for prefabrication of components for the tool install/conversion scope of work. This is inherently reactive in nature and introduces bottlenecks for content generation and delivery based on the traditional methods of flattening geometrical information for comparison and addition of more detailed content for review. As a result of reactive scheduling, additional milestones are introduced into the overall schedule for deadline matching and coordination. This type of scheduling has introduced misunderstood and artificial modeling durations into the overall project timeline.
    b. Dynamic Scheduling is currently identified as the content creation portion of the schedule and allows for scenarios in which negative float can be introduced to the schedule based on excessive design durations and a reactive construction schedule for critical deadline matching.
2) Geometry
    a. The current state process utilizes a multi-modal (2d & 3d) approach to the representation of geometry and introduces information translation bottlenecks into the overall process. The process begins with the creation of a 2-dimensional design package for review by the modeling team and identification of prefabrication scope of work at a trade level. At that point the 2-dimensional information is translated into a 3-dimensional state via BIM and used for trade coordination of routing. Once the 3-dimensional information has been released for fabrication, a detailing process ensues in which the model is again flattened into a 2-dimensional state via spool

drawings, or shop drawings, for use in a fabrication facility. This information is then translated again into a simplified 2-dimensional state as an installation package (coupled with fabrication drawings for in-depth detail of individual component assembly). All of this data is then handed over to the owner for archival in a database format once installed. Usually the 3-dimensional geometry has been stripped of all semantic detail and grouped into a generic solid whereas manipulation at a later date becomes nearly impossible without recreating the geometry.

i. Design Original Information will exist in any process, as that is the function of design. In the observed current state, design original information is introduced into the workflow as a set of 2-dimensional drawings and matrices for review and replication by the trades in a 3-dimensional format (as mandated by the owner).

ii. Construction Original Information - In order to create a prefabrication model, construction information pertaining to the scope of work must be input for representation in a 3-dimensional format for coordination and routing visualization, and all construction manufacturing attributes must be assigned as detail to begin the prefabrication process once the routing has been verified as clash-free during a coordination meeting. This is repetitious in nature and the information created is not currently captured correctly for use at a later date, thus introducing a dead-end process in which similar construction content is recreated throughout every project – Construction Original Information. A state of constant origin has been observed in which reproduction and revisiting of existing conditions ensues at the start of every project. This ultimately leads to individual stakeholder workarounds at each level for shortcutting the overall process which in turn moves away from the idea of standardization within lean theory and introduces an invisible layer of error into each project (breakdown in project controls).

3) Verification & Validation
    a. The current state process introduces a series of verifications throughout the duration of a tool install/conversion scope of work and these verifications are often done without the knowledge of other stakeholders and are engaged for internal reasons. Laser scanning is utilized as a modeling tool and a verification tool for matching virtual geometry against field conditions. This tool becomes overextended to fulfill the following needs:
        1. Non-obtrusive existing conditions verification for design start
        2. Re-verification of changing conditions during detailing process
        3. Overlay for verification of Background Federated Model geometry
        4. Overlay for modeling within base-build geometry

Section 3.4 - Development of Observation Matrix

Following the initial development of a current state workflow, a follow-up survey was administered which intended to understand the different tools utilized for existing conditions capture for upfront modeling as well as inconsistencies within the existing conditions data throughout the modeling for prefabrication process. The survey was designed utilizing a rank-order format. The main components of the survey were split into three categories: Base-Build Model Geometry, Laser Scanning and Field Related Capture. The survey design can be seen in Appendix A. The survey was administered to 16 total team members and received an 87.5% response rate.

The findings of this survey, through comparative analysis, showed disconnect between various stakeholders and team members in the proper utilization and timing of implementation for different BIM tools. This finding filtered across each component of analysis and ultimately aided in creating a more focused approach to observations regarding the usage and timing of implementation for various BIM tools. Graphs depicting minimum and maximum rank-order values for an ideal state, as defined by respondents ranking existing tools and processes in order of importance, can be seen in Figures 20 and 21.

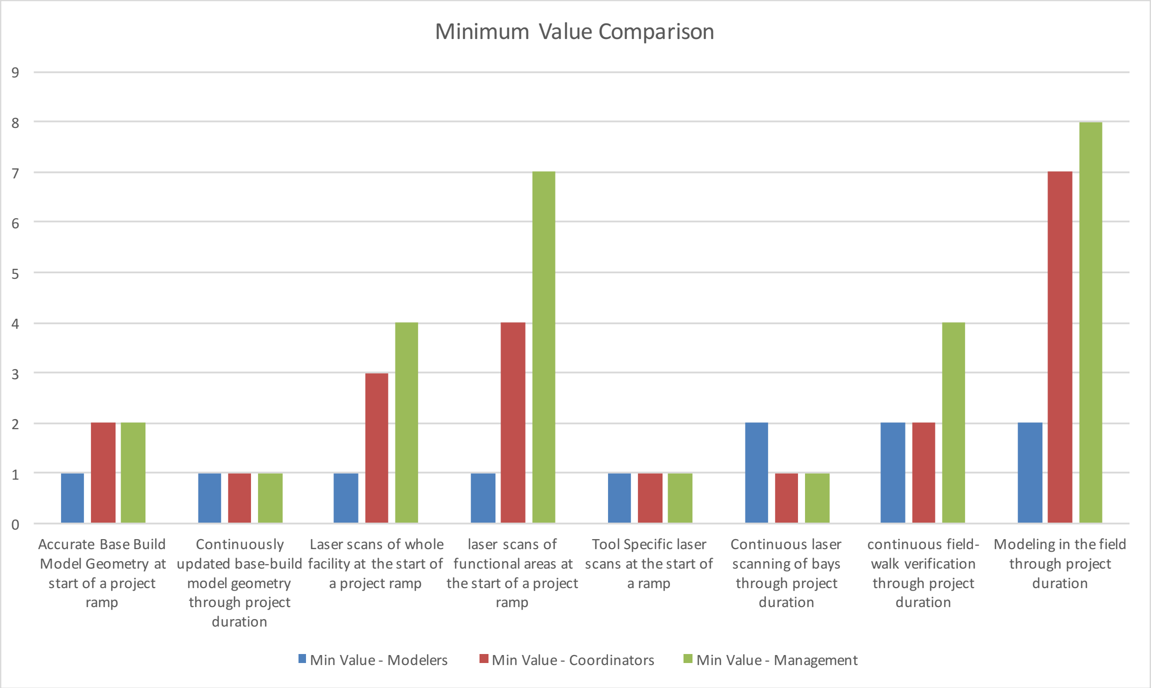


Figure 20: Ideal State Minimum Value Comparison

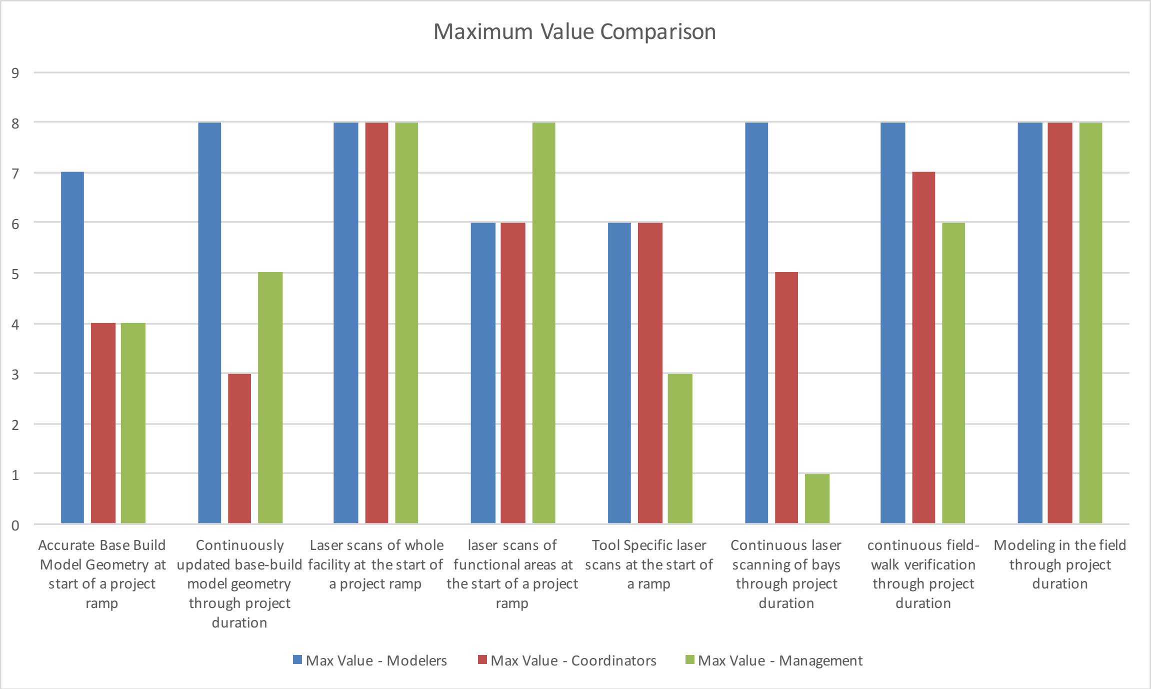
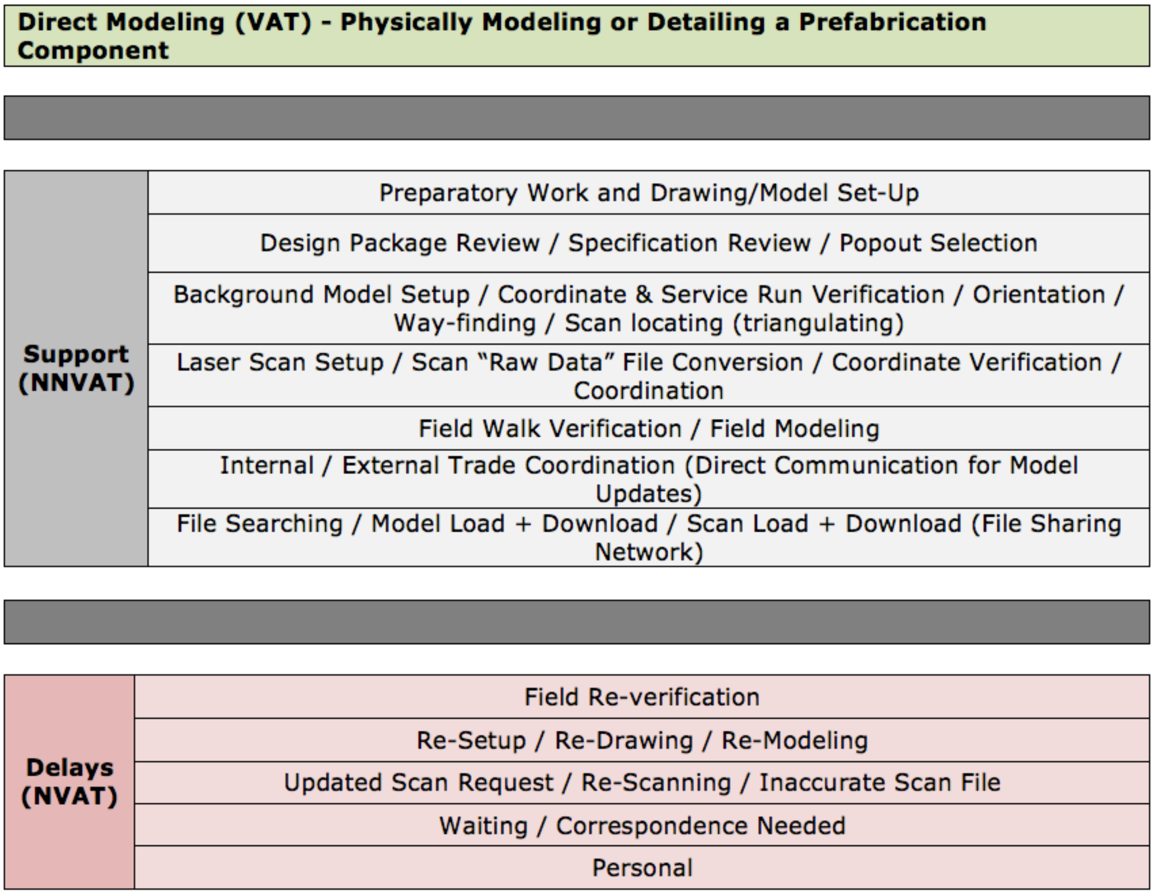


Figure 21: Ideal State Maximum Value Comparison

During the initial direct observation period, in which the current state workflow was identified, a categorical separation of activities was identified via a process-based BIM activity timeline. This categorical separation qualitatively classified modeling activities into a three-tiered matrix with twelve sub-categories defining the particular activity (Figure 22). The separation of activities for classification during observations also began to help illustrate the processes and tools utilized, in turn helping to identify what information is needed and at what time during the modeling process. In the current state workflow for prefabrication, a series of information transfers occurs between 2-dimensional drawing and 3-dimensional model media. It can also be seen in the current state workflow diagram that two separate tools are utilized to inform the creation of construction models for prefabrication: laser scans and a federated BIM. It is hypothesized that this information can be leveraged to lean out the BIM activity and information capture/transfer process.



Direct Modeling (VAT) - Physically Modeling or Detailing a Prefabrication Component

Support (NNVAT)	Preparatory Work and Drawing/Model Set-Up
	Design Package Review / Specification Review / Popout Selection
	Background Model Setup / Coordinate & Service Run Verification / Orientation / Way-finding / Scan locating (triangulating)
	Laser Scan Setup / Scan "Raw Data" File Conversion / Coordinate Verification / Coordination
	Field Walk Verification / Field Modeling
	Internal / External Trade Coordination (Direct Communication for Model Updates)
	File Searching / Model Load + Download / Scan Load + Download (File Sharing Network)

Delays (NVAT)	Field Re-verification
	Re-Setup / Re-Drawing / Re-Modeling
	Updated Scan Request / Re-Scanning / Inaccurate Scan File
	Waiting / Correspondence Needed
	Personal

Figure 22: Direct Observation Matrix

Finally, regarding the Level of Quality in a BIM and subsequent Level of Detail (LOD) for prefabrication, it was noted that while a formal QA/QC checklist exists at the trade level, the utilization of this checklist process is inconsistent between modelers and related prefabrication models. At an inter-trade coordination level, the process for assessing the Level of Quality in BIM is relative to the accuracy of identified critical routes and related systems components. The Level of Quality is therefore driven by the needs for meeting coordination deadlines and BIM coordinator requirements for inter-trade coordination. It is not consistently reflective of internal (to the trade) Level of Quality or Level of Detail requirements for efficient and effective prefabrication of a system. This is important because it furthers the discussion regarding the introduction of placeholder geometry for meeting owner driven deadlines. This process creates a detached model scenario in which a coordinated model is not always the model that is sent to the fabrication facility and ultimately installed.

Systematic approach to modeling – The breakdown of the observation matrix highlighted in the previous section inherently lends itself to breaking apart components of the overall modeling process into different systems. Each of those systems can be analyzed in isolation. The most intriguing system within the overall process is the utilization of existing conditions data for routing design modeling. The observation matrix purposefully separates Background model utilization for design routing from laser scanning and field modeling. This separation initially stemmed from a weeklong direct observation period supplemented with survey data assisting in the definition of how tools were idealized for use by the modeling workforce. Figure 23-25 introduce a breakdown of 16 responses to questions regarding ideal state usage of geometry, point clouds (laser scans) and field walks. This data is a component of a survey that was given to 16 team members on-site at an earlier date. This data begins to further the disparity amongst team members in how to accurately begin the modeling for prefabrication process. This also further enforces the initial hypothesis regarding geometry and upfront process analysis for on-site headcount improvement.

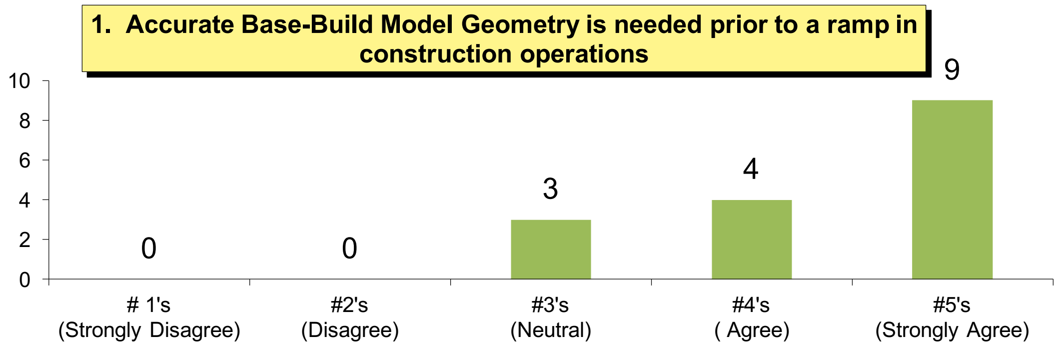


Figure 23: Base-Build Model Likert Scale Response Distribution

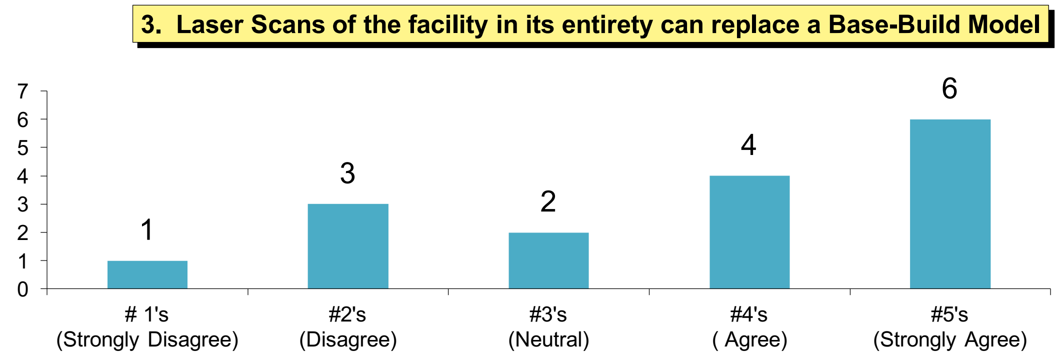


Figure 24: Laser Scan Likert Scale Response Distribution

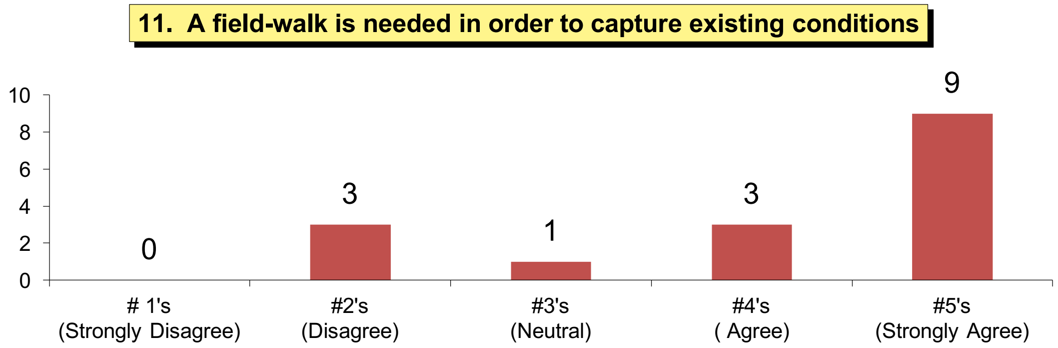


Figure 25: Field Walk Likert Scale Response Distribution

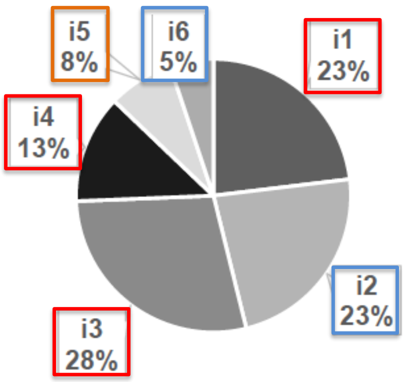
Section 3.5 – Furthering a Hypothesis

After an initial investigation into the prefabrication process for specialized equipment and state-of-the-art techniques for automated prefabrication and as a result of initial findings from site observations and interactions, the initial objective of the research continuation was generated. The research objective to create and implement an optimized workflow at the prefabrication workface (fabrication task level), was re-assessed. It was at this point that the researchers decided to focus solely on upstream construction supply chain information in the form of a Building Information Model. BIM was mandated on the project site for prefabrication of tool install components and services and it was hypothesized that BIM acted as an enabler for successful and reliable prefabrication efforts. However, a disconnect was observed between site based activities and prefabrication needs.

