Analyzing the Impact of Building Information Modeling (BIM) on Labor Productivity in Retrofit Construction: Case Study at a Semiconductor Manufacturing Facility

by

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ABSTRACT

Economic and environmental concerns necessitate the preference for retrofits over new construction in manufacturing facilities for incorporating modern technology, expanding production, becoming more energy-efficient and improving operational efficiency. Despite the technical and functional challenges in retrofits, the expectation from the project team is to; reduce costs, ensure the time to market and maintain a high standard for quality and safety. Thus, the construction supply chain faces increasing pressure to improve performance by ensuring better labor productivity, among other factors, for efficiency gain. Building Information Modeling (BIM) & off-site prefabrication are determined as effective management & production methods to meet these goals. However, there are limited studies assessing their impact on labor productivity within the constraints of a retrofit environment. This study fills the gap by exploring the impact of BIM on labor productivity (metric) in retrofits (context).

BIM use for process tool installation at a semiconductor manufacturing facility serves as an ideal environment for practical observations. Direct site observations indicate a positive correlation between *disruptions in the workflow* attributed to an immature use of BIM, waste due to rework and high non-value added time at the labor work face. Root-cause analysis traces the origins of the said *disruptions* to decision-factors that are critical for the planning, management and implementation of BIM. Analysis shows that stakeholders involved in decision-making during BIM planning, management and implementation identify BIM-value based on their immediate utility for BIM-use instead of the utility for the customers of the process. This differing value-system manifests in the form of unreliable and inaccurate information at the labor work face.

Grounding the analysis in theory and observations, the author hypothesizes that stakeholders of a construction project value BIM and *BIM-aspects* (*i.e.* geometrical information, descriptive information and workflows) differently and the accuracy of *geometrical information* is critical for improving labor productivity when using prefabrication in retrofit construction. In conclusion, this research presents a *BIM-value framework*, associating stakeholders with their relative value for BIM, the decision-factors for the planning, management and implementation of BIM and the potential impact of those decisions on labor productivity.

DEDICATION

For my grandmother, Shefali Ghosh.

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CHAPTER 1

INTRODUCTION

Building Information Modeling (BIM) and Virtual Design and Construction (VDC) are concepts that have become synonymous with successful design and construction projects in the recent years. Even though globally the construction industry is at various levels of BIM adoption, industry reports and academic research show an increased proclivity to BIM and related subject matters as areas for investment, research and growth (Becerik-Gerber & Kensek, 2010; McGraw-Hill Construction, 2012). In addition to efficiencies in documentation and information management in a projects' life cycle; increased BIM adoption is a result of collaborative contracting and project delivery practices, energy-efficient design, lean construction, off-site prefabrication and a trend towards rapid-prototyping and computer-aided manufacturing (CAM) in construction (American Institute of Architects, 2007; Eastman, Teicholz, Sacks, & Liston, 2011; McGraw-Hill Construction, 2011, 2012). Leading academic journals and several industry and research councils have published and endorsed extensive research on BIM. Hence, we can say that BIM has effectively become the *status-quo* for the Architecture-Engineering and Construction (AEC) industries'. Most of the efforts, however, have been focused on either new construction or existing buildings, which have As-Built models or were originally constructed using BIM (Volk, Stengel, & Schultmann, 2014). Research on BIM for existing buildings primarily focusses in the domain of automated reconstruction of As-Built conditions and evaluating their performance (Tang, Huber, Akinci, Lipman, & Lytle, 2010) and capture of project information for facility management, operations & maintenance (East & Brodt, 2007). As it will become clear from the findings of this study, these important technological innovations are pertinent for the successful implementation of BIM. This research explores the *current* conditions of using BIM for retrofits especially focusing on the labor work face, which is of interest, particularly to owners and contractors who are implementing BIM for retrofits and renovations.

In order to discuss the research appropriately, this section first introduces the definitions of BIM, prefabrication and retrofits, as used in the rest of the study. Next, a brief narrative of the current state of the industry develops the motivation for researching this particular topic. The motivation directly leads to the development of the problem statement, research questions and a method for research. In conclusion, the author discusses the contributions of this research.

1.1. Definition of Terms

1.1.1. Building Information Modeling (BIM)

There are wide-ranging definitions of BIM, which creates different perceptions of what constitutes BIM. A literature review of the definitions of BIM (described in detail in Section 2.3) reveals two perspectives, one viewing it as a representation or an object (*model*) and the other describing it as a process or an activity (*modeling*). The most commonly accepted definition is the one provided by the National Institute of Building Sciences (NIBS) in the National BIM Standards as, *"BIM is 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 basis for decisions during its life cycle from inception onwards."* (National Institute of Building Sciences, 2012). This definition, although succinct can also lead to different understandings for phrases like "shared knowledge resource" and "reliable basis for decisions." In their seminal book, *The BIM Handbook,* Eastman et al. (2011) clarified that BIM is not a software but a human activity involving process changes in design, construction and facility management. In all the definitions reviewed, three aspects of BIM become consistently more apparent. Hence, this study will address BIM as a function of those three aspects, namely:

- ***Geometrical information:*** Defined as the three-dimensional parametric modeling of geometry representing physical building components, including factors such as local attributes, spatial attributes and dimensions.
- ***Descriptive information:*** This includes the functional characteristics and semantic data about the objects, including information such as the type, function, material, cost, etc. It constitutes the object, specifications, performance requirements and all the information to construct and maintain the building.

Table 1

Drawing vs. Model

2D/3D CAD Drawing	3D CAD Model
Vector-based drafting system	Three-dimensional representation of an object as solids and/or surfaces
Independent geometries drawn in any sequence irrespective of their meaning (e.g. symbols for a wall and a door can be drawn independently)	Dependent parts modeled in the sequence that resembles the creation of the physical part. (e.g. in order to place a door, first a wall must be present)
Manual updates to the geometry result in corresponding updates to dimension values	Geometry can be changed by controlling the dimensional values
No constraints or relationships between geometric-primitives (typical, can be programmed)	When assembling components, constraints or "rules" can be placed on components to restrict their movement
Updates to one view do not propagate to the rest of the views (e.g. changes in plan view have to be manually edited in the elevation or 3D view)	Changes are made to the object; hence, corresponding updates to all views happen simultaneously
Data reuse is in the form of “blocks” placed as external references or “xrefs” to the master drawing	A project file is typically associated with a “library” file path, which stores parts or assemblies of components

Note. Adapted from *2D to 3D Comparison,* Autodesk, July 2014.

- ***Workflows:*** This aspect refers to the process of planning, implementing and using 3D CAD models with geometric and descriptive information; including, but not limited to acquiring, managing, modifying and updating information.

This dissertation also refrains from using the term “BIM model," rather refers to project documentation by their primary representation, namely: 2D or 3D CAD drawing (two- or three-dimensional computer-aided-design drawing) and 3D CAD model (three-dimensional computer-aided-design model). Table 1 highlights a few differences between the terms “drawing” and

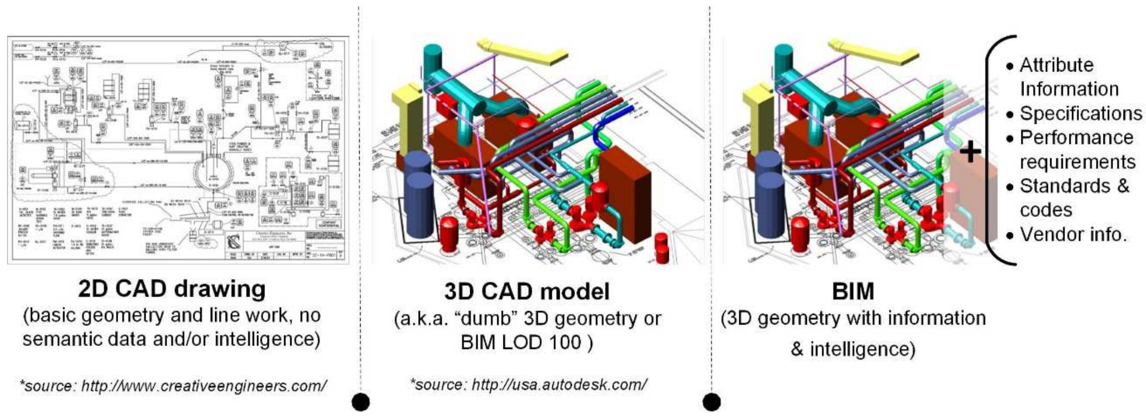

Figure 1. Difference between 2D, 3D and BIM

"model," which is critical in understanding the level of adoption of "true-BIM" and the reasons for differing results from the use of BIM.

To reiterate the above; 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 (see Figure 1).

1.1.2. Retrofit Construction

In recent literature, retrofits and renovations have generally been associated with design changes and modifications related to energy upgrades to meet environmental standards. For the sake of uniformity, this research uses the definition provided by Sanvido & Riggs (1991) for a retrofit project, which is:

> *"A retrofit project is the modification or conversion (not complete replacement) of an existing process, facility, or structure. Such modifications may involve additions, deletions, rearrangements, or not-in-kind replacements of one or more parts of the facility. Changes may alter the kind, quantity, cost or quality of products or services being produced by the facility."*

1.1.3. Prefabrication & Pre-assembly

Prefabrication, pre-assembly, off-site fabrication and modularization, together known as PPMOF, have very similar meanings. They are differentiated based on their fabrication process, location of fabrication plant and number of trades involved. The Construction Industry Institute (CII) provides the following definitions for PPMOF (Haas, O'Connor, Tucker, Eickmann, & Fagerlund, 2000) :

- "**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.
- **Pre-assembly:** A process by which various materials, prefabricated components, and/or equipment are joined together at a remote location for subsequent installation as a unit.
- **Modularization:** Preconstruction of a complete system in modules, away from the job site that is then transported to the site.
- **Offsite fabrication:** The practice of pre-assembly or fabrication of components at a location other than the installation location"

Pre-assembly is generally a combination of prefabrication and modularization. While prefabrication primarily takes place off-site, pre-assembly may use fabricated components manufactured off-site, which are subsequently assembled, near the site or on-site. In the following chapters, prefabrication and pre-assembly would also connote off-site construction.

1.2. Background & Motivation

1.2.1. State of the Architecture-Engineering-Construction (AEC) Industry

The performance of the construction sector is a key barometer of the economic conditions of a country. Even though it forms only a small percentage of the total gross domestic product (3.7% value added of 2013 US GDP – Bureau of Economic Analysis), the trends of this industry influence almost every aspect of the US economy (Huang, Chapman, & Butry, 2009). Dubois & Gadde (2002) observe that the construction industry operates as loosely coupled system as a means for coping with the prevailing complexity of construction operations, favoring short-term productivity and compromising on innovation.