Having an understanding of the current state of BIM use at the case-study site would allow the research team to assess the site-wide productivity rates and begin analyzing areas for improvement based on an ideal state supply-chain model and provide recommendations for future use and implementation. This will allow the introduction of a model-based delivery system for a positive impact on site-wide construction productivity. The hypothesis remains that the prefabrication process is positively enhanced through the use of a reliable model-based delivery system, in a retrofit environment.

Hypothesis - Observations of various modelers across each of the main trades on-site, (electrical, mechanical and process piping) led to the conclusion that redundancies in the process were causing delays and unforeseen complications throughout the project BIM lifecycle. It was hypothesized that the introduction of a dynamic modeling process for retrofit prefabrication – prefaBIM - will help to streamline the BIM process at the modeling work-face and ultimately lead to reliable assumed geometry up-stream and in turn introduce a productivity increase of the install teams down-stream through accuracy and reliability of geometric and semantic information. This hypothesis is rooted in the findings of Ghosh (2015) in regards to interruptions identified on-site during the installation workflow, particularly interruption i1 (inconsistencies in as-built 3d model and existing site conditions), i3 (Clash on site after installed per model), and i4 (Waiting for communication from PM, BIM modeler, foreman). It was hypothesized by the research team, that these interruptions can be remitted through the proper utilization of reliable geometry and a trusted process. Once these areas are addressed and the new process has been validated as having a positive impact, it is then hypothesized that i5 (non-value added time spent on avoidable manual work due to lack of technology use) can be addressed by further implementing the ideal state workflow for dynamic modeling ultimately resulting in the implementation of a model-based delivery system for retrofit projects in which manual work can be transferred into automated processes and expedited workflows introduced. This is illustrated in figure 26.

Focus
- i1 – inconsistencies in as-built
- i3 – Clash on site (after installed per model)
- i4 – Waiting for communication



Side Effect
- i2 – Rework on prefabricated components
- i6 – Incomplete scope of other trade / scope not reflected in federated model

Process Improvement
- i5 – Non-value added time spent on avoidable manual work due to lack of technology use

Figure 26: Field Interruptions due to BIM (adapted from Ghosh, 2015)

Section 3.6 – Conclusions

The initial phase of research utilized participant observation, structured/unstructured interviews, designed surveys and designed direct observations via a structured process-based matrix rooted in compiled data analysis and test-period observations. Each of these research methods was utilized to answer the original research question **R1** (How does the initial process of modeling impact the number of workers on site during construction?). This question will continue to be analyzed in further chapters but has been initially visited through qualitative review of the process mapping survey and rank-order data analysis. The findings in these studies resulted in an understanding that interjecting modelers into the field for field verification, laser scanning and modeling may be adding to the headcount congestion on site and further driving down productivity due to inconsistent processes for modeling across the site.

Question **R1.1** (what is the current work process for prefabrication and who are the stakeholders in the process?) was explored through process-map validation survey analysis as well as direct observations. While the stakeholder categories remained the same as defined by Ghosh (2015), the extension component of the research undertaken by the author dove further into the substructure of stakeholders in order to understand the continuity and/or breakdown in geometrical needs and understanding between the modeling workface whom ultimately creates the content which will be constructed, the coordination team responsible for analyzing site wide activities and supporting the modeling process through consistent and reliable data processing and the management team ultimately responsible for meeting stringent timing and budget constraints.

Question **R1.2** (How does the Level of Quality in BIM correspond with the value added amount of prefabrication delivered and installed on site?) was explored through the lens of qualitative analysis regarding a process mapping review survey. This survey introduced potential breaks in the current state workflow that ultimately impact the timing and accuracy of prefabrication and installation.

Question **R1.2.1 (**how do trades currently measure/enforce the Level of Development (LOD) of BIM's used for prefabrication?) was explored through internal documents review and weekly PIT meetings. This question became embedded in the design of the observation matrix through supplemental notes and later analysis of re-modeling time due to improper or insufficient data and timing for model release for prefabrication.

CHAPTER 4

EXPLORATION: DEVELOPMENT OF A MODEL-BASED DELIVERABLE ROADMAP

The purpose of this chapter is to decipher and deconstruct the datasets that were collected during various site observations and direct modeling observation studies. Section 4.1 – Background: BIM as Enabling Workflow further enforces the research direction in relation to Building Information Modeling and sets the stage for analysis of direct observation data. Section 4.1.1 presents the aggregate, site-wide time utilization rates for modeling for prefabrication. Subsections 4.1.2. and 4.1.3. break apart aggregate data into trade based productivity metrics for mechanical/process piping and electrical trades respectively. Comparative analysis and discussion is introduced in each subsection in order to investigate the relationship between existing conditions capture techniques, geometrical information translation and labor time utilization rates at the modeling for prefabrication workface (modeling task level) for each trade. The following data analysis provides an in depth look at current state labor time utilization rates for modeling for prefabrication on the case-study site. The research methods highlighted in Figure 27 were utilized to set the groundwork for beginning to answer research question R2 and the subsets therein. However, these questions are ultimately answered in Chapter 5. Those questions are:

> **R2:** What is the effect(s) of a process intervention on BIM-for-prefabrication, in a retrofit environment, on modelers' time utilization during construction?
>
> > **R2.1:** What is the subsequent effect, or effects, of a process change on prefabrication supply-chain performance?

From the original research findings, BIM has the ability to offer several advantages for the construction supply chain including:

- Accuracy in prefabrication and hence reduced rework and waste

- Transparency in information sharing and communication
- Faster time to market by eliminating redundancy in workflows
- Predictability and risk management in the construction process (Ghosh, 2014)

This chapter explores how the research will clarify the prefabrication modeling implications on the above assumptions. It introduces a baseline modeling time utilization rate and measurement technique for process improvement comparisons.

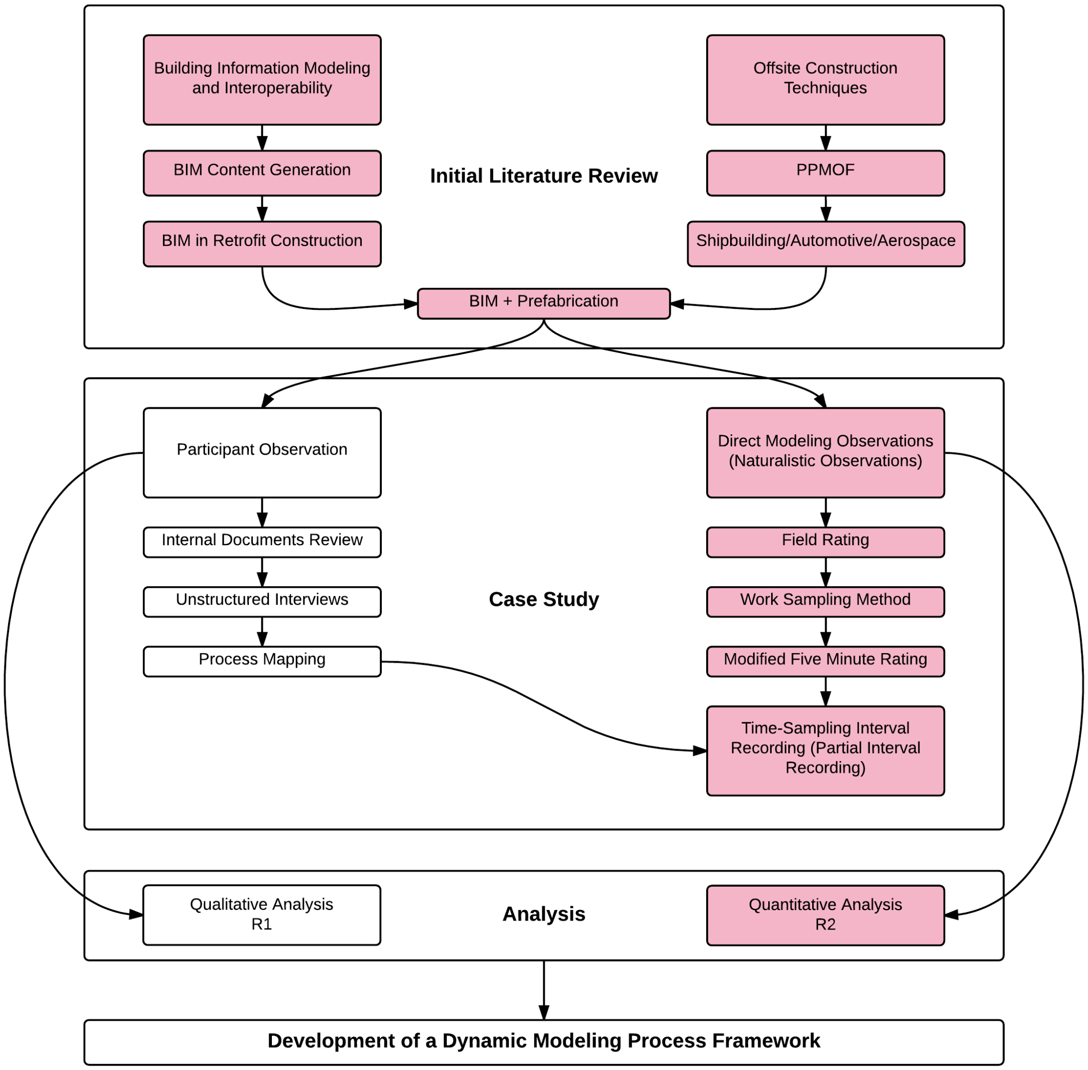


Figure 27: R2 Research Methods

4.1 Background: BIM as Enabling Technology Workflow

Site-wide case-study dynamics have changed dramatically over time and have traditionally mirrored industry trends in implementing construction technology solutions. The initial intent of the research study, as defined by the owner of the case-study facility, was to benchmark jobsite productivity rates for prefabrication and installation of prefabricated components against other industry leaders. This scope intended to identify areas of improvement within the process to realize similar cost and schedule savings as highlighted in recent industry-wide studies and surveys.

As briefly discussed in Chapter 3, the research approach changed direction from the initially outlined owner directive to focus more on how content is generated upstream to enable successful prefabrication and installation downstream in the supply-chain. This is in part due to the specialized nature of the construction process taking place on the case-study site and a lack of samples to benchmark against. It is also important to note that benchmarking against the average for the industry may not necessarily lead to the expected outcomes and results hypothesized by the owner (Daniels, 1952).

4.1.1 Aggregate Site Modeling Time Utilization Rates

Following the current state workflow diagramming exercise described in Chapter 3, the author engaged in a series of direct observations of modelers in their natural conditions. The research team had access to 7 modelers across 3 different specialty trades including: mechanical, process piping and electrical. The initial site observation data collection period ran from April 28, 2015 to June 17, 2015.

During this observation time period, the author utilized random timing techniques to create a schedule of observations between various modelers on-site. To further define the random scheduling techniques, each modeler was given a specific number (for anonymity) and each day was given a specific time-value for maximum and minimum durations per observation session. The numbers representing time-values for each day ranged from 1-6 on Monday, Wednesday and Thursday, and 1-10 on Tuesday and Friday. Each number represents a different length of time, in multiples of 10 minute intervals. Tables 8-10 present this information in a tabular format.

This format for randomized scheduling was utilized throughout the observation period and all subsequent observations on site for validation. The reasoning for utilizing a process such as this was to create an observational technique that reduced the possibility for modelers to recognize time patterns in observations, leading to the Hawthorne effect skewing the overall data (McCambridge, Witton, & Elbourne, 2014). Also, through randomly allocating control measures for observations, the research team intended to introduce a higher statistical probability for ensuring that the total of all observation windows would capture each variable defined in the observation matrix while occurring in its natural state.

During the development of the current state process map described in Chapter 3, a categorical separation of activities, modeling tool usages and processes was identified. It was observed that each identified and separated activity, or task, would occur in durations that would last 5-minutes or more on average. As such, the data points that were collected were subsequently defined as 5-minute intervals. Over the duration of each observational period, a stopwatch would run continuously with alarms set for every 5-minutes. The alarm would signify when a data point would begin and end. Observations would begin at the start of the alarm and end when signaled. The observations would be noted and the data point would then be organized within the observation matrix by category. For instance, when a modeler was observed to be downloading the latest model for routing coordination and use in the modeling process, this time would be placed under the "File Searching / Model Load + Download / Scan Load + Download (File Sharing Network)" category. Furthering the example, when a modeler was observed to be engaging in direct chat windows, emailing, or physical discussions with a modeler or model coordinator regarding the placement of a routing condition or an existing condition within the facility, this data point would fall under the "Internal / External Trade Coordination (Direct Communication for Model Updates) category. Delay data points for instance, were categorized when a modeler was observed to be physically re-verifying a field condition that has already been provided to them in a previous drawing package (2D) format or laser scan format. Also, through the consistency in observations, it was noted that the modeler would engage in re-designing tool routes that had previously been completed due to a trade conflict or miscommunication between modelers (lag time in model upload, misplaced geometry, lack of communication regarding routing needs and requirements, etc.). While many of these remodeling scenarios were easily traceable during the direct observation study, various modelers would also make the re-modeling scenario known via internal trade conversation with management to rectify any issues in schedule that may arise from the re-modeling scenario. This method borrowed from the idea of the 5-minute rating (Dozzi & AbouRizk, 1993) utilized in lean construction theory and was subsequently modified to enable observations of a set of modelers, which had not been done before in this capacity.

Over the course of the 8-week period in which data was gathered, a total of 786 data points were collected via direct observation and another 252 data points were gathered via inter/intra-trade coordination meetings relating to the tasks and models that were under direct observation. A detailed log was also kept during the direct observation period for root-cause analysis at a later point in the research process.

Table 8:

Direct Observation Random Scheduling Matrix

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**
Min. Duration	10 mins.	30 mins.	10 mins.	10 mins.	30 mins.
Max. Duration	1 hour	2 hours	1 hour	1 hour	2 hours
Number Choices	1-6	1-10	1-6	1-6	1-10
Min. Starting Time	0 mins.	30 mins.	0 mins.	0 mins.	30 mins.
Max. Ending Time	60 mins.	120 mins.	60 mins.	60 mins.	120 mins.
Increments	10 mins.	10 mins.	10 mins.	10 mins	10 mins

Table 9:

Direct Observations Daily Increments Matrix

#'s	**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**
1	10 mins.	30 mins.	10 mins.	10 mins.	30 mins.
2	20 mins.	40 mins.	20 mins.	20 mins.	40 mins.
3	30 mins.	50 mins.	30 mins.	30 mins.	50 mins.
4	40 mins.	60 mins.	40 mins.	40 mins.	60 mins.
5	50 mins.	70 mins.	50 mins.	50 mins.	70 mins.
6	60 mins.	80 mins.	60 mins.	60 mins.	80 mins.
7	n/a	90 mins.	n/a	n/a	90 mins.
8	n/a	100 mins.	n/a	n/a	100 mins.
9	n/a	110 mins.	n/a	n/a	110 mins.
10	n/a	120 mins.	n/a	n/a	120 mins.

Table 10:

Total Direct Observations Data

Total Duration of Observations	**Total Duration of Meetings Observed**	**Average Observations per Week**
3930 Mins.	1260 Mins.	741.43 Mins.
65.50 Hours	21.00 Hours	12.36 Hours
786 Data Points	252 Data Points	148.29 Data Points

Referring to section 2.4 – Lean Construction Theory, the idea of Value Added Time (VAT), Non-Value Added Time (NVAT) and Necessary Non-Value Added Time (NNVAT) was borrowed from Lean Manufacturing to assist interpretation of the final data points that were collected. These three categories of time related to the observation matrix wherein Total Direct (VAT), Total Delays (NVAT) and Total Support Work (NNVAT) were defined as the categorical separations. Based on initial aggregate data, the value-added portion of a modeler’s day was observed to be 19% of total time. This portion of time represents the time spent directly modeling a component of a tool design that will eventually be prefabricated off-site and then installed within the fab and/or subfab of the facility.

The necessary non-value added time (NNVAT), or work that is needed to support any value-added time modeling, was observed to be 56% of total time. Support work covers design package review, model/drawing setup time, background model and/or laser scan file coordination and way finding, as well as any initial field verification and inter/intra-trade coordination efforts for modeling and the sharing of digital information (files / drawings / models / packages / etc.) through secure shared document control protocols. It is important to note that within the NNVAT section of the Modeling Observation Matrix, there is a categorical separation between time spent utilizing a 3-dimensional background model (existing geometry) and utilizing a point-cloud or laser scan file for coordination. This was done explicitly to highlight which tool is more important within a modeler's workflow for completion of a detailed model for pre-fabrication off-site; an accurate background model or updated laser scans of existing conditions. This purposeful separation relates back to the rank-order survey defined in Chapter 3 defining ideal tools and becomes the platform from which to further support the research hypothesis that geometry is the most important component of information for the modeling workface.

Finally, the wasted time (NVAT), was observed to be 25% of total time in a modeler's workflow. This suggests that essentially 81% (NNVAT + NVAT) of total time within the modeling workflow can be further analyzed to lean the process and introduce more streamlined approaches to gain more VAT within a modeler's workflow and processes. Figure 28 graphically depicts these percentages. Table 11 denotes the actual observed minutes allocated to each category.

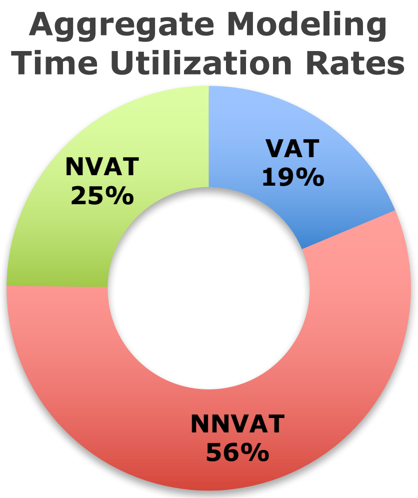


Figure 28: Aggregate Site Time Utilization Rates

Table 11:

Aggregate Site Time Totals Breakout

Total Direct	Total Support	Total Delays	Totals
735 mins.	2220 mins.	975 mins.	3930 mins.
18.70%	56.49%	24.81%	100.00%
12.25 hrs.	**37.00 hrs.**	**16.25 hrs.**	**65.50 hrs.**

Through the design of the observation matrix, support work activities were further dissected into individual processes. Each of these elements related to a process of gathering, communicating or deciphering a component of required information, in various forms; ultimately enabling the modeler to complete a construction model for prefabrication. This support work, or NNVAT component of time, becomes an area where bottlenecks in the overall modeling process begin to be discovered. Figure 29 breaks down the various support activities which take place within the scope of modeling for prefabrication. This categorization of activities also relates to the rank-order survey presented in Chapter 3 and focusses on two tools that are utilized for existing conditions capture. The purpose for breaking the data apart is to understand which technique for existing conditions capture is utilized more often in a modeler’s workflow: utilization of geometry in the form of a background model OR utilization of point-cloud data. It can be seen in Table 12 that modelers utilize a background model for coordination with existing conditions, way finding and coordinate verification (x, y, z coordinate location and measurements) 24.32% of the time as compared to 5.41% of the time for laser scans. This discovery supports the initial hypothesis regarding geometry and further validates the initial year one research done by Ghosh (2015), that geometry holds the most value in a modelers’ workflow. Overall, between the two tools depicting physical constraints and conditions (background model geometry and point-cloud data), a total of 16.6% of a modeler's total day, on average, is spent within a virtual representation of the facility being constructed. This ultimately equates to 1.67 hours, on average, per 10-hour workday. When focusing on the utilization of pure geometry, approximately 1.36 hours, on average, per 10-hour workday, is spent coordinating within a base-build model. The remaining third of an hour is spent utilizing laser scans for modeling. This is a large discrepancy in the utilization of time between the two tools and should be noted accordingly. It is also interesting to note, that during participant observation via the weekly PIT Meetings, discussions pertaining to laser scanning as the sole source of background information for modeling was a common theme amongst the management level for providing accurate facility conditions for the modeling workface. This notion proves to be counter-productive to the workflow needs of the modeling workface. This conclusion was drawn from direct observations in which it was discovered that the utilization of laser scan point cloud data was not the first source of existing conditions information which modelers utilized for the creation of tool routing design. This was confirmed through unstructured interviews with various modelers in which each stated that an accurate background model was preferred in order to expedite the process of modeling for prefabrication.

Communication is a large component of support work time for a modeler. Communication comes in many forms and fashions and can be seen within the trade itself, or amongst multiple trades attempting to work through modeling coordination issues. As a direct result of coordination conversations, an average of 1.5 hours per 10-hour workday is spent communicating internally or externally between modelers and/or management for accuracy within a prefabrication model.

Technology also comes with inherent bottlenecks due to processing speeds, intellectual property (IP) concerns when utilizing digital information and file format exchanges amongst others. This component of time was accounted for during direct observations. Nearly three quarters of an hour, per 10-hour workday, is spent uploading or downloading models and related data to shared servers for intra-trade coordination and model updates. This is purely a lag in the system due to current technological constraints on site but necessary for accuracy amongst the trades.

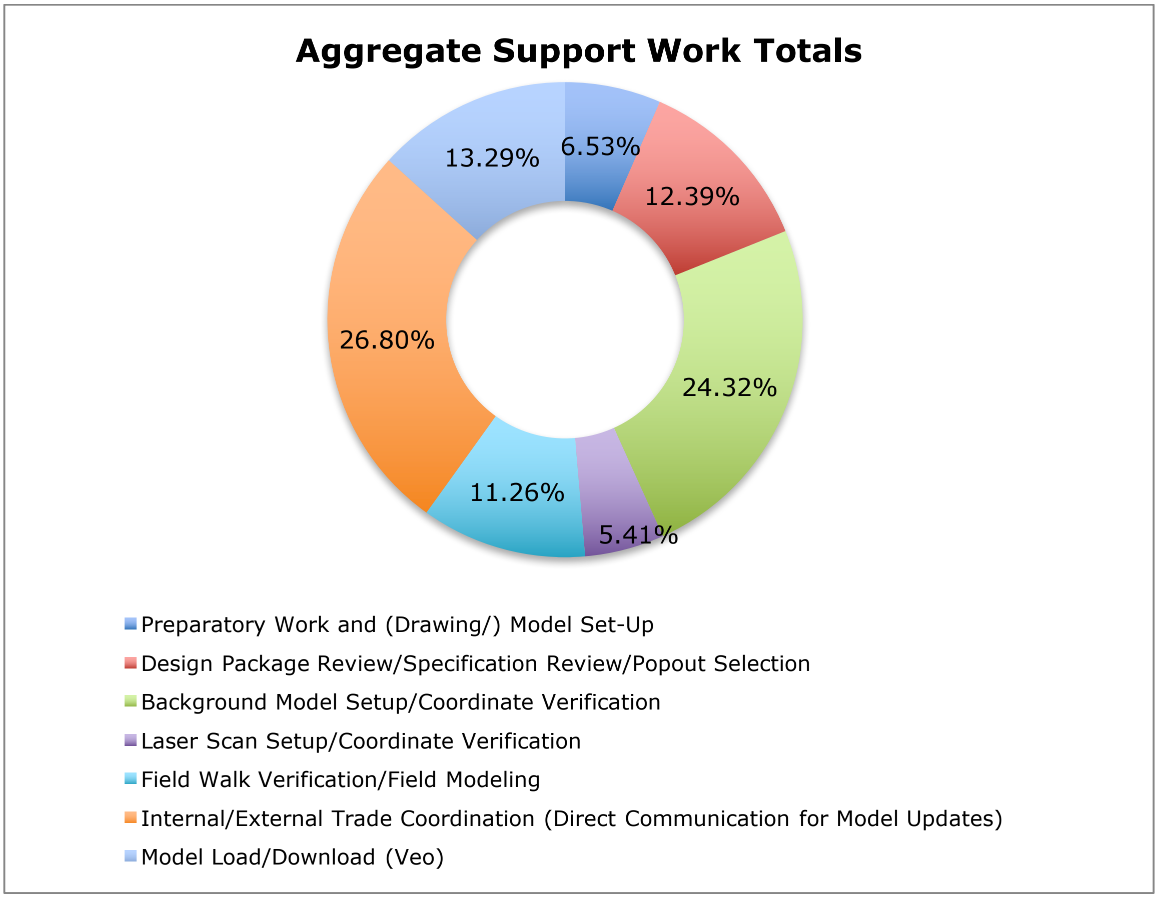


Figure 29: Aggregate Site Support Work (NNVAT) Totals

Table 12:

Aggregate Site Support Work (NNVAT) Time Breakout

	Minutes	**Hours**	**Total Percentage**
Preparatory Work and Drawing / Model Setup	145	2.42	6.53%
Design Package Review / Specification Review / Popout Selection	275	4.58	12.39%
Background Model Setup / Coordinate Verification	540	9.0	24.32%
Laser Scan Setup / Coordinate Verification	120	2.0	5.41%
Field Walk Verification / Field Modeling	250	4.17	11.26%
Internal / External Trade Coordination (Direct Communication for Model Updates)	595	9.92	26.80%
Model Load / Download	295	4.92	13.29%
Totals	2220	37.00	100%

Finally, the delays that were noticed in the system can be categorized as Non-Value Added Time (NVAT) and must be a focus for reduction when leaning out the overall process. Within the observation matrix, delays are identified as any type of rework due to incorrect or insufficient data, missing or inaccurate data from which to begin modeling and any personal breaks that are a result of a standard work day. Figure 30 breaks out the delay’s observed on site. An area of focus when breaking out the delay totals is related to the “Field Re-verification” category. This relates to the owner’s posed research question regarding “reducing on-site headcount.” “Field Re-verification” refers to any time a modeler was observed away from their computer and in the field measuring a known routing condition. This activity was observed to ultimately increase the headcount in the fab/sub-fab environment for the duration of the re-verification process. While this does not seem like a large component of site headcount, simply removing this variable from the total headcount is a step towards optimization of workers on-site. The hypothesis furthers this notion when the modeling variable is removed from on-site conditions and accurate models are enabled through the existence of accurate background geometry. Accuracy in prefabrication modeling should result in better utilization of on-site headcount ultimately leading towards leaning out installation crews to only the necessary members for completion of installation work. It was also observed that due to inaccurate existing conditions models from which to begin the modeling process, the modeling workforce engages in the creation of placeholder geometry. This geometry intends to reserve space within the fly zone above a tool's support equipment or below the tool footprint so as to claim an area in space for modeling coordination purposes. In essence, this is the modeling workforce engaging in a first-come first-serve modeling scenario which leads to miscommunication, inaccurate modeling at the outset of a project and a series of re-modeling processes to meet deadlines. Highlighting the miscommunication issue, when a modeler creates placeholder geometry for a particular route, this essentially allows them to enter a clash detection meeting (schedule milestone) and discuss the constraints of the particular routing environment as it exists with the placeholder model. This route is then signed off on by the model coordinator as an acceptable and clash-free route and as such, the milestone and deliverable requirements are met from an owner's schedule standpoint. Following the milestone event, changes in the route are made by the contractor in an "at-risk" scenario. It was observed that this would cause coordination issues between the trades as the detailed route information changes from milestone signoff to actual detailed model for prefabrication ultimately resulting in coordination error and remodel/redesign taking place. This re-modeling and re-verification process can be seen in Table 13 and equates to nearly 1.4 hours, per 10-hour modeling workday on average.

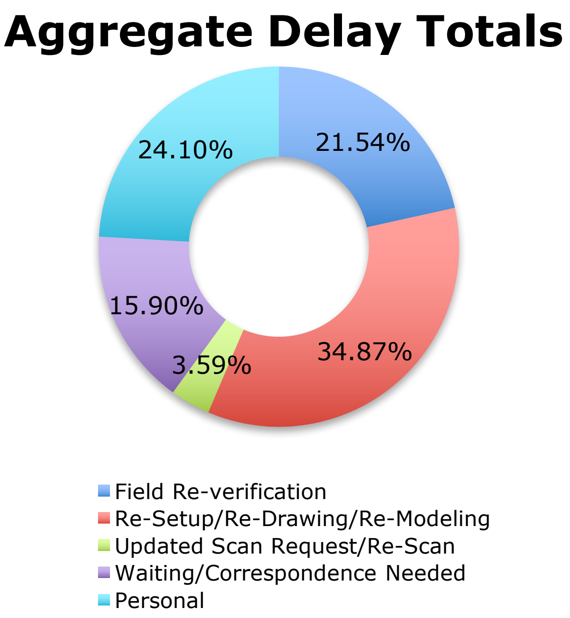


Figure 30: Aggregate Site Delay (NVAT) Totals

Table 13:

Aggregate Site Delay (NVAT) Time Breakout

	Minutes	**Hours**	**Total Percentage**
Field Re-verification	210	3.50	21.54%
Re-Setup / Re-Drawing / Re-Modeling	340	5.67	34.87%
Updated Scan Request / Re-Scan	35	0.58	3.59%
Waiting / Correspondence Needed	155	2.58	15.90%
Personal	235	3.92	24.10%
Totals	975	16.25	100%

As a result of structured observations, an interesting phenomena related to a duplication of process time was noted. This time was allocated for within the initial observation matrix but was also sub-categorized into a process duplication time category and explained via an observation notes log. Many of these process duplications were defined by the modeler when coordinating information internally with another team member and were easily identified when following a specific tool model over the duration of observations. A variety of scenarios were noted as duplication time but most of this time is due to inaccuracies in owner provided data which is ultimately re-verified via multiple, uncoordinated activities, mistrust in the modeling process, updates to internal BIM content libraries and mistranslation of 2D information to its 3D counterpart. A large component of this time can also be allocated to the irregular use of Building Information Modeling across the site for ALL construction related projects. While BIM is mandated for all capital equipment installations, conversions or replacements, it is not mandated for base-build work on the facility itself. While this is seen as a cost and time saving measure for the project from the owner's perspective, this ultimately affects every subsequent project undertaken downstream in the BIM lifecycle. New system tie-ins, structural changes, new equipment placement, etc. all add more complexity to the jobsite which must be converted into a 3-dimensional virtual relationship of existing conditions. Essentially this process duplication time, which is, in essence, time that should not exist in the modeling process, self-perpetuates due to the ever changing nature of the jobsite which is unreliably captured throughout every project. Table 14 presents the observation time related to process duplication time.

Table 14:

Aggregate Site Process Time Duplication Breakout

	Minutes	**Hours**	**Total Percentage**
Process Duplication Time	690	11.50	17.56%
Total Observed Time	3930	65.5	100%

4.1.2 Modeling Time Utilization of Mechanical/Process Piping Trades

Individual trade analysis is an interesting component within the site dynamics of this particular case study. Various internal process and software package differences led to varying modeling time utilization rates. When looking at the mechanical and process-piping trade component, the overall VAT, at 17%, is 2% below the aggregate site VAT for modeling for prefabrication of 19%. This time reduction comes at the expense of a larger support work component, largely contributed to the coordination efforts needed for these trades. Overall, site delays in the process piping/mechanical trade are lower than that of the other trades observed on-site. Figure 31 shows the total aggregate data for the two mechanical trades observed over the 8-week period of initial observations. The observation durations are accounted for in Table 15.

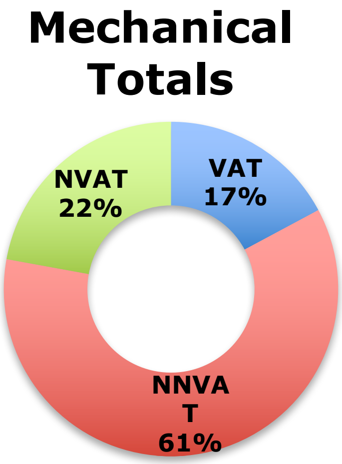


Figure 31: Mechanical Trade Modeling Time Utilization Rates

Table 15:

Mechanical Trade Modeling Time Utilization Totals

Total Direct	Total Support	Total Delays	Totals
225 mins.	795 mins.	290 mins.	1310 mins.
17.18%	60.69%	22.14%	100.00%
3.75 hrs.	**13.25hrs.**	**4.83 hrs.**	**21.83 hrs.**

Support work, or NNVAT, is interesting from a mechanical standpoint. What stands out the most is the reduction in time spent in the intra/inter-trade coordination realm. This may be explained by the fact that the mechanical trades' routes are often the ones that dictate the initial occupation of space in a particular model. In essence, mechanical trades utilize a larger component of volume within a facility and subsequent model, and have less flexibility in routing than their electrical trade counter-parts. This therefore lends toward a scenario in which the freedom to dictate a modeling route falls in the hands of the mechanical/process piping trades.

This same thought process can be traced within the increased utilization of both a background model and laser scan simultaneously for placement of model content. A total increase of 7.17% can be seen in the utilization of laser scan data for coordination of model content. Referring back to the initial rank order survey given on site, it can also be seen that the 2.72% increase in the utilization of the background model for the same modeling process further enhances the idea that accurate geometry is the most important component of information for a modeler to complete their task. Preparatory work and model set up, as well as document control processes such as uploading and downloading of the most recent modeling components and files remains largely unchanged against the aggregate site data, further enforcing this as a static component reliant upon technological capabilities and site-wide protocols. The final piece of data which is relevant for the initial owner directed question regarding reducing on-site headcount is related to the field walk verification and/or field modeling component. This remains nearly identical to site aggregate data which can be read as stating that all trades on site are engaged in field-related modeling process and validation to the same degree of time. Figure 32 depicts this information graphically while Table 16 presents a breakout of observation time related to each category.

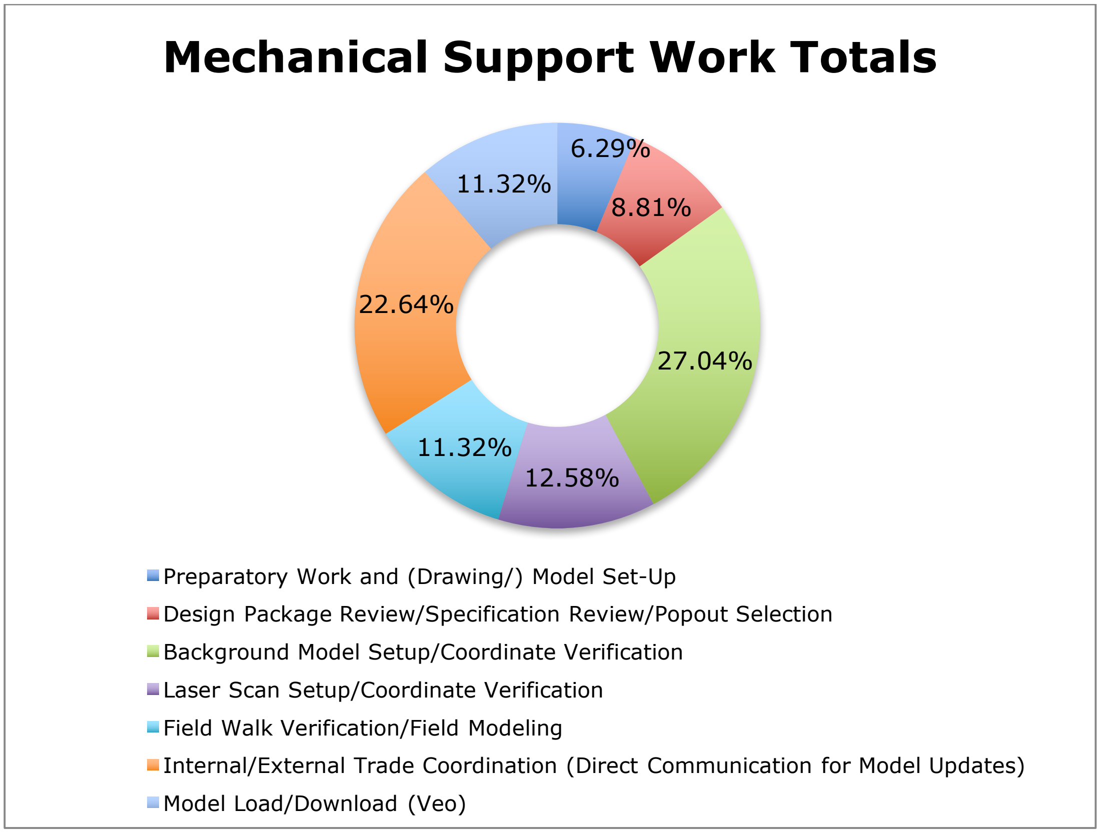


Figure 32: Mechanical Support Work (NNVAT) Totals

Table 16:

Mechanical Trade Support Work (NNVAT) Time Breakout

	Minutes	**Hours**	**Total Percentage**
Preparatory Work and Drawing / Model Setup	50	0.83	6.29%
Design Package Review / Specification Review / Popout Selection	70	1.17	8.81%
Background Model Setup / Coordinate Verification	215	3.58	27.04%
Laser Scan Setup / Coordinate Verification	100	1.67	12.58
Field Walk Verification / Field Modeling	90	1.50	11.32%
Internal / External Trade Coordination (Direct Communication for Model Updates)	180	3.00	22.64%
Model Load / Download	90	1.50	11.32%
Totals	795	13.25	100%

Finally, in regards to the mechanical/process piping trades, a shift in delays against the aggregate site totals becomes obvious. While the aggregate site time utilization rates claim 21.54% of delay-related time in the field re-verification category, the mechanical/process trades utilize a total 29.31% of total delay-related time in this activity. Couple this with the time allocated to updated scan requests/re-scanning processes and a total of nearly 40% of total NVAT is spent collecting existing conditions related data after it has been initially needed to properly begin a modeling job. In hourly terms, this equates to about 1.4 hours per 10-hour modeling workday, on average, of wasted time due to inaccurate data available at the outset of modeling. Figure 33 presents a chart of this data while Table 17 presents the observation time breakout per category.

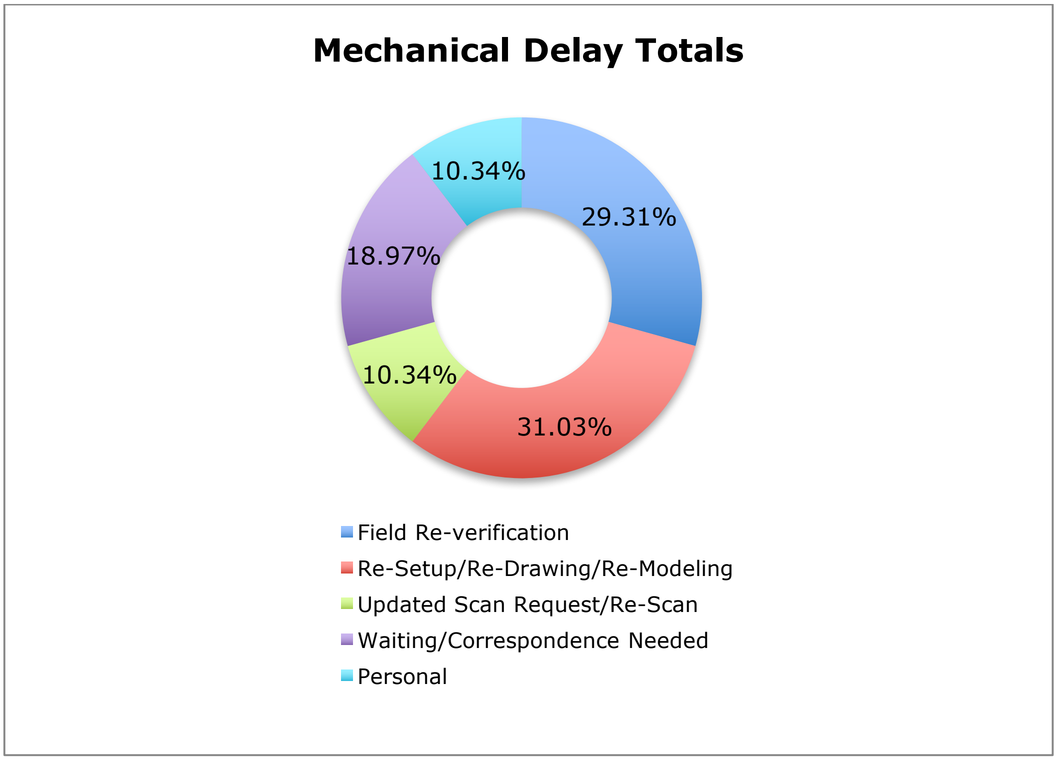


Figure 33: Mechanical Delay (NVAT) Totals

Table 17:

Mechanical Delay (NVAT) Time Breakout

	Minutes	**Hours**	**Total Percentage**
Field Re-verification	85	1.42	29.31%
Re-Setup / Re-Drawing / Re-Modeling	90	1.50	31.04%
Updated Scan Request / Re-Scan	30	0.50	10.34%
Waiting / Correspondence Needed	55	0.92	18.97%
Personal	30	0.50	10.34%
Totals	290	4.84	100%

4.1.3 Modeling Time Utilization of Electrical Trades

The electrical trade on-site at the case-study offered the most complete access to modeling resources during the time of initial observations. Out of the total eight modelers observed, six modelers were electrical trade prefabrication modelers. This speaks to the different management techniques utilized by the trades and is a topic of later discussion.