Allen (1985) reported that construction real output (value add) per hour declined by 2.4% between 1968 and 1978 as stated by the US Bureau of Labor Statistics, which according to his calculations should have been a negative 8.8%. More recently, an often cited analysis on labor productivity by (Teicholz, 2004, 2013) has indicated a declining trend of negative 0.32% per year for construction and a positive 3.06% per year trend for all other non-farm industries, over a period of 48 years from 1964 until 2012 (see Figure 2). Teicholz attributes this trend to conditions that are intrinsic to the construction industry; unique products, project and site conditions, varying and fragmented teams associated by competitive rather than collaborative contracts, loss of data due to lack of interoperability and industry fragmentation. Teicholz's calculations represent industry-level productivity based on macroeconomics data (output = revenue in constant dollars, input = aggregate labor work hours). Although the studies using macroeconomic data suggest a *decline* in construction labor productivity, researchers have argued the validity of the results because of deficiencies in data collection and data processing and the uncertainties represented by the diversity of construction sectors not represented in the changing output-mix (Huang et al., 2009; Rojas & Aramvareekul, 2003). Goodrum, Haas, & Glover (2010) used task-level data for a sample of 200 activities and determined a positive annual labor productivity improvement of 1.2% between 1967 and 1998. This data was collected from three popular cost books; RS Means' Building Construction Cost Data, Richardson's' Process Plant Construction Estimating Standards

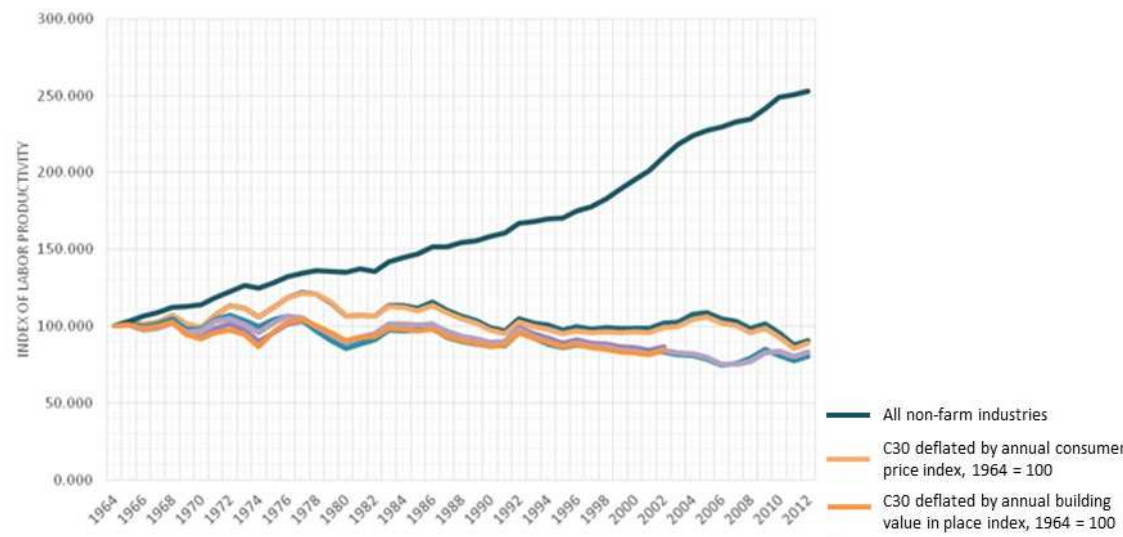

Figure 2. Index of Construction Labor Productivity, 1964-2012 base in Comparison to Labor Productivity in all Non-farm Industries. Reprinted from *Labor Productivity Declines in the Construction Industry: Causes & Remedies (Another Look)* by P. Teicholz, March 2013.

and Dodge Cost Guides. Part of the productivity improvement was attributed to the rising capital per labor ratios among other improvement factors such as technology, worker skills, management systems and workforce relations (Goodrum et al., 2010). These trends determine that construction labor productivity is a critical causal factor of a project's performance as well as the economic growth of the country and hence an important subject for further research.

According to Hanna (2010), poor labor productivity operates at three levels: industry, company, and worker (task). At the industry-level, the loss factors are mostly associated with economics, project delivery systems, the availability of a skilled labor pool and poor quality of design. At the company-level, lacks of training, benchmarking and formal pre-construction planning are reasons for productivity loss. Although at the task-level, Hanna (2010) associates the productivity loss factors to socio-environmental conditions and behavioral factors, the craft workers' perspective is that the top reason affecting their productivity is the unavailability of tools,

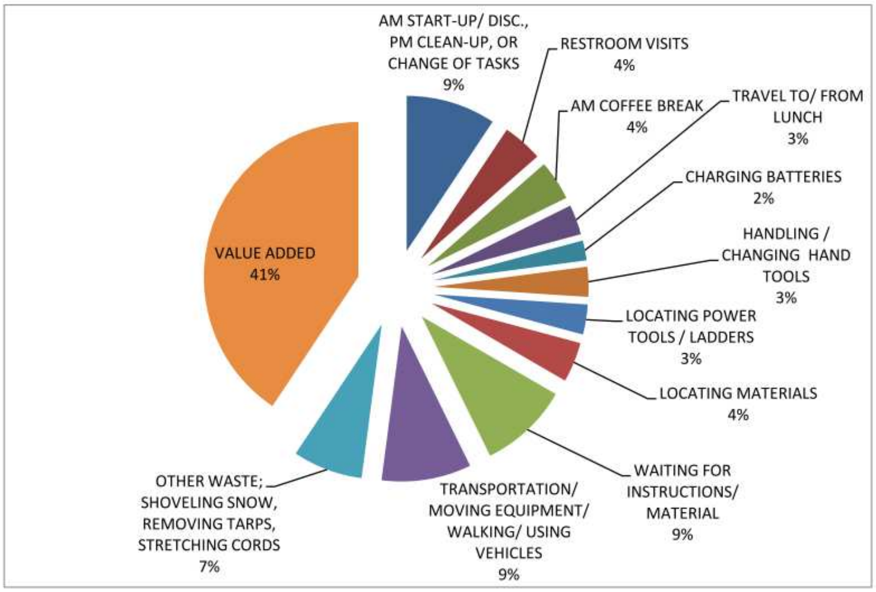

Figure 3. Value-added versus Non-value added Categories in a Typical Workday. Adapted from *Modeling and benchmarking performance for the Integrated Project Delivery (IPD) System* (Doctoral dissertation) by M. El. Asmar, 2012.

materials and equipment and inaccurate engineering drawings (Dai, Goodrum, & Maloney, 2009). Workflow variations and interruptions are attributed as a cause for poor labor productivity at the task level as well (Liu, Ballard, & Ibbs, 2011; Thomas et al., 1990). *"Waste"* i.e. any activity, which does not add value to the process, as perceived by the customer, is also a major cause for concern contributing to productivity loss factors on a day-to-day basis. Rework on an installed component is thus termed as waste. Hanna (2010) shows (as seen in Figure 3) that on an average, 59% of a workday is attributed to wasteful activities, leaving only 41% of the workday for available productive time. Hewage, Gannoruwa, & Ruwanpura (2011) found the direct tool time as 53.7%, including the time spent on rework. Labor costs make up approximately 30-60% of total costs in the construction phase (Liu et al., 2011) and rework can contribute up to 52% of the project's cost growth (Love, 2002). Thus, when discussing task-level labor productivity, it is important to address both, the factors causing a loss in productivity and waste in the process.

Responding to the problems highlighted in the previous paragraphs, the construction industry is undergoing a revolution of kinds with the encouragement of collaboration between parties, risk sharing between stakeholders and a collective desire to improve the construction process by removing "wasteful" activities and adding "value." The conversation around waste and value has led to the increased adoption of lean construction philosophies such as BIM and prefabrication as potential solutions for productivity improvements (Eastman et al., 2011). The next section will provide a background of the current state of BIM and prefabrication.

1.2.2. BIM and Pre-fabrication as Potential Solutions

The global rate of adoption of BIM has been growing steadily since 2007 (see Figure 4) with the US adoption at 71% of the AEC industry in 2012 (Jones, 2013; McGraw-Hill Construction, 2012). Even though Europe has the longest history with BIM and experienced BIM users, the high percentage of renovation work has kept their rate of adoption low (Jones, 2013). The United Kingdom (UK) government has mandated that by 2016, all centrally procured government construction projects, no matter their size, must be delivered using BIM. Khosrowshahi & Arayici (2012) analyzed the understanding of BIM in the UK construction industry and concluded from their findings that while 60% of the respondents indicated an understanding of BIM at Stage 3 (network-based integration), the implementation level for 54% of the industry was at BIM Stage 1 (object-based modeling). While adoption indicates the acceptance of the technology as a key business driver, implementation of BIM will determine its potential. McGraw-Hill Construction (2012) in their Smart Market research report found that the percentage of players using BIM on more than 60% of their projects grew by 15% for architects and engineers, 21% for contractors and 20% for owners from 2009 until 2014.

The top BIM benefits contributing the most value as outlined by McGraw-Hill Construction (2012) are spatial coordination, visualization, improved collective understanding of design intent, improved project quality and the ability to automate quantity take-offs. Despite the positive outlook and perceived benefits, there are several barriers to implementation categorized as, *(a) technical tool functional requirements and needs* such as data organization, version management, validation, data integrity, standards, data security and lack of communication and

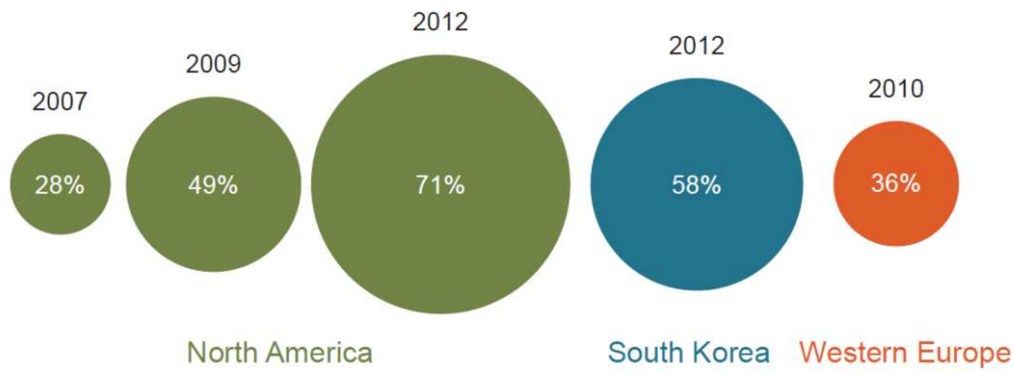

Figure 4. Global BIM Adoption. Reprinted from *Global Industry Trends with Building Information Modeling* by S.A. Jones, 2013 and McGraw-Hill, 2012

information exchange and (b) *non-technical strategic issues* such as changing roles and responsibilities and learning curve (Gu, London, & Dawood, 2010). Other barriers to adoption are attributed to the high investment costs and relatively slow return on the investment (Barlish & Sullivan, 2012; Giel & Issa, 2013).

BIM has shown benefits, especially for MEP contractors. A study of 408 projects by J.C. Cannistraro, an MEP contractor based in Massachusetts, showed that in the big picture, BIM saves more money as the project team becomes more collaborative (see Figure 5). The use of models for fabrication at off-site facilities offers a high degree of accuracy through improved labor productivity at lower cost and greater quality control. Mechanical contractors are the leading users of BIM for fabrication for piping systems and hangers. They are the trade group to have reported the highest productivity on site as shown in Figure 6 and 7 (Jones, 2013). The greatest driver for using prefabrication is improved productivity (82%) and at least 73% of prefabrication and modular construction users in Architecture, Engineering and Construction (AEC) are also users of BIM (McGraw-Hill Construction, 2011). Eastman & Sacks (2008) compared the productivity (value added per employee) of three construction industry sectors with significant off-site fabrication (precast concrete, structural steel & curtain walls) with traditional on-site sectors (cast-in-place concrete, drywall & insulation) and found that off-site productivity grew by 2.32% annually, while the on-site productivity grew by 1.43%. Mikhail (2014) in a survey based research

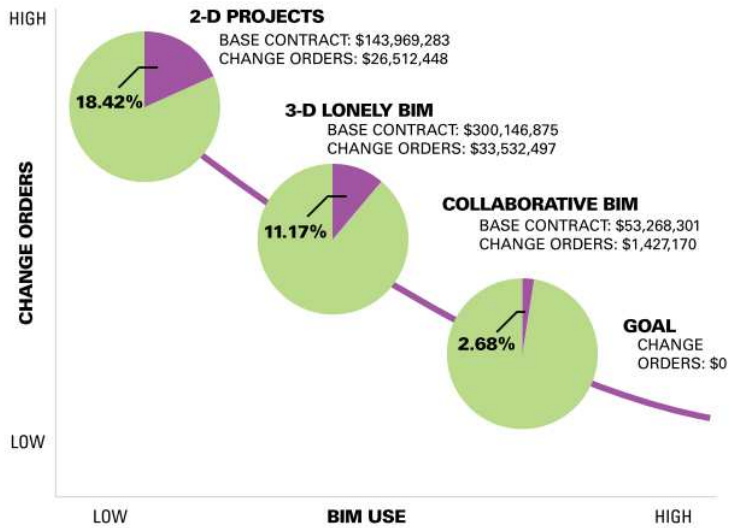

Figure 5. BIM-use versus Change Orders. Reprinted from *SmartMarket Report, The Business Value of BIM in North America* by McGraw-Hill Construction, 2012.

of electrical contractors using prefabrication found that one productive hour in the fabrication shop equals on an average 2.2 hours in the field. Cincinnati, OH based TP Mechanical saw 20% of their field labor hours transferred to the fabrication shop, while Madison, WI based Shapiro & Duncan mechanical contractors have observed a 13% productivity improvement in the past few years (Masterson, 2014). These results indicate that BIM, and prefabrication have shown productivity improvements at the project level by reducing overall project schedule and cost. Few of the above examples indicate that prefabrication has also effectively reduced installation hours spent on site and therefore, has the potential of improving project cost, schedule, quality and safety.

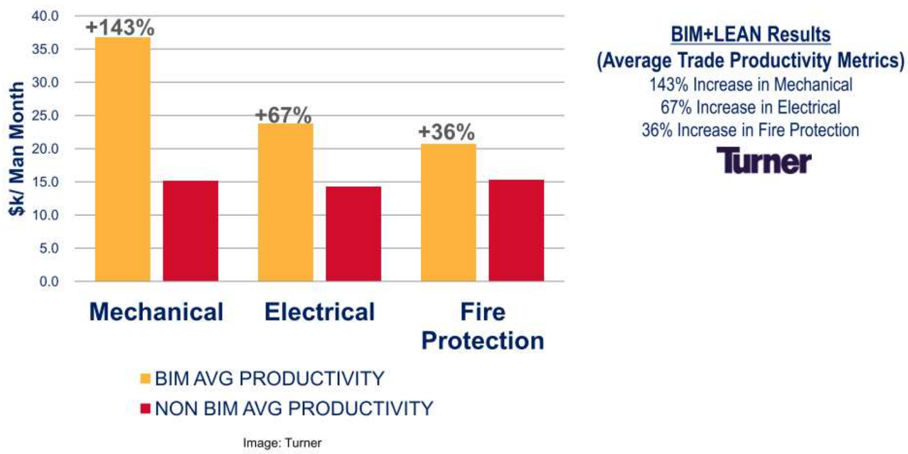

Figure 6. Trade Productivity Improvements by Using BIM. Reprinted from *Global Industry Trends with Building Information Modeling* by S.A. Jones, 2013.

Figure 7. Productivity Improvements in a BIM to Fabrication Workflow for Pipe Racks. Reprinted from *Global Industry Trends with Building Information Modeling* by S.A. Jones, 2013.

What about retrofits? The data presented in the previous section is purely associated with new construction projects. However, retrofits and renovations are a preferred method of construction for several facility owners, especially oil and gas, pharmaceutical, semiconductor manufacturing and other advanced technology development facilities. Past research studies have shown that retrofit projects comprise 64% of all commercial construction projects (McGraw-Hill Construction, 2011) and 70% of all projects in the process industry (Ben-Guang, Fang-Yu, Kraslawski, & Nyström, 2000). This presents a major gap in research and a ripe field for further studies.

1.3. Problem Framing

1.3.1. Problem Statement

As stated before, task-level construction productivity needs improvement and BIM, and prefabrication are potential solutions. However, the current literature primarily concentrates on new construction and very few documented examples of retrofit construction exists. A semiconductor manufacturing plant or “fab” offers the ideal test-bed for exploring the impact of BIM on *retrofits (context)* and *labor productivity (metric)*. Semiconductor manufacturing is also an unexplored sector for analyzing the utility of BIM. For this research, the author conducted a case study at a semiconductor manufacturing facility in the southwestern United States. At the time of this study, the facility was undergoing upgrades for installing new process equipment for accommodating technology improvements. This was the second project for the owner utilizing BIM. The construction supply chain was at various levels of adoption and experience with BIM. The manufacturing facility owner allowed the author access to the design and construction teams, the owners’ representatives and the job-site. Due to the confidential nature of the company and the teams involved, the author has taken extra care to modify the names of organizations and individuals and to ensure that the text does not reveal sensitive and/or proprietary information.

The scope for “process equipment or tool installs" or “re-tooling” includes; demolition of existing tools, conversion-in-place of old tools to the modern technology and the installation of new tools. Technology upgrades, driven by “Moore’s law”[1] can lead to new tool installations or conversions every 18 months. Construction, thus, has limited time to respond. The time to market for a product is critical to the owner to make sure that they are the first to market with their product. Building a new facility each time is expensive and time consuming; hence retrofitting older fabs is the chosen option for most facility owners. Jobsite constraints affecting labor

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[1] *"Moore's law" is the observation that, over the history of computing hardware, the number of transistors in a dense integrated circuit doubles approximately every two years*

productivity, among several factors, include congestion of existing infrastructure, workspace constraints, clean-room protocols, safety and security. Prefabricating components off-site is thus a preferred method for alleviating the constraints of space, safety and protocols posed by an existing and functioning facility. Trade contractors prefabricate high and low purity process pipes, hangers, electric wire-ways and electric boxes at off-site fabrication facilities. The BIM use includes; laser scanning of existing infrastructure, development of a 3D CAD model of the As-Built from the point clouds and legacy data, routing design of electrical, mechanical and piping systems, clash coordination and generation of spool drawings by trade contractors.

The owner's internal research indicates that the use of 3D CAD modeling by the trade contractors for the previous generation of upgrades resulted in schedule savings of 10%, change order savings of 1.95% of total cost, and total project cost savings of 2.17%. It was evident that using 3D CAD resulted in savings. Hence, the owner chose to pursue BIM (3D design, clash coordination, prefabrication) for the current project. Productivity study for the ongoing project was showing that effective value added work as only 2-hours per 10-hour workday. For achieving the target cost set by the owner, productivity calculations had estimated value added work at 5.4-hours per 10-hour workday. This data suggests that while BIM was enabling faster delivery of projects, reducing avoidance costs such as change orders and RFI's, labor productivity (in terms of higher value-added work and reduced non-value added work) had not shown any improvements as determined by the owner. The objective of using BIM, in this case, was to reduce the on-site construction labor headcount due to space and protocol constraints. Hence, combining the gap identified in literature and the data provided by the owner, the author summarizes the problem statement as:

> *To meet the target goals for timely and cost-effective tool-installation, owners adopt the construction practices of BIM and off-site prefabrication. The construction work face faces increasing pressure to improve task-level labor productivity, optimize construction resource headcount and develop efficient, lean and repeatable work-processes. Data suggests that BIM and prefabrication,*

although successful at the project-level, have not shown effective results at the construction labor work face. Hence, through an exploratory case study, this study will research the variables causing this phenomenon and evaluate methods to analyze the impact of BIM-related strategies on labor productivity.

1.3.2. Scope & Limitations

A retrofit situation will have certain inherent constraints (such as trade stacking, congestion, safety, etc.) which can adversely affect labor productivity. The scope of this study is limited to the use and impact of BIM and prefabrication only. For this research, the author observes the application of BIM for piping and electrical contractors for tool installation in the sub-fab area of the manufacturing facility. The sub-fab in contrast to the clean room is where all the ancillary utilities and support tools are located and thus exposed to more construction-related issues.

1.3.3. Research Questions

The following questions guide the research efforts:

R1: **How** can we evaluate the impact of decisions made during the planning, management and implementation of BIM on task-level labor productivity in retrofit construction?

- R1a: **Who** are the decision-makers involved with the planning, management and implementation of BIM and **what** is their expected value from BIM?
- R1b: **What** are the decision-criteria (*i.e.* factors considered during decision making) identified during the planning, management and implementation of BIM?
- R1c: **How** does BIM use impact task-level labor productivity in retrofit construction?

R2: **How** can an owner facilitate the planning, management and implementation of BIM, such that task-level labor productivity is positively impacted?

1.4. Research Method

The lack of existing knowledge led to approaching the problem from a *pragmatic perspective* (problem-centered and pluralistic) using a *mixed-method form of inquiry*. The strategies include an exploratory case study involving interviews (qualitative), and productivity studies through direct field observations (quantitative). A comparative analysis of the findings establishes relationships and helps develop a theory from observations. In *concurrent mixed-method procedures*, such as this, the investigator collects both forms of data (qualitative and quantitative) at the same time during the study and then integrates the information in the interpretation of the overall results (Creswell, 2003).

Yin (1994) describes *case study research* as an "empirical inquiry that investigates a contemporary phenomenon within its real-life context." In a case study, the researcher explores in depth a program, an event, an activity, a process; bounded by time and activity, using a variety of data collection procedures over a sustained period of time (Creswell, 2003). The challenge lies in reproducing results as formal theories. In a research problem, such as this, where no pre-existing theory exists, the effort is towards "theory-building," which begins with an ideal of "no hypothesis to test" because "preordained theoretical perspectives may bias and limit the findings" (Eisenhardt, 1989). The process of theory building from a case study is an iterative one with back and forth comparisons between theory and data. Eisenhardt (1989) encourages various perspectives from multiple investigators and constant discussions on the validity of the constructs as the researcher discovers them, to reduce bias. Although a single graduate student conducted this study, a steering committee from the owner organization deliberated on the findings on a monthly basis, and the progress presented to the dissertation advisor on a bi-weekly basis. A schedule, including the meeting calendar for the research is included in Appendix A. The limitation of this research lies in the absence of multiple case studies to examine the same relationships across organizations and project types. Considering the access extended to the research team by the owner, it was near impossible to find an organization of similar scale and complexity, which would accord a related gesture. Hence, the research presented in this thesis is that of a single organization with multiple supply chain partners. Another risk of theory building from a case study is the idiosyncratic viewpoint, from which the researcher is unable to rise to a level of generalization (Eisenhardt, 1989). The author avoids this pitfall by conducting a hypothesis testing of the generated theory through an industry-wide survey (see Chapter 5). The purpose of this research is to provide new insights into the use of BIM for retrofits by analyzing the value of BIM defined by its aspects as identified by stakeholders from decision-makers to the users of this process.

The author extensively referred literature on Grounded Theory (GT) to inform the methodology. GT is a qualitative research method which involves the development of theory from data (Glaser & Strauss, 1967). The design of GT allows focus on context, process, intentions, and interpretations of key players. Its methodological emphasis is to *"let interpretations emerge from the actors in the field with minimal intervention by the researcher and then compare them with academic concepts of the topic,"* focusing primarily on theory building rather than theory testing (Fendt & Sachs, 2007). According to O'Reilly, Paper, & Marx (2012), the fundamental tenets of GT involve, (a) a constant comparative method, (b) theoretical coding, (c) theoretical sampling, (d) theoretical saturation, and (e) theoretical sensitivity. They postulate that a GT method is successful only when it is considered from *"an epistemological viewpoint and employed as a holistic methodology and not simply as part of the process of data coding and analysis"* (O'Reilly et al., 2012). Although the method followed in this research has the flavors of a GT method, due to a lack of structure and rigor as prescribed by the tenets of the GT method, we cannot classify this research as Grounded Theory.