Comparing the two direct work results, it is noted that the electrical trade realizes a 3% increase in VAT over their mechanical counterpart. There is also a large discrepancy in support work (NNVAT) undertaken by the two trades. The electrical trade is engaged in support work at a rate 7% less than that of the mechanical/process piping trades. This reduction can be allocated to initial investments made by the company in the utilization of different software platforms, customized libraries and responsive components for modeling use. The last component of total time observed, delays or NVAT is seen as a 4% increase over the mechanical/process-piping trades. Figure 34 graphically depicts the observation results for the utilization of time within the electrical trade on-site. Table 18 presents the observation time breakout per category.

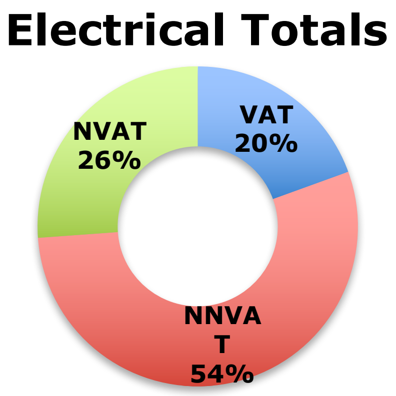


Figure 34: Electrical Trade Time Utilization Rates

Table 18:

Electrical Trade Total Time Breakout

Total Direct	Total Support	Total Delays	Totals
510 mins.	1425 mins.	685 mins.	2620 mins.
19.47%	54.39%	26.15%	100.00%
8.50 hrs.	**23.75 hrs.**	**11.42 hrs.**	**43.67 hrs.**

In analyzing the support work (NNVAT) component of electrical trade modeling time, basic preparatory work for setting up models and subsequent drawings remains similar to both site aggregate and mechanical/process-piping trade totals. There is less than half a percent difference between all trades in this respect. This shows consistency in the upfront setup process and time can then be seen as a software package constraint. The first major difference between time usages in the electrical trade comes in at the design review period where the modelers are reviewing layouts, specifications and proposed pop-outs for routing. It can be seen through comparison of Figure 32 and Figure 35 that the electrical trade spends about 5.58% more time in support work dedicated to processing and reviewing design packages prior to modeling over their mechanical/process trade counterparts. The second difference can be seen in the background model usage and laser scan usage for modeling. The combined total for the two categories is 24.21% of total support work. Remember, this is time spent inside of a virtual representation of the existing facility. This is 15.41% less than their mechanical counterparts. The shift in time comes into play not at the field walk verification/field modeling component, which remains relatively static between the two trades, but within the coordination component of necessary support work. Whereas the mechanical team engages in a total of 22.64% of total support work time in the coordination realm, the electrical trade steps total percentage up by nearly 6.5% to a total of 29.12% of time spent coordinating. This equates to an average daily time block of a little over an hour and a half of modeling time dedicated to internal/external trade coordination. In essence, this is an average of 20 extra minutes/day spent on electrical trade coordination over mechanical trade coordination. Finally, the time spent within the document control process is very similar between the two trades. A slight difference of 10 minutes of total use per day is seen in comparing the two trades but overall this remains largely unchanged between disciplines. This supports the idea of a consistent and standardized process for which models and content is shared across trade lines. Figure 36 presents this information in a graphical format while Table 19 breaks apart related observation time per category.

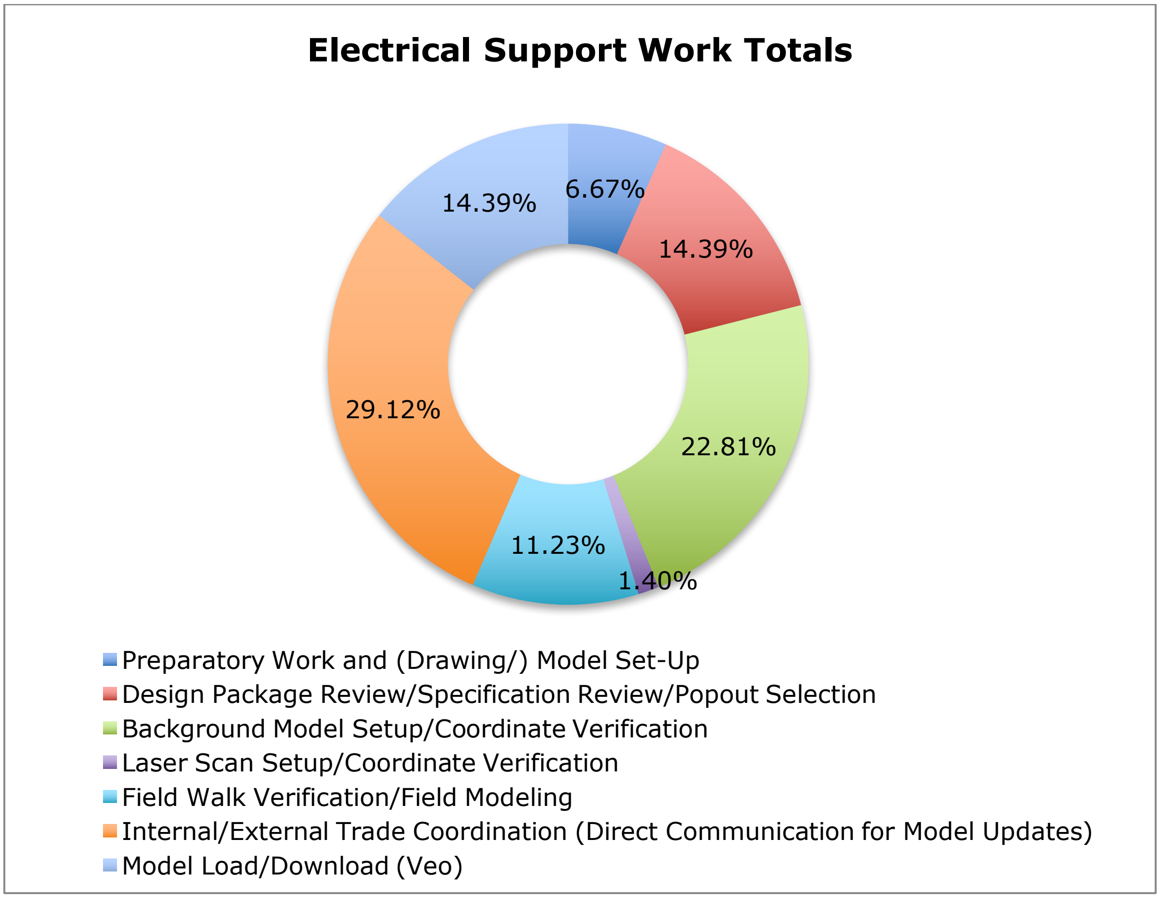


Figure 35: Electrical Trade Support Work (NNVAT) Totals

Table 19:

Electrical Trade Support Work (NNVAT) Time Breakout

	Minutes	**Hours**	**Total Percentage**
Preparatory Work and Drawing / Model Setup	95	1.58	6.67%
Design Package Review / Specification Review / Popout Selection	205	3.42	14.39%
Background Model Setup / Coordinate Verification	325	5.42	22.81%
Laser Scan Setup / Coordinate Verification	20	0.33	1.40%
Field Walk Verification / Field Modeling	160	2.67	11.23%
Internal / External Trade Coordination (Direct Communication for Model Updates)	415	6.92	29.12%
Model Load / Download	205	3.42	14.39%
Totals	1425	23.75	100%

Delay total comparison between electrical and mechanical/process piping trades introduces unique insights and possible areas of focus for addressing bottlenecks in the overall process. Figure 36 presents the total delay percentages. There is an 11.06% difference between the two disciplines in regards to field re-verification delays. While the electrical trade doesn’t engage in field re-verification as often, they do have an increased utilization of re-modeling time at a rate of 36.5% total delay time as compared to 31.03% (5.47% difference) equating to nearly 25 minutes/day on average of extra time dedicated to re-modeling a prefabrication component. While this can be seen as a result of increased flexibility in routing design for conduit runs, this is not always the case when it comes to the design of wire ways. Poor background geometry assists in miscommunication between the mechanical and electrical trades in the routing of larger service and less flexible service components. Laser scan usage differences also become apparent in the delays category. Electrical trade modelers do not seem to spend time waiting for updated scans of the facility. This is observed by pulling out the minimal 0.73% of total delay time versus the 10.34% delay time utilized by the mechanical trades. This shift in process time may offer insight into why the electrical trade spends more time remodeling or redrawing prefabrication components over the mechanical/process piping trades. Finally, both disciplines have a significant waiting time component in their overall processes. The electrical trade was observed to have 14.6% of total delays dedicated to waiting for information or correspondence to execute a modeling process. This results in nearly 38 minutes/day on average. This is relatively similar to that of the mechanical/process-piping trades with a 3 to 4-minute difference in overall daily averages. Table 20 presents the total observation time dedicated to each electrical delay category.

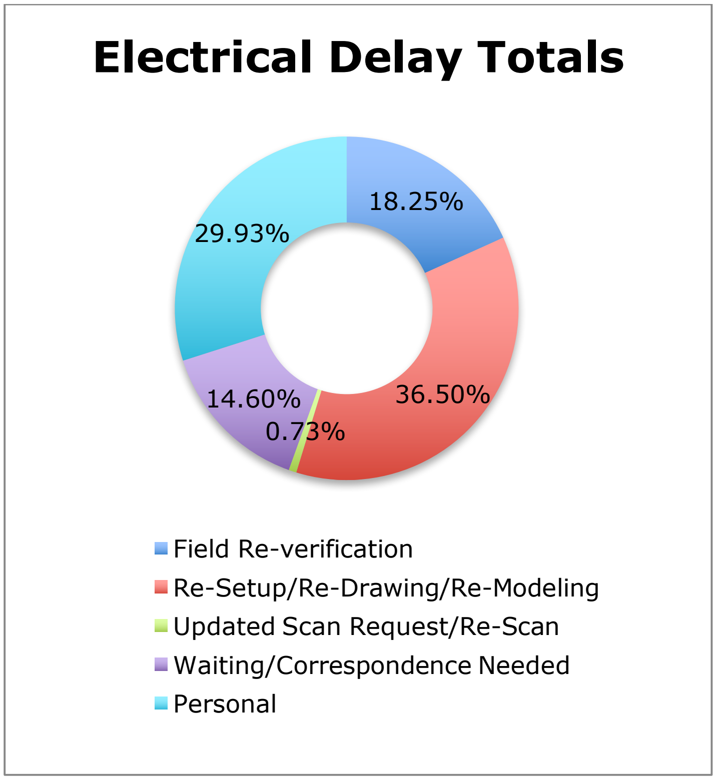


Figure 36: Electrical Delay (NVAT) Totals

Table 20:

Electrical Trade Delay (NVAT) Time Breakout

	Minutes	**Hours**	**Total Percentage**
Field Re-verification	125	2.08	18.25%
Re-Setup / Re-Drawing / Re-Modeling	250	4.17	36.50%
Updated Scan Request / Re-Scan	5	0.08	0.73%
Waiting / Correspondence Needed	100	1.67	14.60%
Personal	205	3.42	29.93%
Totals	685	11.42	100%

4.2 Results & Conclusions

The data outlined in this chapter showcases aggregate and trade related time utilization rates at the modeling workface. These time utilization rates are grounded in lean manufacturing principles, as described in Chapter 2. They equate to value added time (VAT), which describes the direct time spent creating a component of a model which will ultimately be prefabricated and installed on-site, necessary non-value added time (NNVAT), which describes supporting work necessary to engage in direct modeling activities and finally non-value added time (NVAT), or delays, which can be seen as system delay. NVAT should be addressed immediately in the creation of an ideal workflow design. NNVAT begins to uncover the current utilization rates of various modeling tools by the trades and the interconnectedness between the communications needed for accurate prefabrication modeling.

Based on the above data and a review of the current state modeling process outlined in Chapter 3, "prefaBIM" was introduced and developed as the standard workflow process for enhancing the content management and information handoffs from design to installation of each toolset. A geometrically reliable Building Information Model (BIM) may be defined as an exact virtual representation of critically identified parameters of an existing facility as it relates to the field conditions, with accurate and tolerant connections for embedded prefabricated components. Therefore, the hypothesis, grounded in theory and observation, is that by preplanning for a geometrically reliable BIM, a reduction in the amount of workers onsite during a peak ramp in construction operations will be observed. This reduction in workers onsite during a peak ramp is hypothesized to come in various forms including (but not limited to) more efficient utilization of installation teams due to accuracy of provided installation drawings per a coordinated construction model, less congestion due to individual trades engaging in upfront and repetitive non-invasive existing conditions data collection (laser scanning) and an overall reduction in the congestion created by introducing the modeling workforce into the field for further field verification or field modeling processes. By correctly identifying critical facility parameters to virtually represent and track through the various stages of the design, pre-construction, construction, and turnover phases, a BIM can be better managed as a single point of information for all stakeholders and provide more accurate data for various tasks. Such parameters may include: structural member locations and load capacities, service laterals, service tie-in locations and capacity restrictions, waffle slab elevations and catwalk locations, pop out locations and points-of-connection to critical components. This will reduce redundancies and workarounds in stakeholder processes and decrease overall rework that is seen in more traditional construction workflows and the subsequent observations seen on the case-study site. Through the introduction of a single, data-rich model-based delivery system that is trusted as accurate through a field condition to virtual environment validation process, a reallocation of headcount to offsite activities and necessary pre-planning and support activities will be seen, in turn reducing on-site congestion and expediting the installation processes. After observing the current workflow and defining current modeling time utilization rates for each of the trades and the site as a whole, this research will present an ideal state workflow utilizing a model-based delivery system, prefaBIM, to improve overall project team productivity which will be discussed in Chapter 5.

In the current state workflow for prefabrication, a series of information transfers occurs between 2-dimensional drawing and 3-dimensional model media. This has been observed to create a scenario in which human-error is introduced and a series of re-validations occur to continuously check against information discrepancies. It can also be seen in the current state workflow diagram presented in

Chapter 3, that two separate tools are utilized to create construction models for prefabrication: laser scans and a federated BIM utilizing a background model for virtual site conditions representation. It has been observed that neither of these two tools is correctly validated for use in prefabrication as a standalone tool; thus, creating a lack of trust in provided information for modeling use. This lack of validation and trusted, accurate near real-time information creates a bottleneck in the overall system. This causes field re-validation to occur; introducing more physical bodies in the field during installation. Coordination issues between trades arise resulting in the need for multiple clash-detection and inter/intra-trade coordination meetings and a delay in modeling processes occurs due to requests-for-information. It is from this lack of trust in the system that various BIM content milestones have been introduced into the modeling for prefabrication schedule, increasing overall durations from that of traditional methods.

The research questions presented at the beginning of this chapter were initially explored through the direct observation data collection technique. These questions will be further analyzed during a process intervention, outlined in Chapter 5, in order to understand the actual effects of changes to the current workflow.

CHAPTER 5

CONCEPTUALIZING: FRAMEWORK FOR prefaBIM

This chapter introduces an overall framework for an ideal state workflow for modeling for prefabrication. This framework is grounded in the methodologies and findings described in Chapters 3 and 4. It further elaborates on the deficiencies in the current state workflow through qualitative and root-cause analysis of an observation log. The log was completed systematically while observing various modeling tasks at the case-study site. The analysis discussed in Chapter 3 is expanded upon to include the prefabrication supply-chain as a whole, as a way to investigate performance implications of various process interventions. While the presented framework for an ideal state, dynamic modeling workflow, namely prefaBIM, is rooted in the case-study environment, components within the process ideals for the study are intended to be scalable and used in the industry at large. This chapter will present an ideal workflow diagram and describe the overall intent of the workflow, provide a description of various interventions to the current state workflow at the case-study and ultimately present data for use in validating the ideal state workflow. This chapter utilizes the steps highlighted in Figure 39 for developing a viable framework for process improvements in the modeling for prefabrication workflow.

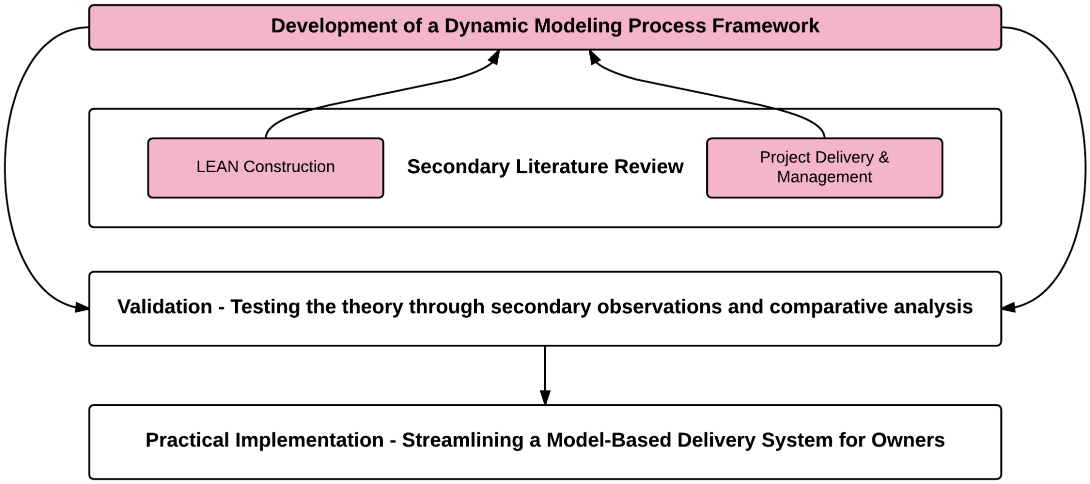


Figure 37: Theory Development Diagram

5.1 Findings and Interpretation of Modeling Time Utilization Rates and PM Strategies

This research continuation has developed an understanding of the prefabrication modeling implications on the analysis presented in Chapter 4 related to the previous research findings. It has introduced a baseline modeling time utilization rate and measurement technique for process improvement comparisons, and finally it has set the stage for a “TOP – UP” approach to Building Information Modeling.

During the data collection period, the amount of information available to each stakeholder in the design/construction/operations lifecycle was observed. This became the basis for which a “TOP-UP” approach to modeling became a viable strategy. Through the proper re-purposing and utilization of existing data and information, it is hypothesized that the design/construction team on-site can piece together an accurate and trusted background model for use in the modeling for prefabrication process without investing an exorbitant amount of time and resources for a complete re-build of data. This can relate directly to existing information in the form of geometry and instead of allowing geometry to remain as a singularity within the overall process, the geometry that exists should be considered a living piece of information informed by consistent updates to introduce accurate representations of the existing site conditions (towards real-time). For this research, TOP-UP BIM (Figure 38) shows a self-perpetuating virtual relationship to a physical facility's parameters utilizing two types of geometric components (static and dynamic geometry) for reliability in retrofit design and construction information. Ultimately, TOP-UP BIM would be defined as follows:

- **Timing** – Frozen Data: Reliability of information handoffs
    - Layout design
    - Tool-block and Point of Connection (POC) location
    - Design Package schedules / Piping & Instrumentation Diagrams (P&ID's)
    - Pop-out selection and isolation
    - Critical fabrication component design and detailing
- **Order** – Revolving Critical Issue for Fabrication (IFF): Reverse design process
    - Coordinate-to-layout and P&ID via pull-plan scheduling
    - Release critical lines for design review and signoff for IFF
    - Database driven design-to-install utilizing standardized detailing
    - Reduce design package information and allow construction detailing to begin at design start – reduce detailing efforts and "suggestions" from various stakeholders
- **Proof** – Validation: install-to-model audit process to close the BIM loop; this validation comes in the form of field installation accuracy against the

prefabrication, construction model. Once the installation is validated to match the model, the construction model can be placed into the background model and trusted as accurate to field conditions.