The following section briefly describes the methods used for data collection, analysis and validation. Later chapters discuss the research method specific to the part of research presented in the particular chapter. Figure 8 diagrammatically explains the research method.

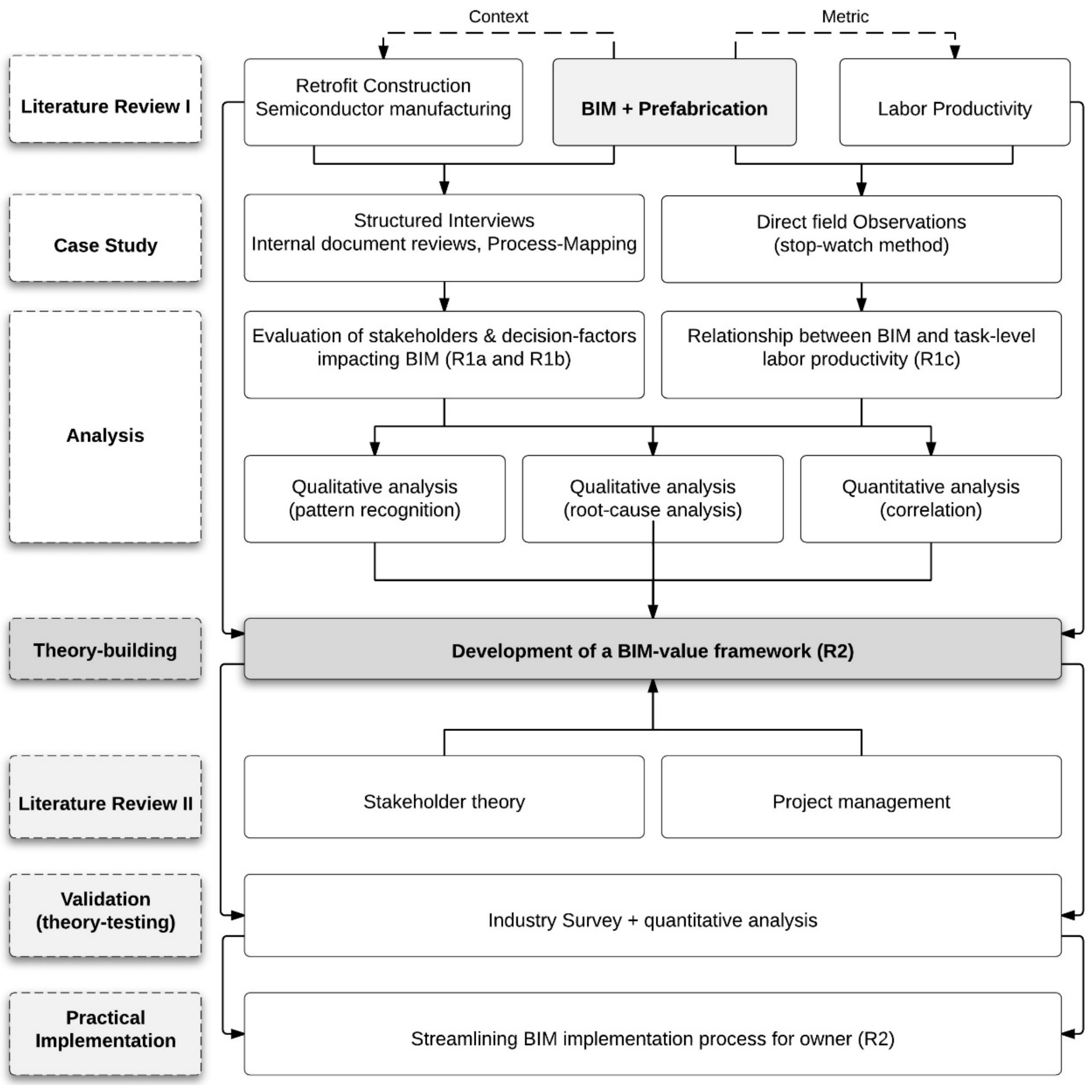


Figure 8. Research Method

1.4.1. Data Collection

The primary source of data for this research comes from the case study at the semiconductor manufacturing facility. As explained in Chapter 3, the owner had several contractors working on the project; hence, the data is effectively from different companies. The other source of information is the extensive literature review conducted by the author referencing a number of leading academic journal publications and industry reports. As shown in Figure 8, the author uses four primary methods for data collection:

- **Interviews:** Interviews permit in-depth information pertaining to the participants' experience and viewpoints on a particular topic (Turner, 2010). For this study, since the participants did not permit voice and/or video recording, the author documented the interviews and conversations in the form of field-notes, which she later transcribed as digital memos and eventually coded by key-phrases. Turner (2010) and McNamara (2009) defines three formats for interview design;
    - Informal conversational interview, in which the researcher does not ask any specific questions, instead relies on the interaction with the participant to guide the interview process (McNamara, 2009).
    - General interview guide approach is more structured than an informal conversation but allows flexibility to probe further through follow-up questions.
    - Standardized open-ended interview is extremely structured in terms of wording of the questions, and all participants are asked the exact set of questions to prevent researcher bias (Turner, 2010).

    The format used throughout this study followed the guidelines of a standardized open-ended interview with several follow-up questions. This type of interview design is useful when there are a number of participants with multiple viewpoints.
- **Archive search:** The owner provided the researcher access to several official documents. The author captured key findings and phrases relevant to this study from these documents and recorded for reference.
- **Process mapping:** In order to capture the actual current BIM processes, it was important to map out the workflows as implemented by the various project participants. The author captured this data was using a Business Process Modeling Notation (BPMN), which was then validated and/or confirmed by the project participant supplying the information. Three methods were used for outlining the workflows:

    - Individual meetings
    - Job-shadow
    - A single two-day process-mapping workshop initiated by the author.
- **Direct field observations:** The research team along with a group of three observers engaged by the owner conducted first hand field observations at the labor workface for six weeks. During this time, three types of data were collected (explained in Chapter 4):
    - The value-added and non-value added time on site using a stopwatch method.
    - Variables identifying the impact of BIM and prefabrication at the jobsite: An initial study identified the perceived benefits of BIM such as reduced conflicts, access to information, accuracy of information, and the perceived benefits of prefabrication such as accuracy and speed of installation. The author formalized and captured this data as workflow disruptions, in order to focus on areas, which needed improvement.
    - A third type of productivity data collected included quantitatively measuring the total output from the workday as total units installed. This data was critical for arriving at a production rate. However, it was difficult for the observers to measure the output due to the variability in the daily tasks performed in the six-week period and their levels of complexity. Chapter 4 further elaborates on this.

1.4.2. Analysis

The author conducts the analysis in two sections: the first evaluates the stakeholder decisions affecting BIM (answering research questions R1a and R1b), and the second analyzes the relationship between BIM and labor productivity (answering research question R1c). The finding from both these analyses is combined to answer the research question; R1 (see Figure 8). As mentioned in section 1.5, the method is that of concurrent mixed-methods utilizing both qualitative and quantitative forms for analyses. They are:

- **Pattern recognition (qualitative):** According to Morse (1994), pattern acquisition is the ability to know where to look, and pattern recognition is the ability to know similarities and differences, based on previous experience.
- **Root-cause analysis (qualitative):** A root cause is the most basic reason a problem has or could occur and root cause analysis is a reactive technique (informal or structured) to determine the causes which management can control (Wilson, Dell & Anderson, 1993).
- **Correlation (quantitative):** The correlation coefficient (r) measures the strength of the linear relationship between two variables, and the sign indicates the type of linear relationship. A value of r closer to +1 suggests that the variables are positively linearly correlated and value of r closer to -1 suggests that the variables are negatively linearly correlated (Weiss, 2011). Correlation, however, does not imply causation.

1.4.3. Validation

The nature of the research led to uncovering findings while the research was in progress. In order to prevent researcher bias, the author presented and discussed the findings with the dissertation advisor on a bi-weekly basis and with a steering committee representing the owner organization on a monthly basis. The author also concurrently compared and validated the findings against past research studies.

The “BIM-value framework," which is the product of this dissertation, underwent validation outside the boundaries of the case study. An anonymous survey elicited responses from 40 participants representing various segments of the AEC industry. Chapter 5 elaborates on the statistical tests used for analysis.

1.5. Research Contributions

This research offers three main contributions to the construction management literature and the AEC industry:

1. Demonstration of BIM-use for retrofits at a semiconductor manufacturing facility.
2. Development of a BIM-value framework to enable decision-makers to analyze the risks of BIM-decisions on labor performance.
3. Development of a BIM implementation framework for owners engaging in retrofit construction.

1.6. Dissertation Organization

Chapter 2 of this dissertation compiles all the Literature Review. It first highlights the fundamental differences between construction and manufacturing and introduces the basic design and construction considerations for the semiconductor tools install. It develops a background knowledge of BIM, prefabrication and labor productivity and the relationship between these concepts, especially from the perspective of retrofitting semiconductor process tools. It then summarizes the major findings from the literature.

Chapter 3 introduces the case study of the semiconductor manufacturing facility followed by an analysis the BIM and prefabrication capability and maturity levels of the construction supply chain. This chapter answers research questions R1a and R1b, drawing a picture of the current BIM implementation, the stakeholders, roles and responsibilities and information exchange. The findings from this chapter help identify the stakeholders and their perceived value from BIM, and the decisions made during the project phases related to BIM.

Chapter 4 presents the observations and analysis from the field. It illustrates the productivity studies and investigates the relationship between labor productivity and BIM. These findings are compared with the literature review to arrive at a list of variables that affect labor productivity. This chapter forms the framework to answer the research question; R1c.

Chapter 5 combines the findings from Chapters 2, 3 and 4 for the theoretical development of the BIM-value framework. It also discusses the design of a survey to validate the framework. The results of the framework are statistically analyzed, and the results presented.

In conclusion, **Chapter 6** discusses the practical implementation of the findings from this research towards the streamlining the BIM process at a semiconductor manufacturing facility. This is a demonstration for the research question; R2. This chapter discusses contributions to knowledge, the major obstacles and limitations of this study and suggests possible future research in the areas of BIM and prefabrication for retrofit construction.

CHAPTER 2

LITERATURE REVIEW

This chapter compiles the entire literature review completed during this study (see Figure 9). The chapter begins with a discussion of the fundamental differences in theories and concepts in Construction and Manufacturing. This is important for understanding the unique characteristics of construction and the reasons for the inherent inefficiencies as compared to manufacturing. Section 2.2 introduces past literature on semiconductor manufacturing facilities, which is essential for understanding the case study. Sections 2.3 and 2.4 provide commentary about BIM, prefabrication and labor productivity and the relationships between them. Section 2.5 summarizes the key findings from the literature review.

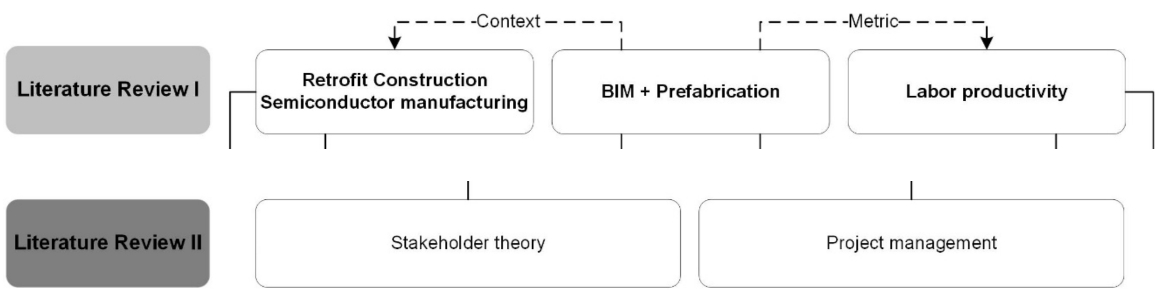


Figure 9. Literature Review

2.1. Construction versus Manufacturing

Construction frequently borrows ideas and innovations from the manufacturing industry. However, the boundaries between construction and manufacturing are indefinite and fuzzy. A comparative analysis of the two industries' (see Table 2) shows that the fundamental differences between construction and manufacturing lie in the structure and culture of the supply chains, the final product and its development process, the production model, time and environment. Thus, it can be argued that "apples to apples" analysis of performance and productivity developments between the two industries may not be a fair comparison (Segerstedt & Olofsson, 2010).