  - Incentivize install-to-model through internal competition
  - Provide laser scans and/or photogrammetry based deliverables for installation validation against construction model
  - Redlines must be provided and updated in the model database in order to complete the prefabrication to installation cycle
- **Unified** – Standards: Model-based parameters for handoffs
  - Owner-driven model turn-over requirements
  - Standardized file naming conventions for all stakeholders
  - Requirements for clash-detection resolution and documentation of major issues
  - Trade-based model to field handoffs for proper installation instructions
  - Reduction in tribal knowledge for ease of project transition
- **Propagation** – Perpetual Updates: Organic accuracy (Model Stacking)
  - Close the modeling loop from design to install via consistent field condition validation; once the static conditions are validated against the BIM an organic transfer of information from dynamic to static can take place via pre-condition identification
  - Model coordinator must validate model content and consistently append files to the federated model for accuracy (future research lends itself towards automated model updates for self-perpetuation of organic accuracy)

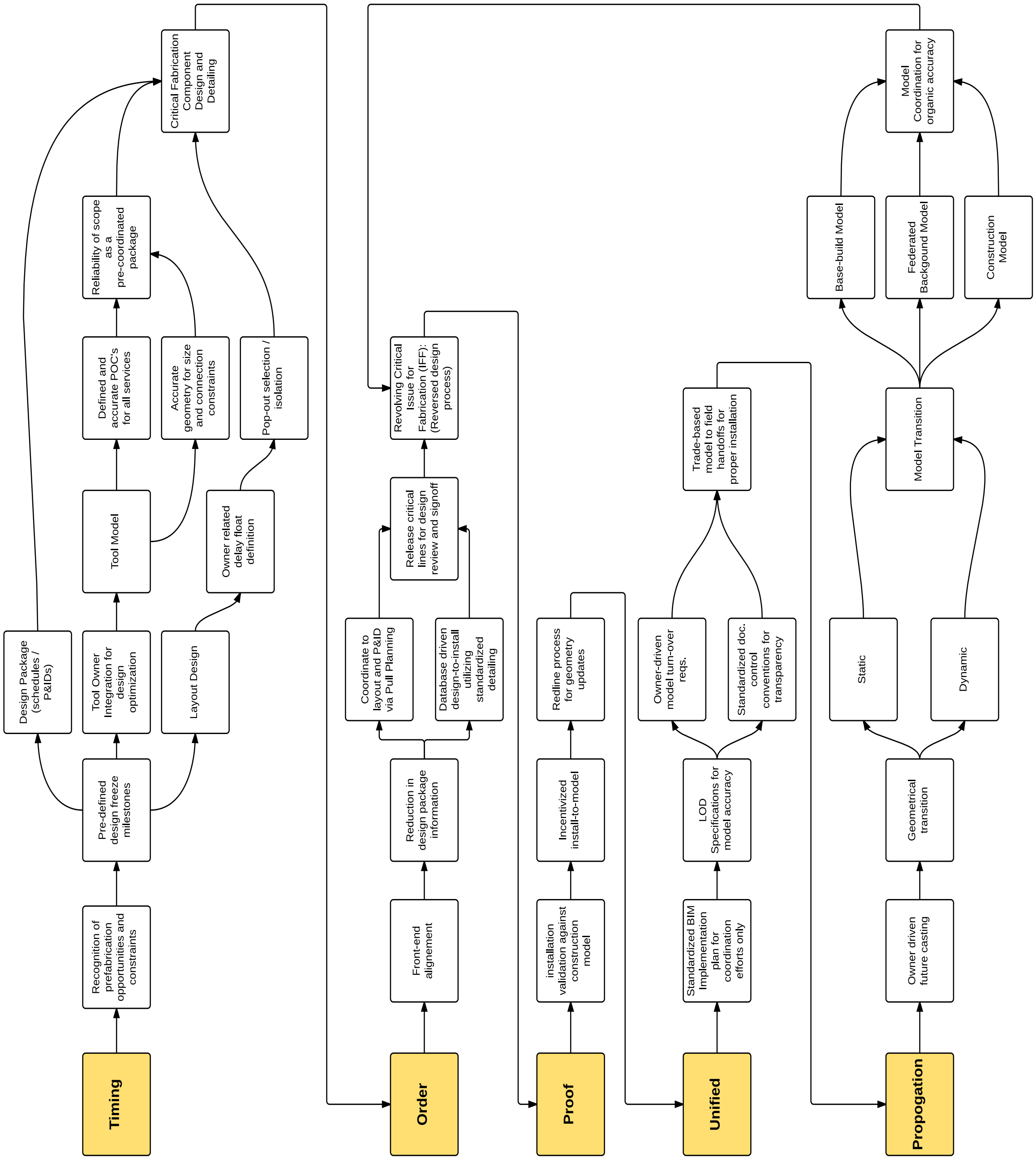


Figure 38: TOP-UP BIM Process

5.2 Definition of Dynamic Modeling for Retrofit Prefabrication: prefaBIM

In Chapter 4, VAT and NNVAT/NVAT was analyzed. This information was utilized as a starting point for defining bottlenecks and over-production components to the current state workflow. It was from this analysis of total time spent modeling (overlaid with the current state workflow diagram) that an ideal state workflow *(Figure 39)* was created to provide visualization for leaning out the overall process of modeling for prefabrication. This ideal state scenario takes into account the entire design through installation timeline, in order to create a scenario where a closed-loop data system is introduced into all workflows and a validation process for accuracy, reliability and trust ensues.

Ideal State Differentiators: The ideal state process for retrofit prefabrication – Dynamic Modeling (prefaBIM Framework) – differs from the current state process in three critical areas:

1) **Scheduling**
    a. **Ideal State** -
        i. *Critical Scheduling* shifts from prefabrication of components to the realistic and timely delivery of accurate and frozen information for use by the trades. In this scenario, by focusing on front-loaded information transfer and tracking of that information through the overall process of design-to-install, trades are relieved of meeting "place-holder content (misrepresented geometry)" coordination meetings. This aids in streamlining content release for prefabrication of components

for identified critical routes (often occurring in an at-risk scenario for the trade contractors despite the deadline stated by the owner) and the trades can begin coordinating based on revolving release of prefabrication components and freezing of attached data. This scenario introduces a critical-chain scheduling technique to the modeling-to-installation portion of the schedule and allows for an overlap in modeling and fabrication durations; in turn reducing the total project duration but still allowing for full modeling and fabrication times of necessary and identified scenarios

ii. *Proactive (Dynamic) Scheduling* is introduced at the trade level and becomes a scenario in which trades are introducing integrated project controls in order to reliably meet a specified fabrication turnover date. This scheduling technique allows for different complexity scenarios within scopes of work to be addressed in tandem vs. isolating them as the critical driver for the entire project and multi-trade scope. This approach assumes (based on information gathered) that reliability of timing and scheduling is more important to the owner of a semi-conductor manufacturing facility than early completion of a project

2) Geometry

a. Ideal State

i. The ideal state removes the bottleneck of information transfer in flattened formats and utilizes a set of *3-dimensional data* *packages* as a workflow. In this scenario, the design will both begin and end in a 3-dimensional format with semantic information attached for ease of database extraction. This process also removes the archival state of geometry and introduces static and dynamic geometric typologies for a closed-loop modeling workflow.

ii. *Design Original Information* – while original content will always exist in the design process, the ideal state process introduces a 3-dimensional approach to design content in order to reduce downstream extrapolation and reproduction of 2-dimensional data in a 3-dimensional state for construction manufacturing.

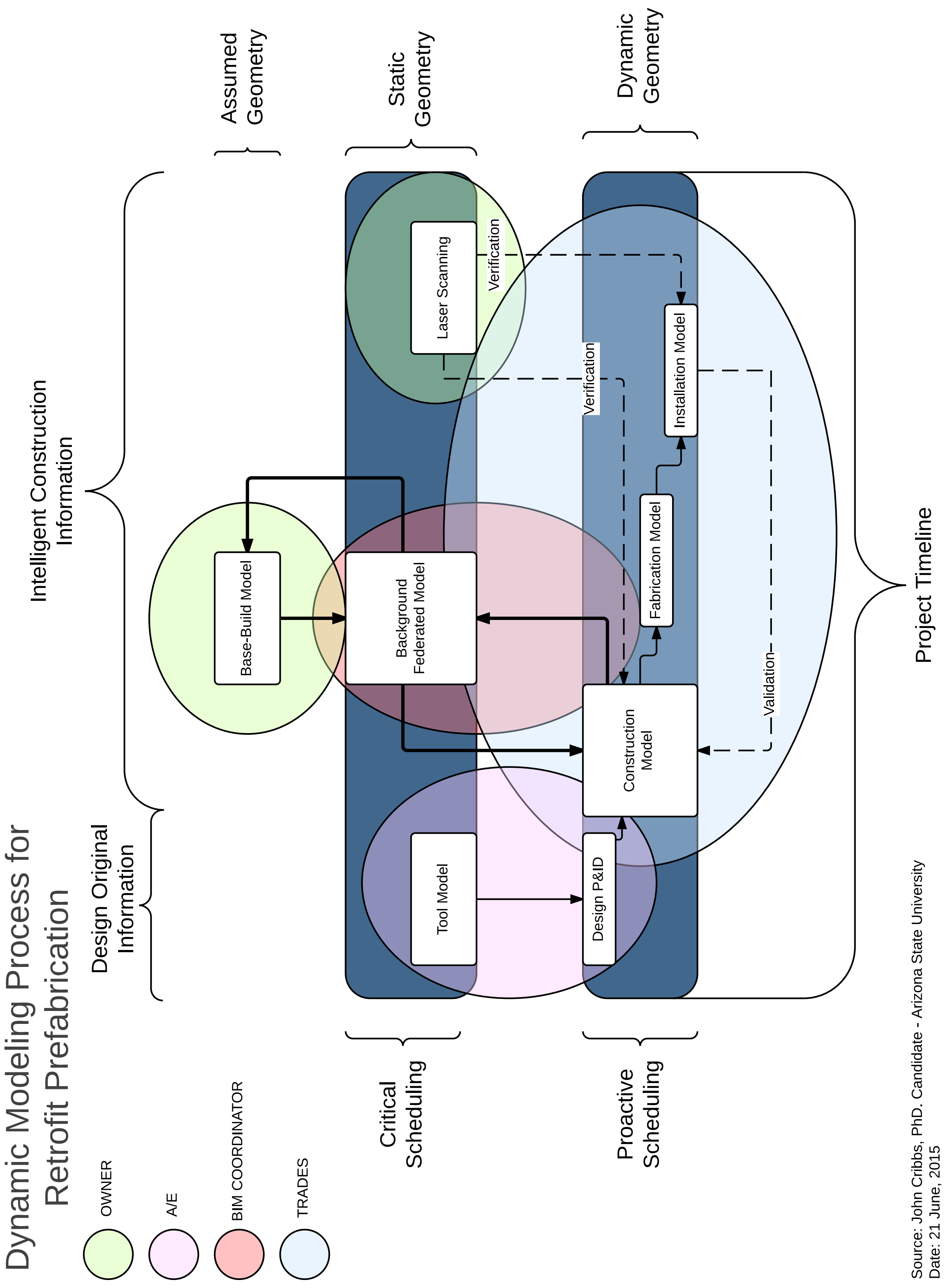
iii. *Intelligent Construction Information* – Information that can be utilized at more than one point in a process is inherently lean information. By introducing construction information that can be utilized throughout the construction detailing- construction manufacturing-install process, re-builds of existing conditions (in a virtual sense) or re-creation of virtual content is not needed and overall durations can be reduced. This type of information can be expanded to include:

    1. Responsive – physical attribute driven geometry in isolated scenarios
    2. Self-recognized – surrounding content driven geometry for use in validation purposes
    3. Data-driven – A/E schedule (drawing not duration) driven geometry for extraction from diagrams (P&ID’s)

3) **Verification vs. Validation**

   a. **Ideal State**

      i. In the ideal state, verification is an after effect of *validation.* Validation is introduced as the last step in the ideal state process (within the scope of this research) to close the loop on virtual geometry and attached data creation. By validating that the routing installation matches the construction model, the information has been verified for accuracy and the information can be re-introduced upstream for use by all stakeholders at the start of the process. In the ideal state tools such as laser scanning are isolated for validation purposes only and the proper form of geometry is then generated against the verified point-cloud for transition into the modeling stream. This process utilizes laser scanning tools for one purpose: Closed-loop modeling (construction manufacturing project controls) - Continuous validation of final product



Source: John Cribbs, PhD. Candidate - Arizona State University
Date: 21 June, 2015

Figure 39: Dynamic Modeling Process for Retrofit Prefabrication

The hypothesis of this research is "*by properly planning for a geometrically reliable BIM, project teams can increase the reliability of off-site prefabrication thus optimizing overall on-site headcount during the installation process*." While prefabrication has been introduced into the construction supply-chain prior to the use of BIM, BIM offers a substantial opportunity for increased productivity on a job-site when planned and managed correctly.

The initial objective of this research was to identify the current state of BIM as a construction tool for prefabrication. The researchers were able to model the current state of information transfer as it relates to BIM content management and propose an ideal state from which to begin phased implementation of recommendations. A distinct mistrust in provided information for modeling was observed and as a result various tools were used to verify existing conditions at more than one point in the process creating bottlenecks in the work processes and redundancies in the overall system.

The second objective of this research was to identify the opportunities for automation within a prefabrication facility to increase overall throughput. This portion of the study remains ongoing and is predicated on correcting the upstream information flow for the modeling workforce.

The construction industry has seen an increase in the use of technologies such as BIM to automate and expedite traditional processes with the intent of introducing lean workflows into the construction process for productivity improvements and waste reduction (Sacks & Koskela, 2010). Building Information Modeling is a transformative technology that must be properly integrated into processes to realize these types of benefits. It cannot simply be tacked on to antiquated processes with the hopes of achieving the same expected results. As discovered in the initial phase of this research, the definition of BIM hinges around two perspectives: “one describing it as a representation or an object (building information model) and the other describing it as a process or an activity (building information modeling)” (Ghosh, 2015). This research continues and further elaborates on the initial research definition component of BIM as a process or an activity (modeling) that encompasses three areas:

- **Initial Research Component:** Three-dimensional parametric modeling of geometrical information representing physical and spatial building components including dimension control
    - **Elaboration:** Static Geometrical Information and Dynamic Geometrical Information
        - **Static Geometry** – Assumed geometry representing the facility DNA creating a virtual relationship to existing conditions. Such DNA might include structural members such as: steel columns and column grid locations, concrete waffle-slabs, lateral service run locations, pop-out locations and control point grids or brass caps, and facility service locations. This category of geometry relates to facility conditions that are not meant to change in the short-term lifecycle of the facility (10-years).
        - **Dynamic Geometry** – Geometry that is created and introduced into the static geometry conditions (background static geometry) for inclusion in the facility lifecycle and validated upon installation for turnover and conversion into static geometry. This category of geometry relates to changes in existing conditions, tool conversions/installations and/or demolitions. This type of geometry will constantly be in flux and

        must be managed by a BIM Commissioning Agent (BIM CxA). In this respect, a BIM Commissioning Agent replaces the BIM coordinator and is explicitly in charge of validating field conditions against the model for accuracy. Much like a commissioning agent (CxA) in general construction is responsible for validating the installation of building systems and components in a facility prior to owner turnover, a BIM CxA is responsible for the same but in a purely digital format.

- **Initial Research Component:** Management of project information for decision making
    - **Elaboration:** Design Original Information and Intelligent Construction Information
        - **Design Original Information** – Geometry and semantics introduced by a design team to respond to facility and process needs
        - **Intelligent Construction Information -** Database geometry and semantics introduced into the model-based delivery lifecycle for use in construction manufacturing and installation
- **Initial Research Component:** Workflows for BIM use and its implementation
    - **Elaboration:** Development of a Model-Based Delivery System Framework for prefabrication in retrofit scenarios based on the following model transitions:
        - **Tool Model** –Three-dimensional, accurate representation of semi-conductor capital equipment with reliable positioning of points of connection (POC's) and capacity requirements for

layout simulation. This model is stripped of all proprietary information for a sole focus on installation means/methods (SEMI Standard is under development – Guide for Facilities Data Package for Semiconductor Equipment Installation).

- **Construction Model** – Trade-centric model designed and coordinated for conversion/installation scope of work and turnover to owner's database. This can be later utilized by owner's FM team – provision based.
- **Fabrication Model** – Detailed model, focused on construction manufacturing as an outcome of the construction model, used for automated prefabrication of tool service components
- **Installation Model** – Augmented reality model utilized by field installers for direct install-to-model audit verification
- **Geometry Validation Model**– Existing conditions capture (laser scan and/or photogrammetry) overlay with background-federated model and construction model for ongoing model validation and reallocation of geometric typologies to create a Model-Stack.
- **Model-Stack** *(Figure 41)* – Seemingly self-perpetuating, real-time, virtual representation of existing facility conditions via ongoing verification and validation process to be known as model commissioning or mCx *(Figure 40)* which ties the following models together for accuracy of information retrieval, at any point along the design/construct/install timeline:

- *Base-Build Model* – Geometrically accurate construction DNA of a facility as it relates to structural and capacity components of a fab and sub-fab (static geometry)
- *Background Federated Model* – Assemblage of BIMs used for real-time modeling of capital conversions in a fab retrofit project typology; this model will be an overlay onto the base-build model for use in locating static conditions and coordinating dynamic components in-flight (semi-dynamic geometry)
- *Construction Model* – Model used to construct any facility updates and/or create service runs from the tool to the subfab equipment and/or facility utility points-of-connection. This model will directly relate to the Background Federated Model and all information to begin the construction modeling process will be pulled from the Background Federated Model geometry as an overlay. A model-to-install audit procedure will need to take place once the conversion/install has been completed, in order to close the loop on updating existing conditions in a dynamic state and relate the model content back to the background federated model and the base-build model for capture in a static conditions state.

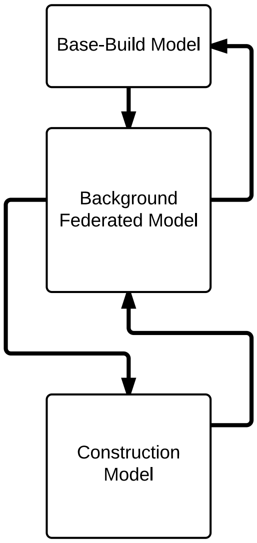


Figure 41: Model-Stack

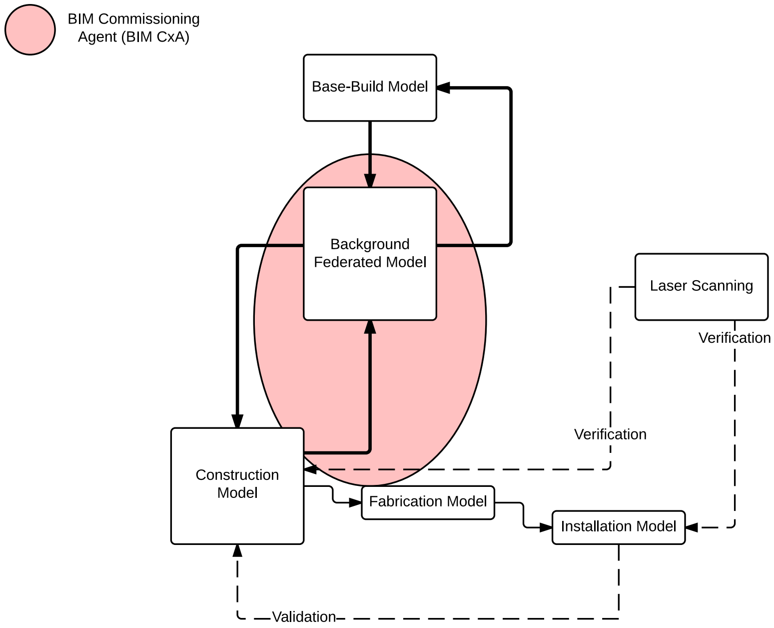


Figure 40: Model Commissioning (mCx)

Utilizing this expanded description of Building Information Modeling, BIM interacts with all processes across the design and construction continuum, particularly when focused on the prefabrication and coordination of multiple trade scopes. It can also enhance philosophies, such as Lean Construction, and engage in productivity improvement (Gerber et al., 2010). As an enabler, one with clear management implications as defined by Ghosh et al. (2014) with the introduction of BIM^2, this technology must be properly planned for and implemented with a common goal in mind for tri-tier execution. Thus, utilization of a single BIM by Project Management teams, modeling teams and installation teams simultaneously. This technology also has implications on the project delivery method and procurement of individual players, as technical expertise is a necessity. Thus, revised contracting language must be present to clearly identify BIM expectations and outcomes. In order to facilitate proper implementation of BIM, standards and interoperability must also be addressed within contract language, in order to provide seamless information delivery flow and ultimately future use deliverables (Nawari, 2012). While BIM automates most of the visualization process, physical effort is still needed to meet information demands and handoffs as identified by the owner.

5.3. Assumptions & Best Practices for Utilizing prefaBIM in a Semiconductor Manufacturing Facility

The development of "prefaBIM," a framework for a construction supply-chain model, namely "prefaBIM," for semiconductor fab capital equipment conversions and upgrade installations utilizing offsite construction methods will enable project teams to introduce an economy of scale to off-site prefabrication operations and identify areas of improvement for capital savings; all while meeting compressed timelines with greater efficiencies and overall quality. The basic assumption from which prefaBIM is predicated relates to strong subcontractor Building Information Modeling capabilities and shared contracting methods.

5.4. Pilot Study Results

Following the definition of an ideal state, dynamic workflow for modeling for prefabrication, a series of interventions was suggested to the project team during subsequent PIT Meetings at which the author was a participant observer. Each prospective intervention was rooted in initial research findings and presented chronologically (via the ideal state process diagram) to the various stakeholders on-site. The realms in which interventions were discussed included:

1. Weekly PIT Meetings as an initial discussion forum- consisting of individual trade BIM managers and an owner's representative.
2. PMT Meetings- consisting of individual design and trade Project Managers, as

well as multiple owner's representatives from various facets of internal management.

3. Owner's Management meetings - consisting of multiple owner personnel from central design and various management sites worldwide.

Each of these meetings built upon one another in order to push interventions into place for implementation on the case-study site. Ultimately, the Pilot Study followed the logic presented in Figure 42 for validating the overall ideal state, dynamic modeling workflow, prefaBIM. To begin the validation process for prefaBIM, the author suggested implementing a process in which existing geometry on-site be separated into their respective static and dynamic components described in the prefaBIM framework.

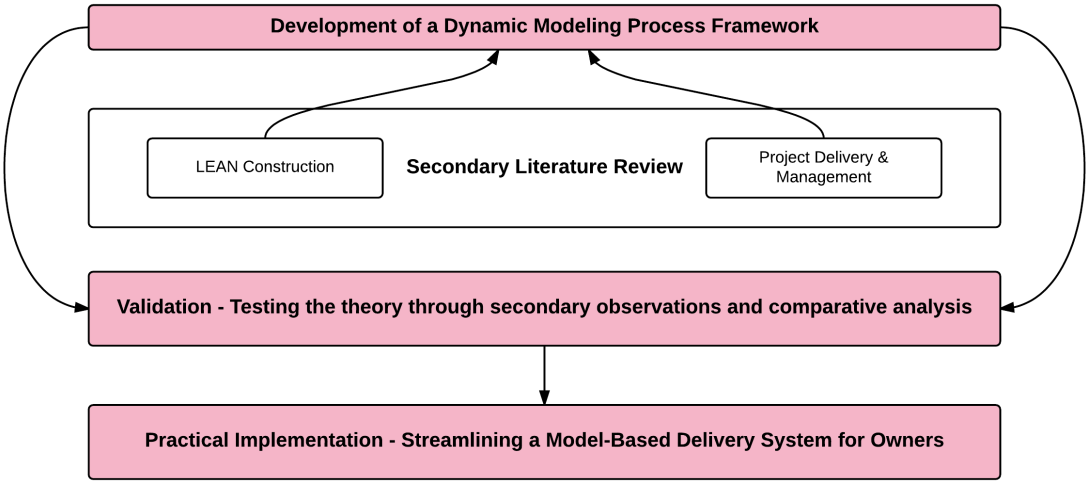


Figure 42: Validation Process Diagram

It was difficult for this initial implementation suggestion to gain traction. The history regarding the creation of existing base-build geometry is a sensitive topic for the owner due to the initial capital invested in the BIM process and deliverable. The original background geometry that was created for the owner, by an outside consultant, was done so without a proper strategy or truly defined end-use goal in mind, thus leading to an unreliable product. This essentially left the owner with an ineffective and, in the minds of the modelers, inaccurate and untrustworthy model of existing conditions which could not be utilized as a single source of truth in the prefabrication modeling process. The idea of revisiting the model to break apart the geometry into defined static and dynamic components was a way to respond to this inherent lack of trust by systematically auditing the existing data and bringing it into an accurate and usable state (during the modeling process for staged development). This is the first step in achieving a “TOP-UP” BIM-process.

In response to the splitting of existing geometry into static and dynamic components, the stakeholders onsite decided that a different method of gathering existing conditions data for use in modeling should be implemented and that method entailed the sole use of laser scans instead of background geometry for modeling. This was an attempt to provide accurate existing conditions data upfront in the process in less time than revisiting previous model files. Observation and internal productivity studies showed that the single act of tracking points-of-connection (POC) for each new/existing tool utilized 3-minutes of extra time per POC. On average, each tool contains nearly 35 POC’s accounting for approximately 1.75 hours of extra time, per trade, being billed against the tool. This was seen as too costly under the current contracting structure and the process was ultimately abandoned. This can be seen described in notes from the PIT Meeting dated 10-6-15 in Appendix C. This was the first point of resistance for a series of possible interventions for validation of a dynamic modeling process for prefabrication. Despite describing the potential productivity gains and how little 1.75 hours of extra time per tool meant in the long term, the short-term project goals ultimately ruled supreme.

The second discussion regarding possible interventions for ideal state validation was the possibility of redefining scheduling milestones to more directly relate to BIM-based deliverables; lending toward a model-based delivery system on-site. The discussion revolved around removing a series of 2D-to-3D-to-2D design document packages (which were set for archive) in order to keep the data in a living 3D environment for a longer period of time. The goal of this process implementation measure was to address the idea of possibly flipping critical scheduling techniques to the owner's scope and allowing dynamic scheduling techniques to take place on the trade/contractor side for introduction of schedule float in the overall process in order to squeeze more productivity out of existing schedule durations. This addresses the delivery and availability of accurate and frozen data at the start of the modeling for the prefabrication process to allow the modeling workface to more accurately create routing models. Ultimately, this intervention should achieve a more accurate construction model with less rework; allowing compressed timelines to be met wherein revolving release for construction of prefabrication components could be utilized (dynamic scheduling). The idea being that when a route is not considered complex or super complex, the duration needed for modeling could be cut down and the super complex routing models could utilize the full schedule duration and multiple labor resources for accuracy in deliverables.

For all intents and purposes, the process intervention related to redefining scheduling milestones was disregarded as suggested and the opposite ensued. Instead of providing frozen design data at the beginning of the process with reliable schedules for the subcontractors to follow, the owner reduced deadlines durations for expedited modeling and released varying packages of design information to the subcontractors for use in beginning the modeling process. The design packages that were released were still undergoing layout and the designs were subject to change.

This became the environment for which a second round of data was collected. The goal of the second round of data collection was to measure productivity rates of the modeling workface during a compressed schedule scenario to further understand the implications of process standardization and the necessity of accuracy for reduced time. In essence, the goal became to utilize a second round of data collection as a possible vehicle for validation of the ideal state utilizing comparative analysis. As the opposite intervention was introduced to the workflow, it was hypothesized that a reduction in productivity rates would be seen and that a shift in the support work and delays would align with areas where prefaBIM was meant to assist in leaning out the process.

For the second round of data collection, the author was given access to the exact same modelers within the electrical trade for continued study. The observations took place utilizing the same observation matrix and random timing techniques as initial observations. This was explicitly done in order to keep all controllable variables constant. Furthering the similarity between observations, the stakeholders and environment around the modeling for prefabrication process remained the same as found during initial observations. The data collected on-site following the intervention; which was the opposite intervention to the scheduling technique described in the ideal-state workflow, supports the prefaBIM workflow. During the scenario in which schedules were compressed and critical scheduling was still focused on sub-contractor related activities, productivity rates for the electrical trade modeling workface actually decreased by 7% to a total VAT of 13% equating to only 78 minutes of value added modeling per normalized 10-hour workday. In this case, the modelers were working overtime to meet compressed deadlines. While this may be the expected outcome as indicated by many studies (Dozzi & AbouRizk, 1993), it is interesting to note how the percentages of time were reorganized and where the shift in the productivity numbers occurred within the support work and delay categories. This is the area where the ideal state workflow appears to become further supported through a time utilization rate trend reversal due to an opposite intervention being implemented. Figure 43 denotes the final labor time utilization rates. Table 21 denotes the corresponding minutes for each category. Figure 44 juxtaposes pre and post intervention results.

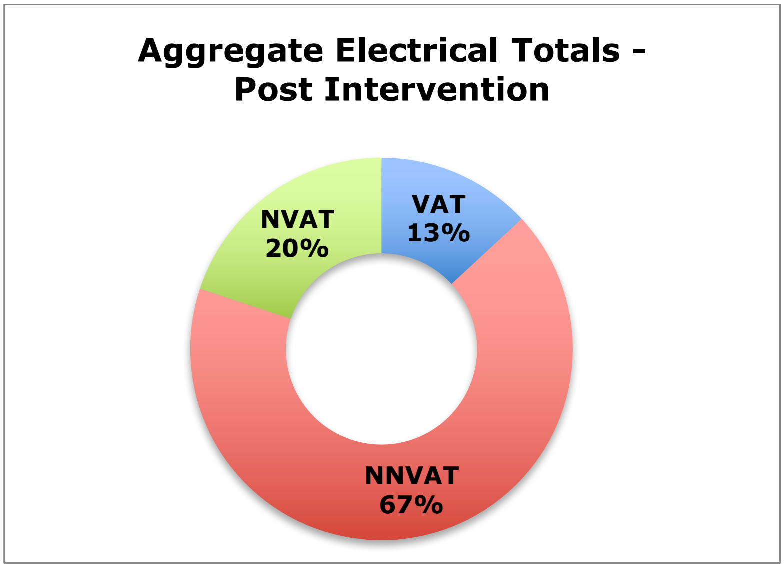


Figure 43: Aggregate Electrical Time Utilization Totals - Post Process Intervention

Table 21:

Aggregate Electrical Time Breakout - Post Process Intervention

Total Direct	Total Support	Total Delays	Totals
135 min.	690 min.	205 min.	1030 min.
13.11%	66.99%	19.90%	100.00%
2.25 hrs.	**11.50 hrs.**	**3.42 hrs.**	**17.17 hrs.**

As the same observation matrix was utilized for the second round of data collection during the validation period, this allowed the data to be broken out into identical categories as that of the original time utilization rate analysis. When comparing the data for the electrical trade, before and after the schedule compression, a shift in support work can be seen mainly in the allocation of time for Internal/External Trade Coordination. This can clearly be seen in Figure 45. Figure 46 and Table 22 breakout this data into the following discussion. Whereas in the original observations this category totaled 29.12% of support work time, during a compressed schedule this jumps to a total of 44.2% of dedicated support work time. Normalizing this data into percentage of a 10-hour work day shows an increase of nearly 84 minutes of total time needed for internal/external trade coordination. This increase in time comes at the expense of upfront design package review and preparatory work for modeling. The time spent properly preparing models via standardized processes and reviewing the released design package for proper information decreased by a combined 6.57% of total support work time, or close to 10 minutes per day. While this doesn't seem like much in the grand scheme of things, add-in the 12-minute decrease in properly uploading and downloading up-to-date models and a severe communication breakdown can be seen, in which current data is not utilized for properly modeling. This process also sees a 6.57% increase in the use of laser scans for supplementing the modeling information equating to an increased time of use of 27.5 minutes per 10-hour day. The question now becomes, "if laser scans are supposed to effectively communicate existing conditions, ultimately replacing the need for existing conditions geometry, in a congested retrofit environment, why do we see such an increase in trade communication for properly executing a prefabrication model when laser scan usage increased seven-fold and overall productivity dropped by 7%, or 42 minutes per 10-hour workday?" The case-study conditions effectively exist in the opposite state of what prefaBIM suggests. While a reduction of nearly 36 minutes per day in delays can be seen, overall performance suffers dramatically and utilization of time for support work has increased by over 20% per 10-hour workday over the initial state of operations.

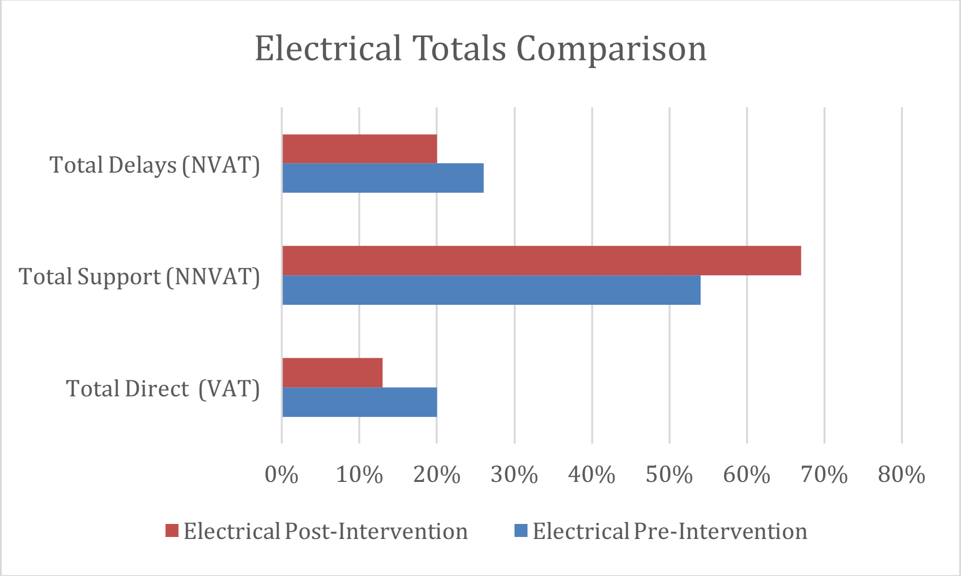


Figure 44: Electrical Trade Time Utilization Comparison

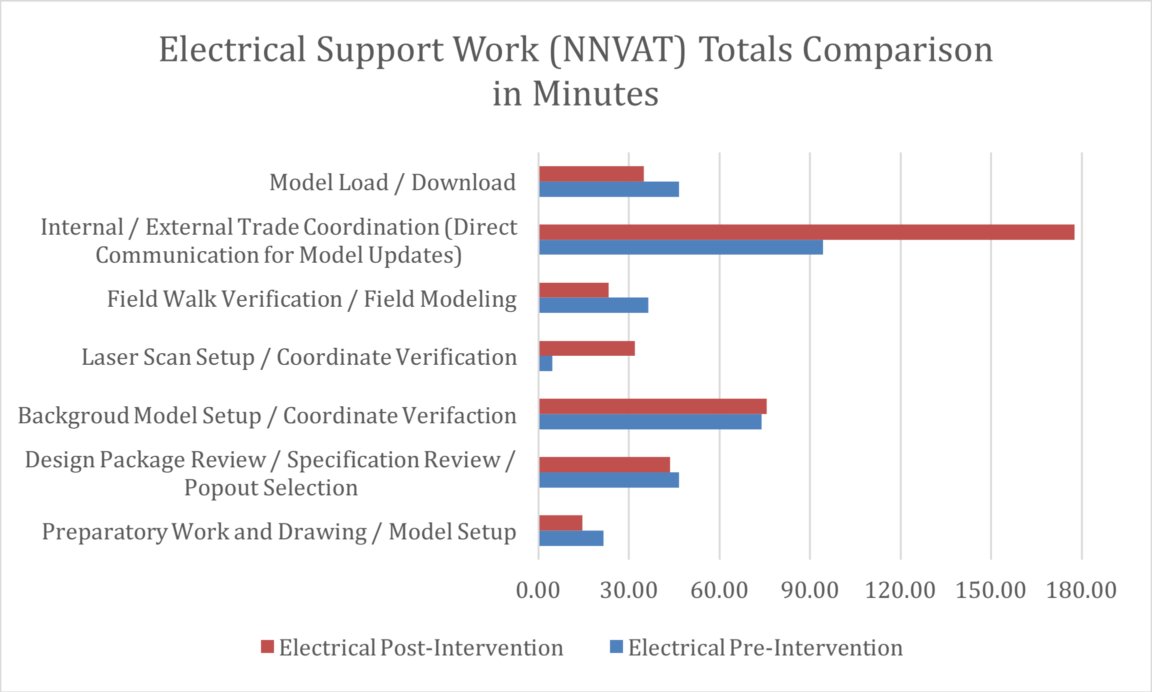


Figure 45: Electrical Trade Support Work Time Utilization Comparison (Mins./10 hr. day)

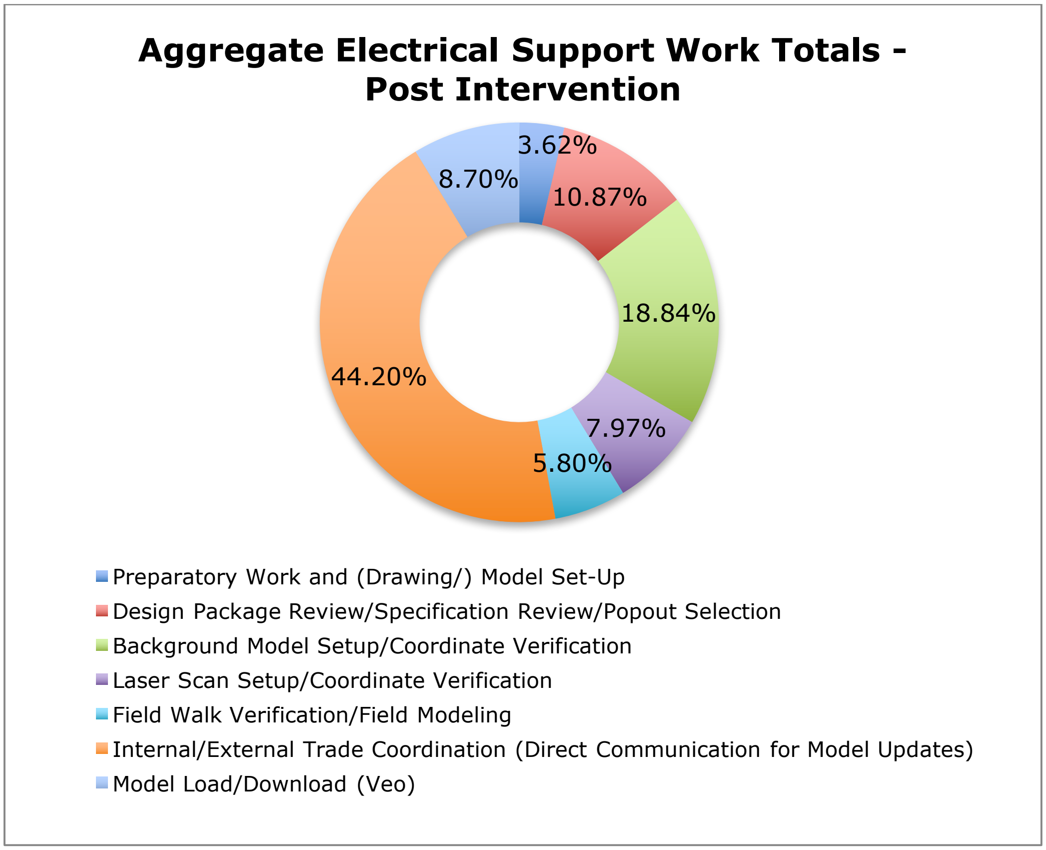


Figure 46: Electrical Trade Support Work (NNVAT) Time Utilization – Post Intervention

Table 22:

Electrical Trade Support Work (NNVAT) Time Breakout

	Minutes	Hours	Total Percentage
Preparatory Work and Drawing / Model Setup	25	0.42	3.62%
Design Package Review / Specification Review / Popout Selection	75	1.25	10.87%
Background Model Setup / Coordinate Verification	130	2.17	18.84%
Laser Scan Setup / Coordinate Verification	55	0.92	7.97%
Field Walk Verification / Field Modeling	40	0.67	5.80%
Internal / External Trade Coordination (Direct Communication for Model Updates)	305	5.08	44.20%
Model Load / Download	60	1.00	8.70%
Totals	690	11.50	100%

Figure 47 and Figure 48 break down the electrical delay totals for labor time utilization. The area of focus becomes that of the re-setup/re-drawing/re-modeling coupled with the field re-verification and updated scan request / re-scan components. Through observations (Table 23), it is noted that the mechanical and process trades usually trump the electrical trade when it comes to access and coordination of routing. As the equipment, systems and routes are generally larger in volume than that of conduit runs and wire way, the first-come first-serve model of routing design falls short from an electrical standpoint. While mechanical and process trades begin the design process, the electrical trade generally will be seen modeling placeholder routes while waiting for correspondence from the mechanical and process trades regarding where they plan to run a particular reference. While this was typically seen in the current state process during the first round of observations, when the schedule was compressed this was not the case. The electrical trade spent more time coordinating through various communication channels (such as emails and instant messages) while waiting for final routing conditions to be known. The interesting thing to note is that while the electrical trade spent more time communicating with the mechanical and process trades regarding routing, the reciprocal did not take place. It was observed that the mechanical and process trades would engage in existing conditions verification and laser scanning without communicating back to the electrical trade for coordination of scan locations. It can be seen that the mechanical and process trades were the drivers of overall schedule and the electrical trade was constantly playing catchup to meet deadlines. This can be seen in the overall reduction in re-modeling and field re-verification, at a total of a little more than 20 minutes per 10-hour workday because they would stall the modeling process and rely on previous laser scan data and updated screen shots of coordinated background models provided by the mechanical trade, as well as the non-existent re-scanning process for up to date existing conditions capture. Finally, overall duplication of time (Table 24) throughout the process decreased by a total of 6.3%, or approximately 38 minutes per 10-hour workday. This can be allocated to the extensive shift in time utilized for coordination communication and lag-time in the process due to mechanical and process piping driven modeling techniques.