Ballard & Howell (1998, August) reason that simple projects can become more like manufacturing by introducing initiatives like standardization, while dynamic projects must manage any manufacturing strategy with the characteristic construction conditions of *"site production, unique product and temporary organization."* Areas of product design, production model development and project management can borrow strategies from manufacturing in order to bridge some of the productivity gaps. For example, modularization, prefabrication and lean, find their origins in the manufacturing industry. Some processes inherent to construction such as the assembly of mechanical and electrical systems, manufacture of pipefittings, and prefabrication of concrete, wood and metal building components and other standard systems and sub-systems are similar to the manufacturing of products. We can argue that increased prefabrication is pushing construction into the realm of manufacturing. Cost saving associated with prefabrication and off-site fabrication is based on the hypothesis that insulating part of the production process from the unique conditions found at a project site should increase labor productivity by reducing the commonly occurring non-value adding activities on-site.

Table 2

Manufacturing vs. Construction Supply Chains

Characteristic	Manufacturing	Construction
Industry characteristics	• Positive trend for labor productivity • Only new products produced	• Negative trend for labor productivity • High proportion of remodeling, upgrading and maintenance work
Supply chain structure	• Highly consolidated • High interdependencies	• Highly fragmented • Low interdependencies • Predominantly local markets • Short lived and rapidly configured
Supply chain culture	• Integrated company culture with aligned performance goals • Long term supplier relationships • Shared benefits and incentives	• Project based culture exhibited due to indirect relationships between various participants • Adversarial attitude between parties *(typical)*
Workforce	• High barriers to entry • Employers control the work process	• Low barriers to entry • Mobile and itinerant workforce • Greater autonomy to the workforce
Production model	• Design to order • Make to order/customization • Make to forecast	• Concept to order • Design to order
Production environment	• Fixed locations • Highly automated environment, standardization, production routes are defined - lower variability	• transient locations • dynamic site management • open environment, lack of standardization and tolerance management, space availability
Production time	• Long term stable environment	• Fixed project duration
Product design & development	• Design and manufacture scope maintained by the same entity • Product development begins with the decision to modify existing or create new	• Traditional Design-Bid-Build separates design and construction *(typical)* • Sequential thinking
Final product	• Standardized and repetitive • Mass produced • Shipped to final point of use	• Can be repetitive but non-standard • Final project is customized • Built on site (in situ)
Information flow	• Highly integrated, highly shared, fast and transparent	• Recreated several times, lack of sharing between trades, slow
Owner Involvement	• Owners are consumers who remain anonymous until receipt of product and thus have indirect influence	• Owner involvement throughout project delivery *(typical)*
Outside Industry perspectives	• Mass production viewed as bureaucratic, hierarchical and inflexible	• Flexible, capable of working in networks, ability to respond to clients idiosyncratic needs

Note. Adapted from Azambuja & O'Brien, 2009; Benton & McHenry, 2010.; Pryke, 2009; Riley & Clare-Brown, 2001; Teicholz, 2013; Winch, 2003

Typically, for the sake of comparison, researchers and practitioners acknowledge the automobile industry as the paradigm of best practices. According to Winch (2003), there is a tendency to treat manufacturing as a homogeneous bundle of best practices rather than borrowing impactful strategies from sectors with practices similar to construction. He also debates that problems to re-engineer the construction process persists because of the inclination towards mass-production models (and more recently the lean manufacturing model) and instead suggests focusing on complex systems production models, such as railways or shipbuilding, to draw conclusive strategic parallels. At a meta-level, construction can be organized as several different typologies based on end-use, scale etc., hence strategies can be borrowed from not one but all three models (mass-production, complex-systems production and lean production) depending on the sub-category of construction. Management techniques and principles applied to the manufacturing industry, need to be modified before they are applied to the construction industry for them to be effective (Lahdenpera, 1995; Morledge, Knight, & Grada, 2009; Riley & Clare-Brown, 2001). The next section discusses some popular project management theories, the construction supply chain and the importance of relationships and transactions within the supply chain.

2.1.1. Theories of Project Management

The Project Management Institute's Body of Knowledge (PMBoK) defines project management as, *"the application of knowledge, skills, tools, and techniques to project activities to meet the project requirements*" (Project Management Institute, 2014). Several authors and practitioners have argued the need for a theoretical basis of project management as applied to construction projects, replacing the quasi-experimental and personal nature intrinsic to the practice. The theory of construction is an ongoing debate. Notable amongst them are Koskela & Ballard (2006) who espouse a production theory for project management, forming the basis of lean construction and Winch (2006) presenting an economics and social science based theory for project management.

Lean Construction. Production theory conceptualizes projects as temporary production systems. In his seminal work on lean construction, Koskela argued that the theory of production must encompass three fundamental elements: Transformation (of inputs to outputs), Flow (of time, work and variability) and Value generation (for the customer based on quality). The goal of this theoretical construct is to eliminate waste and increase value by designing, operating and improving the production system. Lean, a hallmark of the Toyota Production System (TPS) is the systematic elimination of waste *(muda),* supported by three philosophies; just in time (JIT), continuous improvement *(kaizen)* and automation *(jidoka).* The essence of JIT is to reduce waste associated with overproduction by doing work in response to customer request and consequently eliminating the wait time prior to use of the work output. As per Jørgensen & Emmitt (2008), lean in manufacturing is typically applied to repetitive, high-volume production processes with measures to achieve progressive decreases in lead times. They argue that organizational concepts influence the transfer of lean production processes to construction projects by leading to a de-coupling of "lean" from its original meaning, resulting in a widespread rhetorical adoption over a preferred substantial adoption. They attribute much of this dichotomy to the lack of proper definitions for lean construction, lean design and lean thinking. The lack of clarity in published literature has created avenues for debate but also allowed interpretation and contextual renegotiations of the term. Hence, it is critical for this research study to understand lean construction from the perspective of its original authors.

Lean is not an attempt to turn construction into repetitive manufacturing. As explained in the previous section, there are peculiar differences between construction and manufacturing which warrant discussion. Ballard & Koskela (2011) clarify that lean construction should naturally arise from lean product development. The two central concepts of lean are thus:

1. Conceptualizing the project as a production system for managing and organizing and,
2. Eliminating waste as a focus for improvement and consequently improving customer value.

The Last Planner System of Production Control, workflow scheduling and management, work structuring, work-process simulation and optimizing batch sizes and minimizing buffers, set-based design and value-stream mapping are some of the popular tools and techniques used for the application of lean construction (Ballard & Howell, 1998). A pre-requisite for developing standard procedures is streamlining the work processes through effective mapping of the production process *i.e.* value-stream mapping, which is a common practice in the manufacturing industry.

Other Project Management theories. Winch (2006) argues that the theory of project management is inherently an organizational innovation, which should focus on value for the client and be performance driven. His viewpoint is rooted in Transaction Cost Economics (TCE) which advocates that transaction costs and production costs must be economized by creating appropriate governance structures (contractual and organizational) within organizations. According to this theory, a project is an information processing system and project management is essentially a coordination of production with the primary goal of reducing uncertainty in the process. Other models presented in literature are the empirically based, project oriented, supply chain oriented and network oriented models (Bygballe, Håkansson, & Jahre, 2013). We must note that all the models mentioned do not capture the totality of construction project management, but are rather different approaches to decision-making. In summary, it can be said that project management has evolved over the years with each stage adding to the existing body of knowledge (Pryke, 2009):

- Traditional project management having a production or assembly oriented focus of efficiency,
- Functional or strategic front-end management, such as partnering, supply chain management and lean production,
- Information processing or the input-output model of managing projects,
- Relationship approach based on project performance and client satisfaction achieved through the management of dyadic relationships.

2.1.2. Supply Chain Management in Construction

Supply chain management (SCM) concerns value creation for customers by coordinating various activities, functions and participants. The concept of SCM originated and developed in the manufacturing industry in the 1980's with its roots tracing back to the JIT delivery system as a part of the Toyota Production System (Morledge et al., 2009). SCM builds upon the framework of logistics management (flow of goods, services and information) and includes the characteristics of the linkages and their interdependencies such as the relationship between the participants and the coordination and control of processes. Christopher (1992) provides a formal definition for SCM as *"the management of upstream and downstream relationships with suppliers and customers to deliver superior customer value at less cost to the supply chain as a whole."* This definition alludes to the existence of multiple suppliers and customers who make up the supply chain and hence, we can say that SCM is in essence the management of a "network of organizations." The linearity expressed by the term "supply chain," especially in the context of construction, exists only at a higher level of abstraction and at the level of application or execution, there exists a complex web of social and technical systems (Pryke 2009).

Responding to the variability and complexities of the construction supply chain, Vrijhoef & Koskela (2000) identify four roles of SCM in construction (described in Table 3) depending on whether the focus is on the supply chain, the site or both. These roles are not mutually exclusive and construction projects often apply them together. In each of these roles, problems tend to arise due to the complexity, variability and various degrees of control found in different projects. The variations in supply chains and conditions in different projects challenge the assumption that landmark projects with particular relational contracting strategies will diffuse change throughout the industry. However, according to Vrijhoef & London (2009), organizations adopting SCM are more likely to achieve short-term objectives and develop long-term relationships outside the boundaries of an individual project. Thus the goal of SCM in construction is to manage the flow of goods, information and money to improve operational efficiency, promote innovation and

Table 3

Four Roles of SCM in Construction

Role	Goal	Application	Who can adopt
1. Improving the interface between the supply chain and the construction site	Reduce cost and duration of on-site activities	Logistics, just-in-time, Last Planner method	Contractor
2. Improving the supply chain	Reduce costs related to logistics, lead-time, and inventory	Prefabricated elements and assemblies (concrete, elevators)	Vendors (materials, components)
3. Transferring activities from the construction site to the supply chain	Reduce total costs and durations by avoiding variability and inferior conditions on-site	Off-site fabrication	Sub-contractors, vendors
4. Integrated management of the construction site and the supply chain	Flexibility for the decision maker	Design flexibility (open-plan, separation of shell and core), Design-Build	Owners, vendors and contractors

Note. Adapted from *The four roles of supply chain management in construction* by R. Vrijhoef & L. Koskela, 2000

continuous improvement, create value for clients and ultimately improve profitability for the construction industry (Pryke, 2009; Vaidyanathan & Howell, 2007).

2.1.3. Summary

This discussion was important to distinguish the notions developed from the practices in the two industries; construction and manufacturing, by highlighting the following key factors:

- Strategies borrowed from manufacturing need modifications before application to the construction industry for them to be effective.
- Cost savings associated with prefabrication is based on the hypothesis that insulating part of the production process from the unique conditions found at a project site should increase labor productivity by reducing the commonly occurring non-value adding activities on-site.

- Lean is not an attempt to convert construction into repetitive manufacturing, rather its goal is to eliminate waste and increase value by designing, operating and improving the production system. A pre-requisite for developing standard procedures is streamlining the work processes through effective mapping of the production process.
- The goal of SCM in construction is to manage the flow of goods, information and money to improve operational efficiency, promote innovation and continuous improvement, create value for clients and ultimately improve profitability for the construction industry.

The case study considered for this research is a process tool installation project at a semiconductor manufacturing facility. Owners of similar manufacturing and advanced technology facilities tend to translate strategies from manufacturing to construction verbatim and expect similar productivity improvements in short time periods. Discussion of this research within this context is necessary to remove any bias associated with technology improvements, rather analyze the observations from a neutral standpoint. The next section will provide a brief background of the semiconductor industry, the manufacturing process and the design and construction support required for such unique facilities. This will further help in framing the problem, the need for greater productivity improvements with BIM use and the major obstacles that impact labor productivity.

2.2. Semiconductor Manufacturing Facilities

One of the most important inventions of our time is the *Integrated Circuit* also known as IC, chip or microchip. ICs are the key element found in computers, mobile phones, automobiles, consumer electronics, industrial appliances and currently, digital television, cloud computing, sensors and the *"internet of things"* or wearable technology. There are four major classifications of facilities manufacturing IC's:

- Integrated Design Manufacturers (IDMs) design and manufacture their own ICs (e.g. Intel Corporation, Samsung Electronics, STMicroelectronics etc.)
- Fabless fabs design and sell ICs but outsource manufacturing (e.g. Qualcomm Inc., Nvidia Corporation and Advanced Micro Devices Inc. etc.)
- Foundries design the process techniques but not the actual IC design (e.g. Taiwan Semiconductor Manufacturing Company Limited, United Microelectronics Corporation, Global Foundries etc.)
- Assembly and testing companies do not manufacture but receive ICs from fabrication facilities and test, package and ship finished products (Amkor Technology, Cascade Microtech etc.)

Semiconductor manufacturing facilities (or fabs) convert silicon to ICs through a series of highly complex processes. A fab is a high-technology facility housing manufacturing tools necessary for the production of semiconductors or chips (Gil, Tommelein, Stout, & Garrett, 2005). There are three phases in the manufacturing process for an integrated circuit, (1) *Materials*: preparation of the silicon wafer, (2) *Wafer fabrication*: processing the silicon wafer to make the integrated circuits and (3) *Assembly and test*: testing the final circuit and packaging the chip for installation in a product. Figure 10 provides a description of these steps. Typically, a major semiconductor manufacturer will purchase wafers from a company that specializes in making the silicon ingot, slicing the ingot into wafers, and polishing them so they are ready for processing.

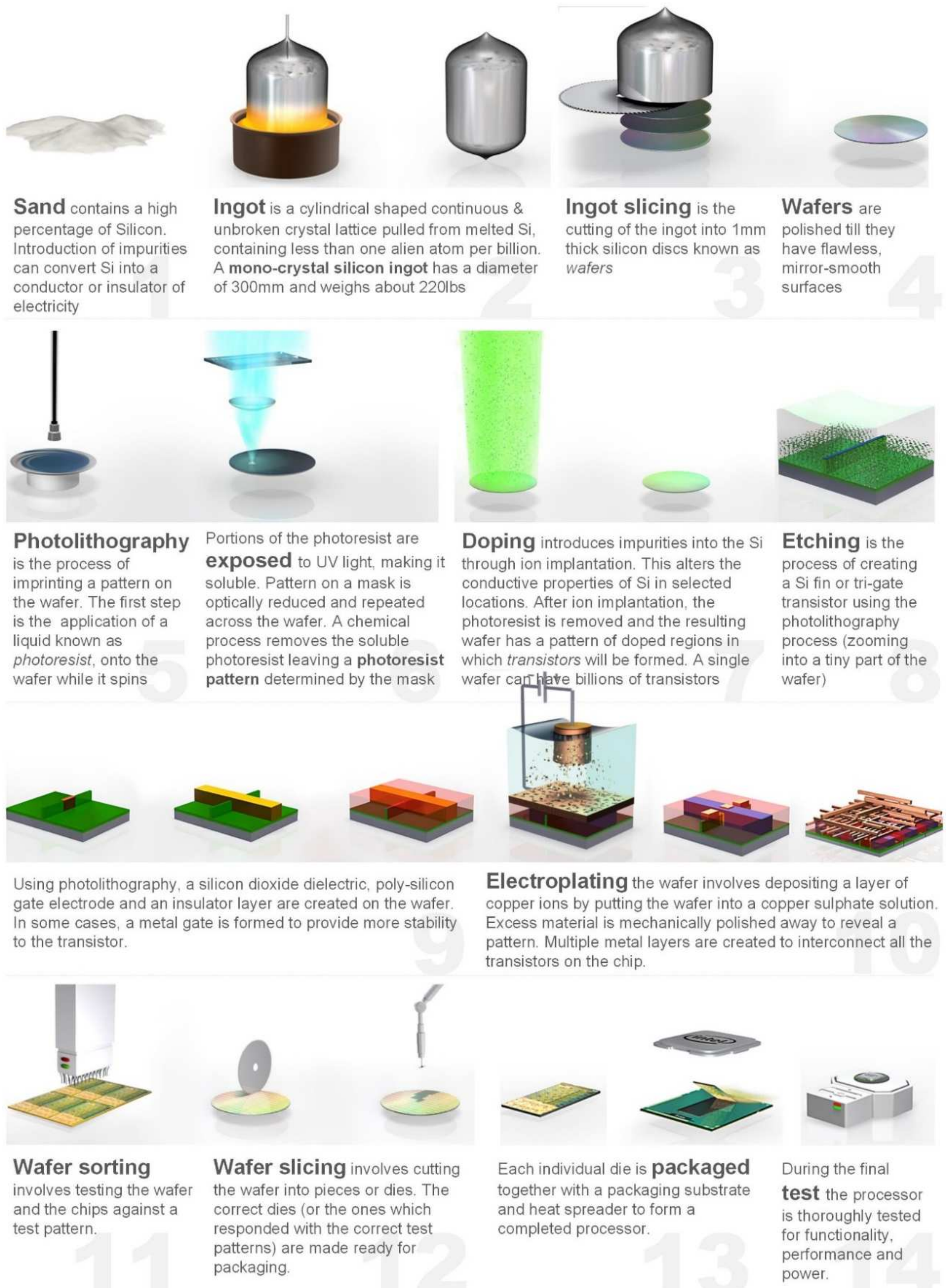


Figure 10. Silicon to Microprocessor Manufacturing Steps. Adapted from, *From Sand to Silicon,* 2012 by R. Kelton

The semiconductor manufacturer will then put the wafers through the integrated circuit fabrication process, comprising of the following four main processes:

- *Oxidation:* Depositing or growing a thin film of Si on the surface of the wafer
- *Photolithography:* Transferring a circuit pattern to a mask layer on the film
- *Etching:* Removing the areas of the film not protected by the mask layer
- *Ion Implantation (Doping) or Diffusion:* Processing the exposed areas of the wafer

These steps repeat several times during the complete manufacturing process. For the current generation of computer chips, this process may take 30-45 days and involve 100 or more processing steps. A logic circuit or computer chip may contain more than 1,000,000 transistors on a single chip substrate.

2.2.1. Semiconductor Industry Trends

The semiconductor industry is steadily growing worldwide. North America, South Korea, Japan, Taiwan and Europe are the major players in this industry with the Asia-Pacific being the fastest growing region with a market share of approximately 60%. Performance in the global semiconductor industry is bifurcated across two major tiers: the top five and the rest. Together, the top five players in the industry; Intel Corporation, Qualcomm Incorporated, Taiwan Semiconductor Manufacturing Company (TSMC), Texas Instruments Incorporated, and SK Hynix; produced 30% of the global semiconductor industry’s revenue and 52% of the industry’s earnings before interest, taxes depreciation and amortization (EBITDA) in 2013 (AlixPartners, 2014). According to the World Semiconductor Trade Statistics forecast (WSTS, 2014), the semiconductor market showed a solid growth of 9% up to US$333 billion in 2014 and is forecasted to be up by 3.4% (US$345 billion) in 2015 and 3.1% (US$355 billion) in 2016. Demands from the communication (smartphones) and automotive markets mainly drive this growth. At the same time, the capital expenditure for this industry is extremely high. SEMI, a global industry association for the microelectronics manufacturing supply chains, forecasts a market growth of 17.8% for wafer processing equipment, 30.6% for assembly and packaging equipment and 26.5% for test equipment in 2014. They also forecast the fab facility, masks and wafer manufacturing to increase by 14.8% in 2014. The increasing costs of manufacturing equipment will drive the average cost of semiconductor fabs to between $15 billion and $20 billion by 2020 (Gartner, 2012).

The growth of the semiconductor technology is dependent on economizing the production of ICs. In April 1965, Gordon E. Moore, co-founder of Intel Corp., published a paper titled *"Cramming more components onto Integrated Circuits."* In this paper, Moore posited that the number of transistors on an integrated circuit doubles approximately every two years (Moore, 1965). This prediction, popularized as Moore's first law, became a target goal for the R&D departments of several semiconductor-manufacturing companies and a "road-map" for determining processes, capacities, production rates and investment cycles. Moore's paper noted that the cost per chip was inversely proportional to the number of transistors per chip, but that diminishing returns occurred as the circuit grew more complex. In other words, eventually there would come a time when it just wouldn't be *economically* worthwhile to put more transistors on a chip (Ross, 2003). This argument stems from the economic constraints (such as fabrication costs) and not the possible technological capabilities. Arthur Rock, an investor in Silicon Valley, predicted that the cost of semiconductor tools double every four years commonly dubbed as Rocks' law or Moore's second law (Schaller, 1997). By that logic, the cost of a fabrication facility should have increased exponentially. However, the demand for the products has also increased simultaneously and so has productivity and throughput.

Growing chip throughput and greater chip demand motivates the production of larger wafer sizes. A larger wafer diameter can be profitable if the percentage increase in manufacturing costs per wafer from advancements in technology is smaller than percentage increase in revenue from the larger real estate of silicon (Mulay, 2014). For example, the transition from a 200 mm diameter wafer to a 300 mm diameter wafer increases the wafer surface area by 125%, producing 142% more chips per wafer, increasing the chip throughput by 125%, increasing tool costs by 30% and potentially reducing the overall capital expenditure per chip by 40% (Sonderman, 2011). However, according to Mulay (2014), for every succeeding increase in wafer size, there is approximately a 1.4 times increase in costs of manufacturing. Traditional 300mm fabs have 20,000 to 30,000 wafer starts per month (wpm). Manufacturers such as Samsung and Hynix have ramped up their production to 80,000 to 110,000 wpm. Historic trends show that a reduction in line widths and an increase in wafer size are the two main strategies adopted by semiconductor manufacturers to reduce costs by increasing the number of chips per wafer (Chasey & Merchant, 2000). The next technology improvement is the 450 mm wafer size using the 22nm or 14nm technology (see Figure 11). It is predicted that the 450mm transition will reduce capital expenditure by approximately 25% and cost per chip by as much as 20-25% at 22nm (Sonderman, 2011). According to Mulay (2014), in order to sustain the progress of the semiconductor industry based on Moore's law and justify the ever-increasing capital-intensive investments for transitioning to 450 mm diameter wafers, there must also be a robust economic demand for electronic products.