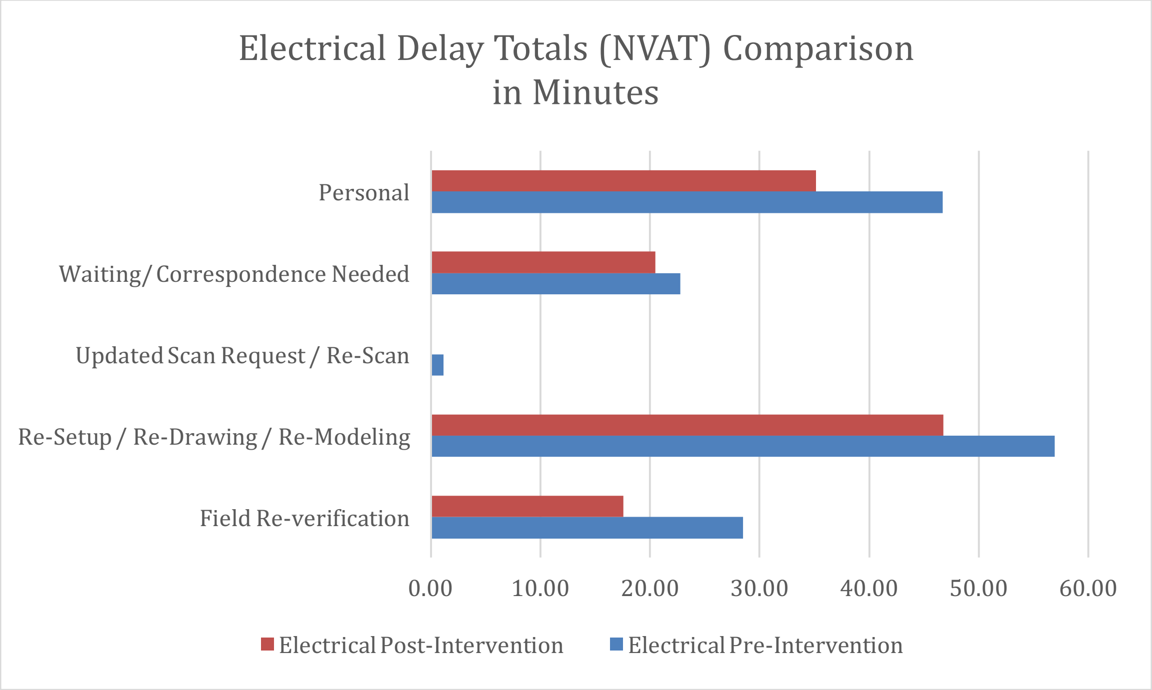


Figure 47: Electrical Delay Totals Comparison in minutes/10 hour workday

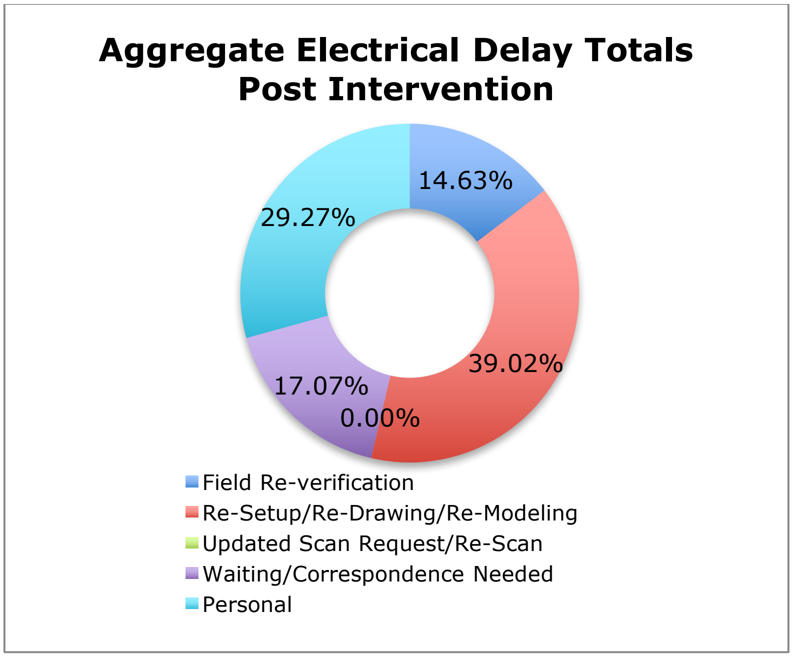


Figure 48: Electrical Trade Delay (NVAT) Time Utilization Post Intervention

Table 23:

Electrical Trade Delay (NVAT) Time Breakout

	Minutes	**Hours**	**Total Percentage**
Field Re-verification	30	0.50	14.63%
Re-Setup / Re-Drawing / Re-Modeling	80	1.33	39.02%
Updated Scan Request / Re-Scan	0	0.00	0.00%
Waiting / Correspondence Needed	35	0.58	17.08%
Personal	60	1.00	29.27%
Totals	205	3.42	100%

Table 24:

Electrical Trade Process Duplication Time Breakout (Post-Intervention)

	Minutes	**Hours**	**Total Percentage**
Process Duplication Time	110	1.83	10.68%
Total Observed Time	1030	17.17	100%

CHAPTER 6

DENOUEMENT: A DISCUSSION

This chapter will introduce the research results and contributions to the greater body of knowledge. Section 6.1 – Scalability of prefaBIM Framework Development discusses the applicability of the prefaBIM framework and overall procedure for utilizing the research findings on a global scale. Section 6.2 – Research Limitations revisits the nature of the research approach and presents limitations that should be considered when procedures presented in this dissertation are applied to future studies. Section 6.3 – Future Research presents directions for furthering the findings of this study towards the establishment of a roadmap for a model-based delivery system in retrofit construction. Finally, Section 6.4 – Closing Statements highlights the main takeaways from the research.

The research discussed in this dissertation is an immersive look at BIM use for retrofit tool installation/conversion at a cutting-edge semiconductor manufacturing facility. The research focused on the modeling-workface and analyzed the overall labor time utilization for the creation of prefabrication, construction models. Furthering the discussion, the research utilizes Lean Manufacturing theory to categorize the observations regarding modeling time into VAT, NNVAT and NVAT and investigated the links between various modeling tools and the subsequent implications on overall workflows. The basis for observation is rooted in a comprehensive literature review and the findings of surveys taken by case-study stakeholders at varying levels of decision-making. Based on this foundation, it was concluded *that the planning efforts surrounding the development of accurate and reliable/trusted geometry is the most important component for successful implementation of a BIM for prefabrication workflow, in a retrofit environment*. This conclusion is the basis for the development of the dynamic modeling workflow, prefaBIM, presented in Chapter 5 and subsequent observation matrix for effectively measuring process changes presented in Chapter 3. The research elaborates on this conclusion in the following ways:

- In a retrofit environment, accurate and trusted geometrical information is seen as the most important component of information for modeler's reference/use in the creation of routing designs for prefabrication. Accurate geometry relates to the following:
    - Validated and trusted base-build geometric conditions
    - Accurate and consistent capture of evolving existing conditions and related changing physical constraints.
    - Trade provided routing geometry for timely and consistent coordination.
- Critical scheduling components for prefabrication efforts in retrofit environments lie within upfront planning efforts for the provisions of accurate and appropriate 3D geometry and proper freezing of related data at established milestones.
- Translation of information between 2D and 3D design packages introduces process confusion and adds to the introduction of inaccuracies in modeling for prefabrication. Proper identification of 3D geometry requirements is needed at both the macro and micro level of project planning.

6.1 – Scalability of prefaBIM Framework Development

By comparing the current state modeling practices vs. ideal state modeling practices, a roadmap for BIM implementation in a retrofit scenario was created. This ideal state - prefaBIM, while defined through an immersive study within a specialized environment, can be extended to the global field of retrofit construction. The following method assisted this project and can be extracted for replication:

- **Goal:** To maximize labor time utilization of the modeling workforce related to Value Added Time (VAT) in the creation of reliable construction models for prefabrication of MEP components, in a retrofit construction environment.
- **Objectives:**
    - Identify the current state of information delivery to the modeling workface
    - Define the current state modeling process and distinguish deviations in the workflow from that of the ideal state presented in Chapter Five
    - Recommend and measure the impacts of process changes in order to document and achieve the a dynamic modeling workflow – prefaBIM, for the retrofit project typology
- **Procedure:**
    - *Step One* – Identify the BIM phases within the project execution plan and define the geometrical needs for each deliverable in the phase.
    - *Step Two* - Identify the procedures for existing conditions capture in the construction project and translation of the data to each stakeholder.
    - *Step Three* – Define the timing for informational handoffs between BIM Stakeholders in the construction modeling process.
    - *Step Four* – Identify the informational needs of the modeling work force to effectively create construction, routing models for

    prefabrication.

    - *Step Five* – Utilize the Observation Matrix to measure labor time utilization (the duration of identified tasks) at the modeling workface.
    - *Step Six* – Discuss the trends in workflows and observations at an aggregate site and trade-centric level to address both macro and micro project management procedures affecting labor time utilization.
    - *Step Seven* – Implement process changes as an organization, or project team, which lend towards the creation of a dynamic modeling workflow as identified in Chapter 5.
    - *Step Eight* – Utilize the Observation Matrix regularly to measure the effects any process changes undertaken by the project team and further the documentation of best practices related to the prefaBIM framework.

As an increase in VAT was not directly seen during the case-study following the various interventions and process changes and since the retrofit construction efforts are still on-going at the case study site, this research puts forth several recommendations to the owner. In order to further validate the prefaBIM, dynamic modeling workflow for the complex environment, the following recommendations are made:

- Verify and validate background model geometry to achieve the assumed geometry in the Ideal State condition
    - Implement a system to track changes and updates to the model for reduction in duplication of efforts

    - Utilize a staged (piecemeal) approach to consolidating the federated model for use in dynamic modeling for prefabrication

A balanced approach to updating the assumed geometry in the Ideal State process over time can be introduced to begin assembling a more usable and reliable background and base-build model for simultaneous deployment. It is imperative to close the modeling loop on installation of prefabrication routes and subsequent accuracy of correlated construction models.

6.2 – Research Limitations

Due to the specialized and complex nature of the case-study environment, a few limitations must be highlighted for consideration in future research endeavors.

- Access to similar sites for comparative research was not possible due to the complex nature of the case-study site. Thus, this research is unable to directly introduce more generalized results from a multiple case study approach as it relates to the constraints of the case study. This being said, the research methods and research findings can be extracted and applied to the retrofit construction industry at large from a holistic standpoint. The findings relating to geometrical importance in the preplanning through execution phases are intended to assist project teams in successfully prefabricating in any retrofit construction environment through the introduction of a singular model-based delivery system.
- While the timing of the study aligned with a ramp in construction operations at the case study site, the existence of multiple variables created conditions that were, at times, difficult to control for an extensive collection of data at multiple time frames. Due to this scenario, in order to create ideal data collection conditions for acceptable comparison, timing

constraints became the driver for the amount of data points that were ultimately collected and presented in Chapter 4.

- Continued cooperation and access to the stakeholders and related modeling teams involved in the research presented both a research constraint and limitation. Free access to measure modelers was not always, or consistently, granted by each stakeholder, thus limiting the amount of data available for collection. Modeler turnover was also present throughout the study due to the nature of internal resource leveling and matching headcount to workload. This also presented a limitation in data available for comparative analysis.

6.3 – Future Research

Leveraging BIM for construction automation has been identified as a potential for increased site-wide construction productivity and offers the potential for greater return-on-investment. By leveraging the full capabilities of BIM for off-site construction techniques and introducing a dynamic modeling process for prefabrication, it is further hypothesized that productivity increases and reliability of processes may be seen in retrofit construction. The following areas of research lend themselves towards future research avenues based on observations and findings of this study:

- Further developing the implementation plan and corresponding capabilities matrix for prefaBIM and developing a system for optimizing the amount of prefabrication undertaken during a retrofit/conversion project.
- Developing the various workflows and information exchanges for the introduction of a life cycle, model-based delivery system for facilities utilizing the ideal state presented in these research findings.

- Interjecting augmented reality into the layout and/or installation process of semiconductor capital equipment conversions to reduce the need for manual processes and begin automating the overall information transfer process. This responds to the need for 3D geometrical information to exist longer in the overall BIM process.
- Data standardization for the introduction of rules-based modeling and just-in-time modeling techniques for automated routing of services.

6.4 – Closing Statements

Revisiting Section 3.5, the conclusion of this research is that *the introduction of a dynamic modeling process for retrofit prefabrication – prefaBIM - will help to streamline the BIM process at the modeling work-face and ultimately lead to reliable assumed geometry up-stream and in turn introduce a productivity increase of the install teams down-stream through accuracy and reliability of geometric and semantic information.* While prefabrication has been introduced into the construction supply-chain prior to the use of BIM, BIM offers a substantial opportunity for increased productivity on a jobsite when planned and managed correctly.

The initial objective of this research was to identify the current state of BIM as a construction tool for prefabrication. The researcher was able to model the current state of information transfer as it relates to BIM content management and propose an ideal state for which to begin phased implementation of recommendations. It was observed that there was a distinct mistrust in provided information for modeling and as a result various tools were used to verify existing conditions at more than one point in the modeling process. This duplication of existing conditions capture and the use of various tools throughout the process created bottlenecks in the work processes and redundancies in the overall system.

The second objective of the research was to identify the opportunities for automation within a prefabrication facility to increase overall throughput. This portion of the study remains ongoing and components for advancing this research have been identified in Section 6.3 – Future Research. It was observed that these areas of future research are predicated on correcting the upstream information flow for the modeling workface.

Utilizing BIM in a retrofit setting is an area with little research focus and documented best practices. This research study has successfully utilized a mixed-method research procedure to present labor time utilization rates for how time is utilized in the process of modeling for prefabrication in a live, semiconductor manufacturing facility retrofit setting.

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APPENDIX A

SURVEY INSTRUMENTS

Interview: Structured Questions

General (Skipped if short on time):

What is the facility type?
Is it a new construction or retrofit?
What is the preferred project delivery method and contracting procedure?
What is the project size (sq.ft.)?
Where is the project located?
What is the proposed schedule for completion? Requirements?
What is the total project cost?
What is the cost of BIM services (as a %age of total cost)?
What is the cost of prefab (as a %age of total cost)?
What type of PPMOF (modules versus site assembly) was utilized?

Owner

Was BIM a contract requirement? Y/N and why?
Was prefabrication a contract requirement?
What is the expected outcome from BIM and prefab?
Subcontractor procurement? Low bid or performance based?
Schedule driver and impact? Time to market?
Project Manager/BIM Coordinator
What functionalities of BIM are being used?
What software is being used?
What is the final deliverable?
What is the goal at turnover for the BIM deliverable?

Trades

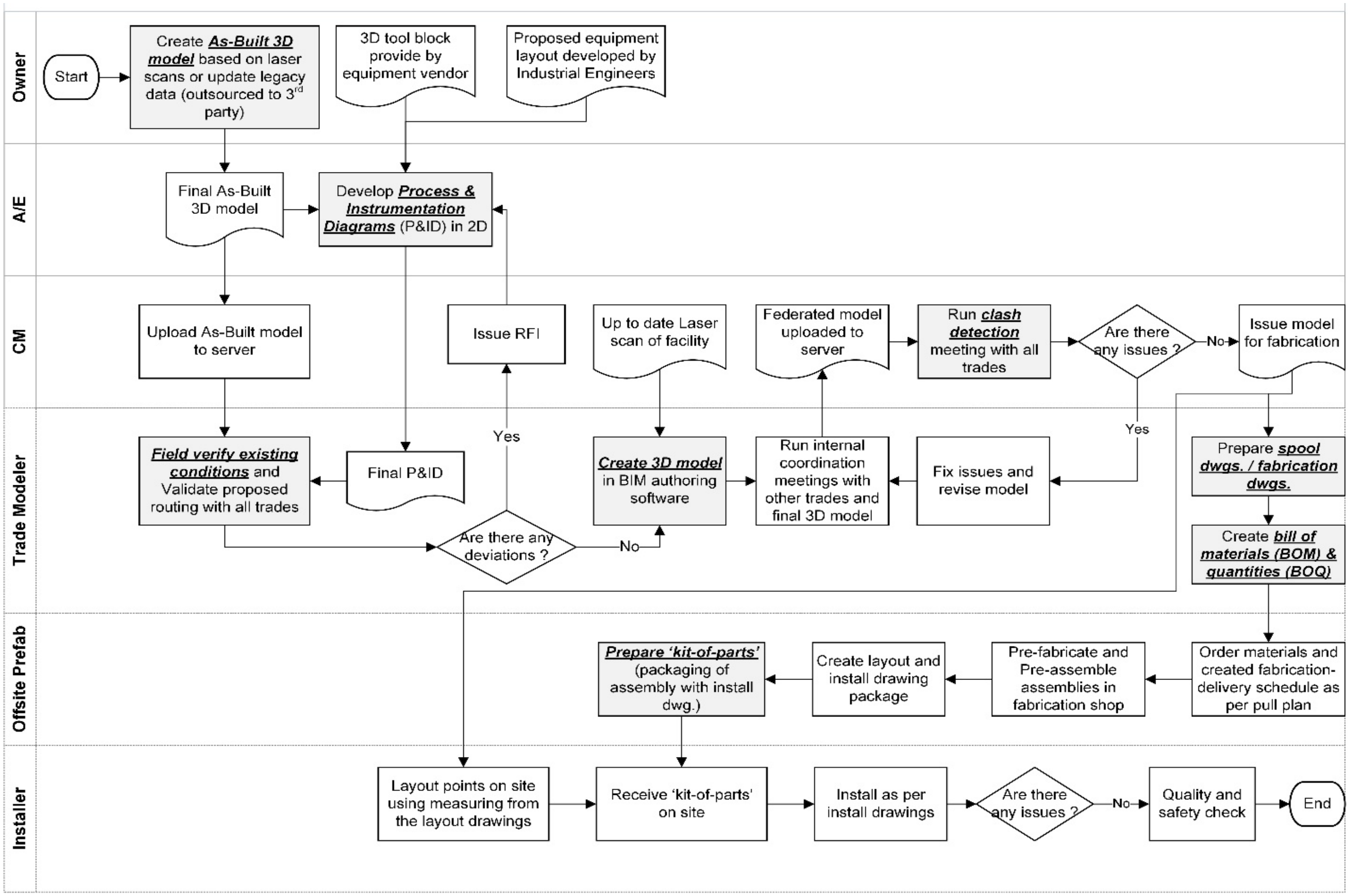
Do you do your own 3D modeling or outsource?
What software is used within your company?
Do you own your own prefabrication facilities?
How do you decide how much to prefabricate? When in the project lifecycle do you begin prefabrication?
What drives prefabrication: schedule, cost, labor, materials, owner requested?
What is the process for routing design and detailing?
Are you collaborating with other trades for prefabrication? Example: shared hangers
What is the process for collaboration for BIM?
How are spool drawings created? From the BIM model or hand detailed
How do you track materials/prefabricated assemblies?
Do you use any automation for prefabrication and installation?
What are the main constraints you've identified when implementing a prefabrication solution for facility construction: on site and off site (physical, management, personnel, schedule, materials, cost)?