Semiconductor companies have reported weak revenues (global growth of 0.7% in the 12-month period ending in the third quarter of 2013) and EBITDA margin growth (EBITDA grew 8.9% during that same time frame), according to AlixPartners (2014), a leading global advisory firm. They attribute these results to the soft macroeconomic market environments in key geographies, intense competition, pricing pressure, and short and costly product life cycles. The cyclical and capital-intensive nature of the semiconductor industry combined with the relatively short product life cycles necessitates reducing overhead costs and the continuous management of supply chain costs (AlixPartners, 2014). The return on investment on the capital-intensive semiconductor manufacturing facilities can be maximized only if they are built in the right time to meet the market window (Pindukuri, 2011). In summary, we can describe the semiconductor industry as crucial, complex and costly.

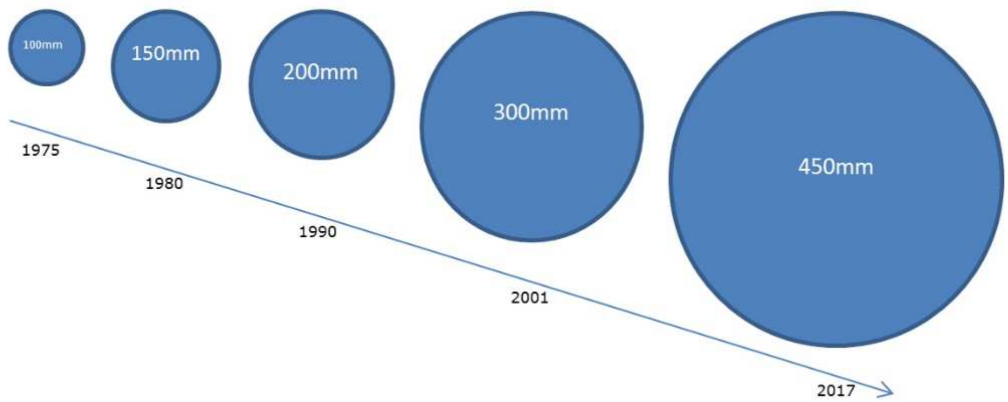


Figure 11. Wafer Size Timeline. Reprinted from. *Does size matter? Understanding wafer size,* 2012, Anysilicon.

The next sections will describe the design, construction and operation of a wafer fab and discuss some of the constraints and considerations that are unique to such facility types.

2.2.2. Programming & Design of a Fab

This section will look at the facility requirements for the IC fabrication process. A fab will typically consist of a micro-contaminant controlled cleanroom space, a clean sub-fab housing the utilities and extra tools that support the main tools in the clean room and a utility level consisting of all other support systems (see Figure 12). The major programmatic spaces include the fab building (approx. 65% of total), the central utility plant building (approx. 15% of total) and an office building (approx. 20% of total).

Cleanrooms. A semiconductor cleanroom is a controlled environment, where contamination is prevented from entering the area by filtering the air delivered to the clean space, in order to ensure the manufacturing processes are accomplished with the highest possible degree of success. A human hair is about 75-100 micrometer in diameter. A particle 0.5 micrometer in diameter (200 times smaller than the human hair) can cause major disaster in a cleanroom. Thus, any contaminants originating from particulate matter (*i.e.* dust, fibers), dispersed films (*i.e.* gases, liquids), biological material (*i.e*. bacteria, algae) and energy (*i.e.* heat, light), can create local defects and increase the chance of device failure and major losses for the manufacturer. The *ISO14644-1: Classification of air cleanliness standard,* specifies the number of particles 0.1 micrometer or larger permitted per cubic meter of air. For example, an ISO 3 (or Class 1) cleanroom should have a maximum of 1,000 particles >= 0.1 micrometer per cubic meter of air. The sensitivity of the product determines the "class" of a cleanroom. The better the class, the better the yield, and more expensive facility and operations. The best method for controlling contamination is to remove or replace the source. If the source is a vital component or system, then the transport must be moved. Described below are some of the basic elements of contamination control in a cleanroom:

- Airflow in a cleanroom must be laminar, *i.e.* unidirectional and non-turbulent, to prevent the formation of vortices, which can locally concentrate contamination.
- High Efficiency Particulate Air (HEPA) filters in the ceiling can effectively remove 99.9997% of all particles larger and smaller than 0.3 micrometers in size.
- Cleanroom walls are usually non-load bearing special powder-coated movable aluminum panels. The flooring is an aluminum raised access floor with 2'x2' perforated tiles, which allow the air to flow through the grates to the return air system. The raised flooring also provides an area for the distribution of process piping, electrical conduit, control wiring, and waste piping below the tool.
- Cleanroom garments are required in most fab spaces depending on the class level. Bunny suits (jumpsuits), gloves and booties are standard in nearly every cleanroom environment. Gowning and de-gowning procedures are strictly enforced in cleanroom spaces for both engineers and construction personnel entering these spaces.

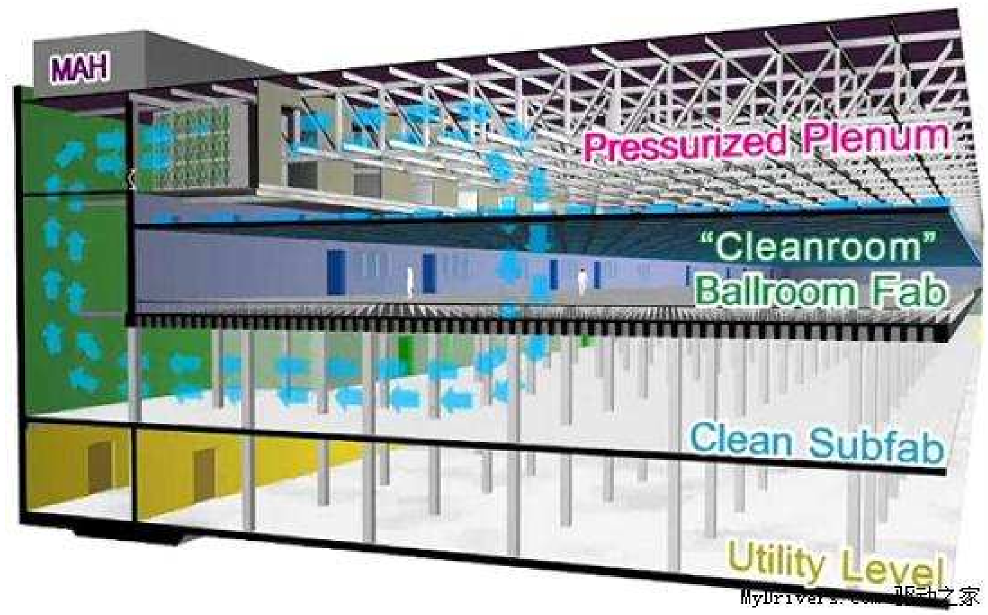


Figure 12. Cross-section of a Wafer Manufacturing Fab. Reprinted from *Intel/Micron 25nm process fab day tour* by Shu, 2010

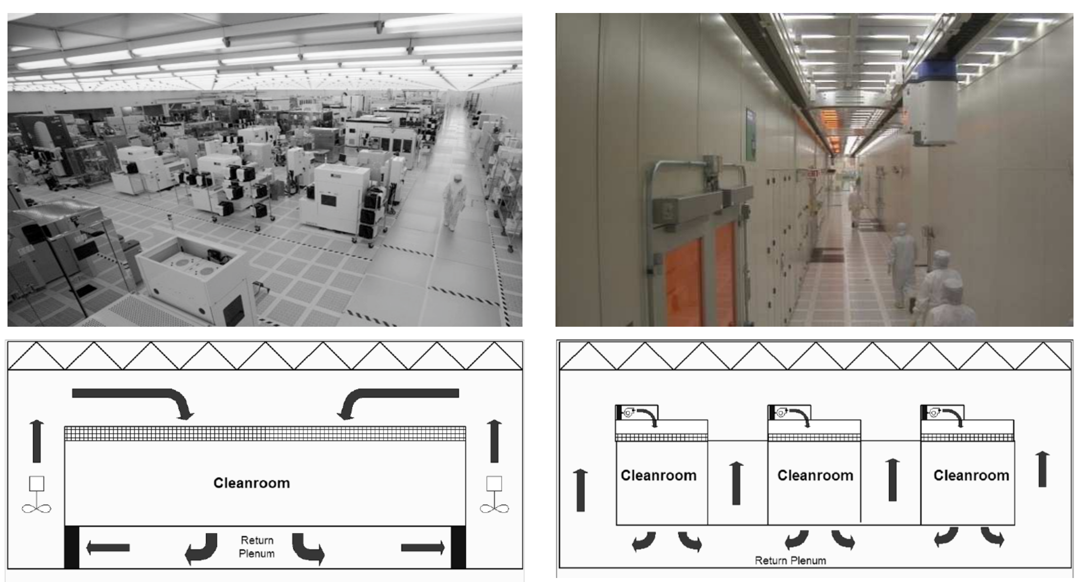


Figure 13. Ballroom and Bay-chase Cleanroom Layouts. Adapted from *Semiconductor research and development options for rapid commercialization* by M. Liehr, 2010 and, *Fab 32 – Featured Photography,* Intel, n.d.

There are two types of cleanroom layouts; Ballroom and Bay-Chase layouts (see Figure 13). The Ballroom layout is an open layout with clean minienvironments that house the semiconductor tools. This type of layout has no walls and allows for flexible tool layout. However, since there is no air segregation it involves a higher operating cost. The Bay-Chase layout is the traditional layout with clean bays for processing and less clean chases for equipment and/or return air. The advantages of this layout include segregation of maintenance, lower airflow and ceiling costs. The disadvantage is that it is less flexible (Pindukuri, 2011).

Structure and Vibrations. A cleanroom consumes about 100 times more mechanical power than a conventional office building of the same size, while critical process tools are 100 times more sensitive to vibration than people. Thus, schedule, economics and the capability to dampen vibrations from mechanical equipment drives the structural design of a semiconductor manufacturing facility. To achieve the desired vibration characteristics, both vertical and horizontal structural stiffness must be achieved. The depth of the floor framing system in combination with the column spacing controls the vertical stiffness, which keeps the floor from sagging. In addition, shear walls control the horizontal stiffness, which keeps the facility from swaying in a lateral fashion. However, column spacing in the sub-fab affects the usefulness of the facility with respect to the accommodation of production tools and their auxiliary components and piping systems. In most facilities, a standard cast-in-place concrete “waffle” structural system is frames the fab level floor. Alternative systems include inverted precast concrete double tees, precast concrete “U” channels and precast concrete waffle sections. “Unistrut” channels are cast into the waffle slab to accommodate hangers for piping, ductwork, and conduit. Weld plates cast into columns allow for installation of prefabricated piping racks between columns.

HVAC systems. The HVAC system of a semiconductor manufacturing facility is comprised of the air systems (dry side) and the water/steam systems (wet side). The air system consists of cleanroom re-circulation air, make-up air, process exhaust (corrosive exhaust, VOC exhaust, pyrophoric exhaust and ammonia) and heat exhaust. The wet system includes chilled water generation and distribution system, glycol chilled water generation and distribution system, steam generation and distribution system and heating water system. Some of the auxiliary HVAC systems include Process Cooling Water (PCW) for the production tools and Hot De-ionized or Ultrapure Water (UPW) for process improvements.

Ultra-Pure Water (UPW) system. The UPW system provides pure water for the removal of contaminants from the wafer surface, and is hence critical to the manufacturing process. The UPW process removes particles, dissolved solids (ions), bacteria, organic matter and dissolved gases from the water before it can be used in the manufacturing process. The various steps in the purification process include filtration, chemical treatment, reverse osmosis, de-gassification, de-ionization and ultraviolet sterilization. The UPW system is usually located in the Central Utilities Building and the system is sized based on the consumption per make-up flow estimates. For example, a 300mm wafer fab would require 10 gallons of UPW per day per square feet of clean room space, which means for a typical 200,000 square feet facility, approximately 2,000,000 gallons of UPW must be processes per day and supplied to the process tools.