BIM Process Map

Name: ______________ Date: ______________

Please verify the process for your position (add any relevant steps not currently included/ subtract any steps that do not pertain to existing processes):

Circle your role in the process on the left side (ie. Owner, AE, CM, Trade Modeler, Offsite Prefab, Installer)



Critical Success Factors – Conversion Tools

Name: ____________________

Company/Trade: ______________________

Date: ________________

Existing Conditions Capture

In an ideal state, place the following existing conditions capture techniques in order of most useful to least useful when modeling for prefabrication for tool conversion. Number 1 through 8 where 1 = most useful and 8 = least useful:

______ Accurate base-build model geometry at the start of a project ramp

______Continuously updated base-build model geometry through project duration

______Laser scans of whole facility at the start of a project ramp

______Laser scans of functional areas at the start of a project ramp

______Tool specific laser scans at the start of a project ramp

______Continuous laser scanning of bays through project duration

______Continuous field-walk verification through project duration

______Modeling in the field through project duration

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
Existing Conditions Capture					
1. Accurate Base-Build Model Geometry is needed prior to a ramp in construction operations	1	2	3	4	5
2. Continuously updated Base-Build Model Geometry is needed throughout the duration of construction operations.	1	2	3	4	5
3. Laser Scans of the facility in its entirety can replace a Base-Build Model	1	2	3	4	5
4. Laser scans must be externally validated by a model coordinator before being used in modeling process for prefabrication	1	2	3	4	5
5. Laser scans must be internally validated by trade organization before being used in modeling process for prefabrication	1	2	3	4	5
6. Continuous laser scans of each functional area would expedite the modeling process	1	2	3	4	5
7. Verified laser scans of specific sub-fab bays would expedite the modeling process	1	2	3	4	5
8. Laser scans are always out-dated	1	2	3	4	5
9. Laser scans are too slow in capturing the sub-fab environment throughout the duration of a conversion project	1	2	3	4	5
10. A base-build model is needed in order to accurately model for prefabrication	1	2	3	4	5
11. A field-walk is needed in order to capture existing conditions	1	2	3	4	5
12. Modeling in the field is the best way to verify existing conditions	1	2	3	4	5
13. Once validated by the model coordinator, a facility base-build model can be utilized for measurements	1	2	3	4	5
14. Continuous field walks are the best way to verify existing conditions	1	2	3	4	5

Critical Success Factors – Retrofit Prefabrication

Name: ______________________

Company/Trade: ________________________

Date: ________________

Fabrication Model Detailing Process

In an ideal state, place the following existing conditions capture techniques in order of most useful to least useful when modeling or detailing for prefabrication for retrofit construction projects. Number 1 through 7 where 1 = most useful and 7 = least useful:

______ Accurate base-build model geometry at the start of a project

______Continuously updated base-build model geometry through project duration

______Laser scans of whole facility at the start of a project ramp

______Laser scans of critical areas at the start of a project ramp

______Continuous laser scanning of installations through project duration

______Continuous field-walk verification through project duration

______Modeling in the field through project duration

	Strongly disagree	Somewh at disagree	Neither agree nor disagree	Somewh at agree	Strongly agree
Fabrication Process					
1. Accurate Geometry is needed in order to reliably model and prefabricate assemblies	1	2	3	4	5
2. Design freeze is needed in order to reduce re-work of prefabricated components	1	2	3	4	5
3. Automated technologies could help introduce reliability in prefabricated assemblies	1	2	3	4	5
4. Automating spool drawings helps expedite the process of detailing for prefabrication	1	2	3	4	5
5. Model to machine (CAD to CAM) is the ideal state for prefabrication facilities	1	2	3	4	5
6. You always receive the necessary information to reliably detail a prefabricated component the first time	1	2	3	4	5
7. Modeled geometry from the field is physically constructible the first time	1	2	3	4	5

Critical Success Factors – Conversion Tools

Name: ______________________ Company/Trade: ______________________

Position: ________________________ Date: ______________________

Modeling Infrastructure Survey

1) Would a single server enhance BIM activities (circle)? Y / N

2) Where do you currently model for prefabrication (circle)? on-site / off-site

3) Does your team automate spool drawings (circle)? Y / N

4) Does your team utilize automated fabrication techniques ie. CAD-to-CAM (circle)?

Y / N

5) Does your team verify installation to match the model (circle)? Y / N

6) As an estimate, what percentage of installation is checked against the model?

7) Do you prefer co-location (modeling in the same room with all critical trades) when modeling (circle)? Y / N

8) What value does co-location bring and/or takeaway from the modeling process (short answer below)?

9) What platform do you utilize for modeling (ie. authoring tools)? Please list below:

APPENDIX B

INFORMATION FROM SURVEYS

Task: Process Mapping Review Comments			Themes			Summary
			Field Verification	Construction Modeling	Installation	
Modeling Workface						
Modeler 1						
ID	1	Identified Process at Owner Level	update(s)	n/a	n/a	*Process:* field validation is critical to resource effectiveness *Document(s):* more accountability needed for updated and accurate information
Component	1.1	*Process: Create As-Built 3d model based on laser scans or update legacy data (outsourced to 3rd party)*				
Comment	1.2	If Scans are not up to date alternative is field validation. Uses up twice the amount of time and resources				
ID	2	Identified Document at Owner Level	incorrect tool block	verify	n/a	
Component	2.1	*Document: 3D tool block provide d by equipment vendor*				
Comment	2.2	Tool owner needs to verify the tool block more often. We usually get the incorrect block more than once in the ramp.				
ID	3	Identified Document at CM level	n/a	update(s)	n/a	
Component	3.1	*Document: Federated Model uploaded to server*				
Comment	3.2	Not updated frequently				
ID	4	Identified Process at Trade Modeler Level	validation	n/a	n/a	
Component	4.1	*Process: Field verify existing conditons and validate proposed routing with all trades*				
Comment	4.2	This should be first!				
Modeler 2						
ID	1	Identified Process at Owner Level	scope definition	scope definition	scope definition	*Process:*definition needed for modeling *Document(s):*duplication of process for accuracy
Component	1.1	*Process: Create As-Built 3d model based on laser scans or update legacy data (outsourced to 3rd party)*				
Comment	1.2	Not necessarily needed for all projects				
ID	2	Identified Document at Owner Level	incorrect tool block	incorrect tool block	n/a	
Component	2.1	*Document: 3D tool block provide d by equipment vendor*				
Comment	2.2	Usually need to create an internal tool block - mostly unusable from tool owner				
Modeler 3						
ID	1	Identified Process at Owner Level	update(s)	update(s)	n/a	*Process:* modeling tools are not consistent
Component	1.1	*Process: Create As-Built 3d model based on laser scans or update legacy data (outsourced to 3rd party)*				
Comment	1.2	As a modeler, if I have updated scans I won't even load a basebuild/as-built model				
Modeler 4						
ID	1	Identified Document at A/E Level	n/a	modeling tool	n/a	*Process:* existing and design geometry needed for coordination *Document(s):* background geometry needed for construction modeling
Component	1.1	*Document: Final As-Built 3D model*				
Comment	1.2	This should be utilized as a background for modeling				
ID	2	Identifed Process at CM Level	n/a	modeling tool	n/a	
Component	2.1	*Process: Upload As-Build model to server*				
Comment	2.2	This should be the modeling background				
ID	3	Identified Process at Trade Modeler Level	geometry	geometry	n/a	
Component	3.1	Process: Create 3D model in BIM authoring software				
Comment	3.2	Most important for coordination is 3D				
BIM Coordinators						
Coordinator 1						
ID	1	Identified Document at A/E Level	outdated	outdated	n/a	*Process:* timing issues related to clash-detection meetings *Document(s):* outdated models and document control procedures (milestone issues)
Component	1.1	*Document: Final As-Built 3D model*				
Comment	1.2	Model is out of date				
ID	2	Identifed Process at CM Level	n/a	outdated	n/a	
Component	2.1	*Process: Run clash detection meeting with all trades*				
Comment	2.2	Difficult to hold clash detection meeting with out of date background and construction models				
ID	3	Identified Document at CM level	n/a	document control	document control	
Component	3.1	Document: Issue model for fabrication				
Comment	3.2	No document control release for final coordination at this point; trades release but sometimes continue detailing the construction model				
Coordinator 2						
ID	1	Identified Process at Owner Level	incorrect	incorrect	incorrect	
Component	1.1	*Process: Create As-Built 3d model based on laser scans or update legacy data (outsourced to 3rd party)*				
Comment	1.2	As-Built model has never been correct				

ID	2.1	Identified Document at Owner Level	incorrect tool block	incorrect tool block	n/a	*Process:* Modeling information lacks accuracy needed for proper routing extending the length of time needed for validated routing *Document(s):* 2D to 3D translation of data causes coordination and accountability issues
Component	2.1	*Document: 3D tool block provide d by equipment vendor*				
Comment	2.2	Tool blocks don't show what is needed for a contractor to model for prefabrication; usually incorrect blocks; recreated by modelers				
ID	3	Identified Document at Owner Level	change(s)	change(s)	change(s)	
Component	3.1	*Document: Proposed equipment layout developed by Industrial Engineers*				
Comment	3.2	Layout takes too long and creates change issues for meeting deadlines				
ID	4	Identified Document at A/E Level	incorrect	incorrect	incorrect	
Component	4.1	*Document: Final As-Built 3D model*				
Comment	4.2	not correct				
ID	5	Identified Document at A/E Level	2D	incorrect	n/a	
Component	5.1	*Document: Develop Process & Instrumentation Diagrams (P&ID) in 2D*				
Comment	5.2	2D package is never correct; coordination issues happen from the start of modeling				
ID	6	Identifed Process at CM Level	update(s)	update(s)	n/a	
Component	6.1	*Process: Upload As-Build model to server*				
Comment	6.2	Not happening for updates				
ID	7	Identified Process at Trade Modeler Level	change(s)	change(s)	change(s)	
Component	7.1	*Process: Field verify existing conditons and validate proposed routing with all trades*				
Comment	7.2	Proposed routing changes all the time during modeling				
Coordinator 3						
ID	1	Identified Process at Owner Level	validation	validation	n/a	*Process:* Information handoffs become complicated when transitioned from 2d to 3d; Validation happens after design package releases causing modeling rework which isn't captured against the field installation; Automation opportunity for simultaneous BOM/BOQ for all trades *Document(s):* Critical routing components need to drive schedule
Component	1.1	*Process: Create As-Built 3d model based on laser scans or update legacy data (outsourced to 3rd party)*				
Comment	1.2	Trades should validate changes to models for construction				
ID	2	Identified Process at Trade Modeler Level	change(s); 2D	change(s); 2D	n/a	
Component	2.1	*Process: Field verify existing conditons and validate proposed routin with all trades*				
Comment	2.2	If there are deviations an email markup or RFI log needs to be submitted and translated to the P&ID drawing package but the A/E team doesn't always release updated packages in time for modeling				
ID	3	Identifed Process at CM Level	n/a	BIM-coordinator	n/a	
Component	3.1	*Process: Run clash detection meeting with all trades*				
Comment	3.2	This should be a trade-level coordinator not an A/E BIM coordinator				
ID	4	Identified Document at CM level	n/a	critical components	n/a	
Component	4.1	*Document: Issue model for fabrication*				
Comment	4.2	There needs to be a quicker process for critical IFF components				
ID	5	Identified Process at Trade Modeler Level	n/a	accuracy	n/a	
Component	5.1	*Process: Prepare spool dwgs./fabrication dwgs. & Create bill of materials (BOM) & quantities (BOQ)*				
Comment	5.2	These steps should happen simultaneously. Seperating causes problems in accuracy				
ID	6	Identified Process at Offsite Prefab Level	n/a	timing	2D	
Component	6.1	*Process: Create layout and install drawing package*				
Comment	6.2	This should happen when spool dwgs. And BOM/BOQ's are created based off of construction model not recreated drawings				
ID	7	Identified Process at Installer Level	n/a	validation	validation	
Component	7.1	*Process: Quality and Safety Check*				
Comment	7.2	There needs to be a way to track rework consistantly in order to redline construction models.				
Coordinator 4						
ID	1	Identifed Process at CM Level	outdated	outdated	n/a	*Process:* Outdated models create inconsistent and innacurate clash-detection
Component	1.1	*Process: Federated model upload to server*				
Comment	1.2	Model is out of date				
ID	2	Identifed Process at CM Level	outdated	outdated	constructability	
Component	2.1	*Process: Run clash detection meeting with all trades*				
Comment	2.2	Federated model not up to date to do this meeting but it is important for team agreement at 100% validation for constructability				
Management Team						
Manager 1						
ID	1	Identified Process at Owner Level				
Component	1.1	*Process: Create As-Built 3d model based on laser scans or update legacy data (outsourced to 3rd party)*				

Comment	1.2	Use existing base-build model	modeling tool	modeling tool	n/a	*Process:* Consistent validation and verification process is non-standard and not repeatable *Document(s):* Upfront information is not delivered to trades in usable format
ID	2	Identified Document at Owner Level				
Component	2.1	*Document: 3D tool block provide d by equipment vendor*				
Comment	2.2	Owner needs to provide accurate block	incorrect tool block	incorrect tool block	n/a	
ID	3	Identified Document at A/E Level				
Component	3.1	*Document: Final As-Built 3D model*				
Comment	3.2	This step is not needed at an A/E level. Not accurate for trade use.	accuracy	accuracy	n/a	
ID	4	Identified Process at CM Level				
Component	4.1	*Process: Upload As-Build model to server*				
Comment	4.2	Updated laser scans should be uploaded at this point as well	modeling tool	modeling tool	n/a	
ID	5	Identified Process at Trade Modeler Level				
Component	5.1	*Process: Field verify existing conditons and validate proposed routing with all trades*				
Comment	5.2	Uploaded scans should also be validated during field verification for routing	validation	verify	n/a	
ID	6	Identified Process at Trade Modeler Level				
Component	6.1	*Process: Run internal coordination meetings with other trades and final 3D model*				
Comment	6.2	Clashing against scans should happen here	n/a	modeling tool	n/a	
Manager 2						
ID	1	Identified Document at Owner Level				*Document(s):* 3d to 2d data packaging causes confusion accuracy issues leading to supplemental validation by individual trades
Component	1.1	*Document: Proposed equipment layout developed by Industrial Engineers*				
Comment	1.2	Why is there a 3D toolblock and 2D layout? Use 3D only.	geometry; 2D	geometry; 2D	n/a	
ID	2	Identified Document at A/E Level				
Component	2.1	*Document: Final As-Built 3D model*				
Comment	2.2	Will it be continuously updated? If not it is always not accurate	update(s)	accuracy	n/a	
ID	3	Identified Document at Trade Modeler Level				
Component	3.1	*Document: Final P&ID*				
Comment	3.2	The trades should validate P&ID in field before final package release	validation	n/a	n/a	
ID	4	Identified Document at CM level				
Component	4.1	*Document: Up to date Laser scan of facility*				
Comment	4.2	This is important	n/a	modeling tool	n/a	
ID	5	Identified Process at CM Level				*Process:* Clash meetings are inconsistent leading to issues with accurate BOM/BOQ's *Decision:* follow-up steps need to be taken for QA/QC of installed routing against geometry
Component	5.1	*Process: Run clash detection meeting with all trades*				
Comment	5.2	This is not happening	n/a	timing	n/a	
ID	6	Identified Process at Trade Modeler Level				
Component	6.1	*Process: Prepare spool dwgs./fabrication dwgs. & Create bill of materials (BOM) & quantities (BOQ)*				
Comment	6.2	Completed installation drawings should come before spool drawings. Issues are found with install drawings that need to be corrected later.	n/a	timing	timing	
ID	7	Identified Decision at Installer Level				
Component	7.1	*Decision: Are there any issues (following "install as per install drawings" process)?*				
Comment	7.2	Field QA/QC against model for updates needed	validation	verify	validation	
Manager 3						
ID	1	Identified Decision at Installer Level				*Decision:* Installation issues need to be captured in models
Component	1.1	*Decision: Are there any issues (following "install as per install drawings" process)?*				
Comment	1.2	If there is an issue with installation the construction model must be revised	verify	update(s)	incorrect	

APPENDIX C

NOTES FROM BIM PIT TEAM MEETINGS

BIM PIT Meeting – 5-12-15

Datum's are set off of **2-d** package – Doesn't match the **3-d** model

Brass plates don't match **3-d** and a shift is needed to match **2-d** package layouts

Piping to the model (when doesn't fit because of column grid not lining up with brass-caps trades are sending out a change order)

Problem is when package comes out to set datum's in the field it is based off of **2d** package but **3d** model shift doesn't match (referencing columns in 3d model)

Model Coordinator doesn't actually coordinate – creating *work-around(s)* instead

A/E dimensions off of column grid; structural contractor layout off the brass caps (two do not match)

Sub-fab level is not aligned with Fab level (shift occurred to mask the error in the field)

First step is to begin layout off of 3-d Model (and translate over time to remove shift)

Naming Conventions for doc control is relaxed – Individuals are adding their own tags and making it difficult to find files that are needed (Variations)

IFM nomenclature changed to Design Finish (main schedule says IFF – Design Finish; Confusion)

There needs to be a package release after DF package (Main site doesn't want **3d** involved with durations – standardize); Change Order and RFI's happen because of the lack of follow-up packages involved with **3d** (Design team and model coordinator doesn't have a contract to send out a final package after DF)

Installation package needs to match what the installers are viewing in the model

Tool owner's constantly make changes – Model is Real-Time?

This is a design-bid-build environment where the Contractors are utilizing CM@Risk but owner is trying to capture the team under what they feel is an IPD contract

5-day AE contract vs. 4-day Contractor SLA

The wheels are falling off of this team's train (**Design exact in 2d cannot match design exact in 3d**)

Why is a **2d** package inherently different than a **3d** package?

There is a gap in pedestals – **Model coordinator** is not responsible for modeling pedestals – that is an A/E role but they don't have a separate contract to do the pedestals

Model Coordinator is not allowing model updates past a certain date (contract issues)

If you wait to field verify the last 2 feet then there is no wasted material but there is wasted man-hours

When you send a field verified spool to the fabrication shop they will call the modelers to ask why there is a differing dimension or missing dimension

Not modeling the last 2 feet gives the installation crew an excuse to "field-fix"

Equipment in the sub-fab is not placed in square (hence the shift)

BIM PIT Meeting – 10-6-15

New pedestal placement from model to model via laser scan (copy data)

PM Software – functional area coordination files are created (automated appending for background)
-600 files over last 3 weeks
-300 files today

NWC's uploaded to PM Software will be placed into the background

Convert in place pedestal model w/ tool block – needed for conversions (1/30 needed) – no fab changes don't need extra information

Trade deliverable for POC file and file management

POC file per tool to be combined

Won't Implement - 35 POC average per tool @3-minutes per POC too costly against contract

Set commands and set processes

Execution needs time in the system to make a new routine

FALSE MILESTONES

The fix is mandated at a trade level to make public for owner to use and own **(IPD contract is not working)** - target adjustment to pay the trades (3-hour increase in durations)

Broken reassignment system - **all workarounds have become routine process**

To be managed correctly the trades need to own the changes (manage the work)

20-minutes for POC xyz location (ROI won't be captured immediately)

Buffer has been taken out of durations (Subfab is not any easier to work in- it is only getting more congested)

Profitability needs to be seen on a quarterly basis not second life tool project

Model quality for mechanical/process trade has decreased since the implementation of scanning.

Mechanical scanned and modeled only to scan (non-invasive measurement and saved 4-weeks of scaffolding erection time)

Clash versus scans (BIM Cx)

100's of field measurements can be taken but the scan catches the single bust possible for an entire line

28-days for a super complex tool

Main site is doing it cheaper through hand drawing

Systemic from use of multiple tools (scans, models, drawings and field measurement)

False content milestones

Main site where standards are created has more space and zoned Subfab and case-study site has lost the zones

BIM is a planning tool to enable allows you to see the future not just existing routing

Toolblock database decisions and accuracy issues based on contractor notes and markups.

Flex connections after gas sticks are proven and okay by vendor but not an owner accepted standard.

FWR (Markups) - 1DR (markups become live) - Design finish is final package - IFF - IFC two days after IFF

Scan schedule per tool not per contractor

Systemic from muddied waters trying to define new process and differences between old process for comparison and implementation.