Gases and chemicals. Gases and chemicals are the building blocks for manufacturing integrated circuits. The gases and chemicals used in semiconductor manufacturing facilities are broadly classified as bulk gases, specialty gas systems and bulk chemicals (solvents/corrosives/oxidizers). Gas and chemical systems are designed based on the highest minimum pressure required by any tool, purity requirement, supply method, demand and pressure, tool uptime and reliability, and shift related load factors. The piping systems are always designed for leak detection, and sometimes for accommodating greater capacities for future expansion. Table 4 highlights the gases, chemicals, piping materials and the method of supply, storage and distribution.

Table 4

Gases and Chemical Systems in a Fab

Gases and chemicals	Piping material	Supply & Distribution
	Bulk gases	
Nitrogen, Oxygen, Argon, Hydrogen, Helium	Depends on the gas. SS for high purity gas.	*Supply:* cryogenic tacks and vaporizers. All supply is contained in piping
	Bulk chemicals	
Solvents (Ethyl lactate, Methanol), Heavy Metals (Copper), Aqueous (HF, H_2O_2, H_2SO_4), Slurry	Solvent: 316SS Aqueous/Copper: Sch.40 clear PVC with PFA tubing.	*Supply:* Chemical dispense module (CMD), valve manifold boxes (VMB). *Distribution:* piping system
	Specialty gas systems	
Reactants (C_2F_6, CHF_3, SF_6, CF_4) Corrosives (HCl, BF_3, WF_6, BCl_3, NH_3) Oxidizers (NF_3, Cl_2) Flammable/Toxics (PH_3, AsH_3, B_2H_6 mixtures in H_2 and inerts) Pyrophoric (SiH_4)	316L Stainless Steel electropolish, 5-20 Ra., 1/4” to 3/8” size *Supply:* gas cabinets, gas panels, valve manifold boxes (VMB), valve manifold panel (VMP), & Bulk specialty gas system (BSGS).	*Distribution:* Piping system routing highway for multiple gas lines, proximity to tools and structure egress, interface with facility services

Electrical systems. Electrical systems for a semiconductor manufacturing facility consist of normal power supply for the facility support and process equipment, emergency power for the ventilation system in the cleanroom area, corrosive and solvent exhaust fans and make-up air units, uninterruptible power system for emergency and exit lighting, building automation systems, and critical process equipment requirements (process cooling water, loop pumps, solvent exhaust controls and life safety systems). The design of electrical systems for a semiconductor manufacturing facility must consider factors such as safety, reliability, simplicity of operation, voltage maintenance, flexibility, cost, loads, demand, system, equipment location, voltage selection and utility service (Pindukuri, 2011).

2.2.3. Construction & Operations

As mentioned in the previous section, fab construction is a complex system incorporating a specialty building structure, specific utility requirements and installation of manufacturing tools and equipment under strict guidelines and cleanliness protocols. Fab construction is characterized by aggressive schedules, budget limitations, and a high-degree of uncertainty. Because of the aggressive schedules, semiconductor facilities can suffer from lack of project control, front end planning or pre-project planning, which are critical for project success (Kedem-Yemini, Rabinowitz, & Pliskin, 2004).

There are two major phases in the design and construction of a semiconductor manufacturing facility:

1. ***Base Build*** includes the installation of a base factory building, services, and fit-up of equipment to establish functional environmental controls and utilities to support production equipment installation (Ammenheuser, Lewis, & Huebner, 1998).
2. ***Tool Install*** refers to the various semiconductor manufacturing equipment (process tools) installed in the facility for the processes such as Thin Film, Dry Etch, Wet Etch, Diffusion, Lithography and Implant. This phase includes procurement of tools, detailed design and pre-facilitation, tool hook-up and equipment qualification. Qualification is the testing of the semiconductor processes under rigorous conditions before release for wafer production. The categories of tool installation in a retrofit project include demolition, installation of brand-new tools and/or conversion-in-place to the new technology upgrade.

Another important aspect is the Process Specific Support Systems (PSSS) such as gas and chemical delivery systems (supply, storage and distribution) that are required for the functioning of the process tools, whose characteristics are likely to change with major design criteria changes due to the next generation upgrades (Gil et al., 2005; Pindukuri, 2011). Thus, the design and implementation of these systems can be delayed to accommodate late changes and flexibility. Figure 14 shows how the various systems come together and form the semiconductor manufacturing facility.

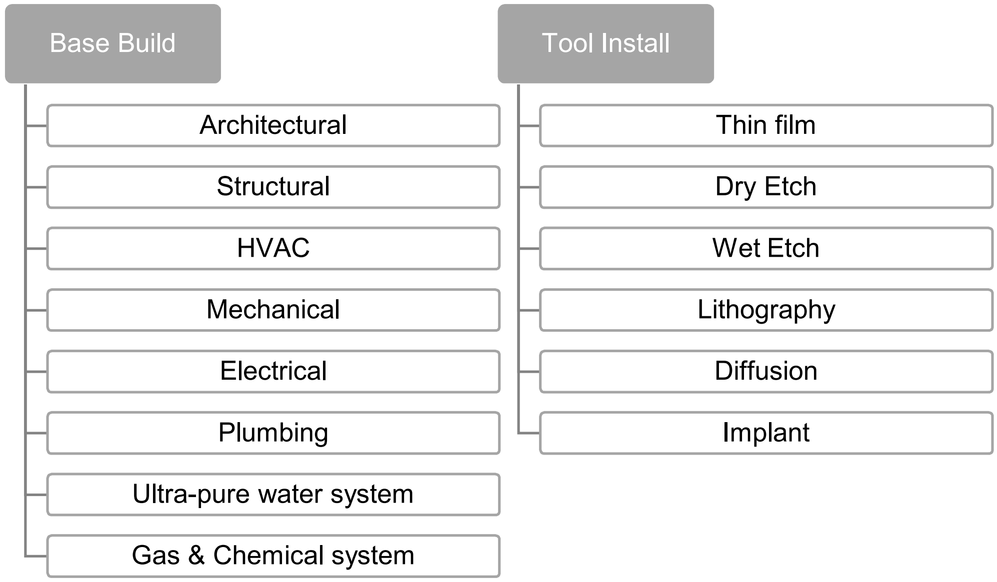


Figure 14. Components of a Semiconductor Fabrication Facility. Adapted from *Implementation of Building Information Modeling for Wafer Fab Construction* by S. Pindukuri, 2011

The purpose of the fab determines the design and construction delivery. Fabs can be for: (1) technology development (TD), (2) high-volume manufacturing (HVM) and (3) production only foundries. The TD fabs house pilot lines of tools, for the research and development of new chip manufacturing processes, while HVM fab projects house lines of tools fine-tuned in a TD fab (Gil et al., 2005). Owners can use several different delivery methods for constructing the facility. Fab delivery consists of several overlapping phases as shown in Figure 15, in order to reduce the overall schedule. Gil et al. (2005) provide the following definitions:

1. *Programming:* including definition of fab performance requirements, type of product, production requirements and preliminary list of manufacturing tools. These are converted to design criteria using historical rule of thumbs.

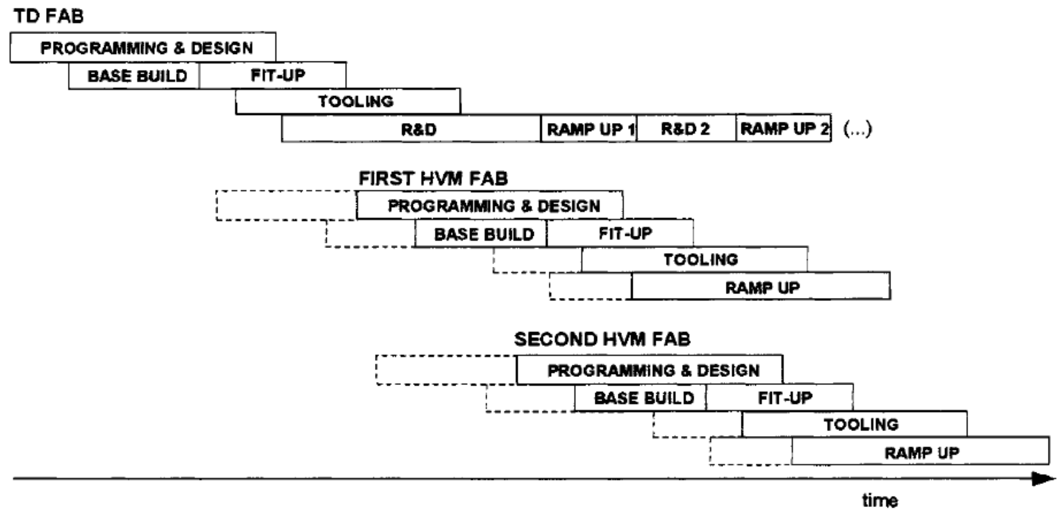


Figure 15. Fab Delivery Stages. Adapted from *Embodying product and process flexibility to cope with challenging project deliveries* by N. Gil, I. D. Tommelein, A. Stout and T. Garrett, 2005

2. *Design:* includes the design of support systems and utilities (mechanical, electrical, piping, architectural) represented in P&IDs.
3. *Base-build:* consists of construction operations for the construction of the building envelope. In the case of retrofits, this phase will not exist, however the base-build As-Built data would need updating.
4. *Fit-up:* includes the installation of the main and lateral utility routings in the sub-fab.
5. *Tool-install:* includes the design of the systems to install the tools, the installation of the tools in the cleanroom, and the installation of their support equipment *e.g.,* vacuum pumps, heat exchangers, and gas cabinets in the sub-fab. During tool hookup, Mechanical-Electrical-Plumbing (MEP) contractors connect the multiple tool connection points with the points of connection for the numerous chemicals, gasses, drain lines, safety/environmental sensors, and exhaust lines.
6. *Ramp-up:* includes increase of the factory production to the target production rates while the chip manufacturing processes are fine-tuned simultaneously.

The scope of this research is concerned with the tool-installation phase. The next section will discuss in detail the design and construction activities for tool installation, the information flow and major challenges. Figure 16 shows the cross section of the fab (clean room) and the sub-fab with the processing equipment (tool), support equipment (tool) and utilities.

2.2.4. Tool Installation

Process Tool Accommodation or Tool Installation is a method by which semiconductor-processing equipment is installed in a cost-effective and timely manner. The Semiconductor Equipment and Materials International (SEMI) develops and publishes international standards in the form of specifications, guides, test methods, terminology and practices for perusal by the industry. The SEMI E6-Guide for semiconductor equipment installation documentation; E51-Guide for typical facility services and termination matrix; and E70-Guide for tool accommodation process; provide guidelines for cost effective and timely tool installation process.

The tool installation *design* begins with the owners' industrial engineering team providing a generic master design showing the new tools and the utilities that connect to it. This is used as a template for creating a location specific design package (LSP) by the design/engineering team showing the tool layout in a specific fab in relation to support equipment in the sub fab, reference tools and auxiliary systems and the utility source point of connections or facility-POC. The design-engineering team provides this information to the contractors in the form of Piping & Instrumentation drawings (P&IDs) and a design package. The trade contractor will then develop a detailed routing design showing coordination with the base-build systems, bill of materials, fabrication isometrics and weld logs (Pindukuri, 2011).

Preparation for *construction* involves validating a utility matrix, the facilities data sheets, tool position and layout, tool automation, safety protocols and existing conditions documentation. The utility matrix is a database identifying all utilities required in the fab, including details about the equipment, electrical, heat-load, exhaust, gases, liquids and process supplies. It is used to verify space for additional utilities to be brought into the renovated area and determine which

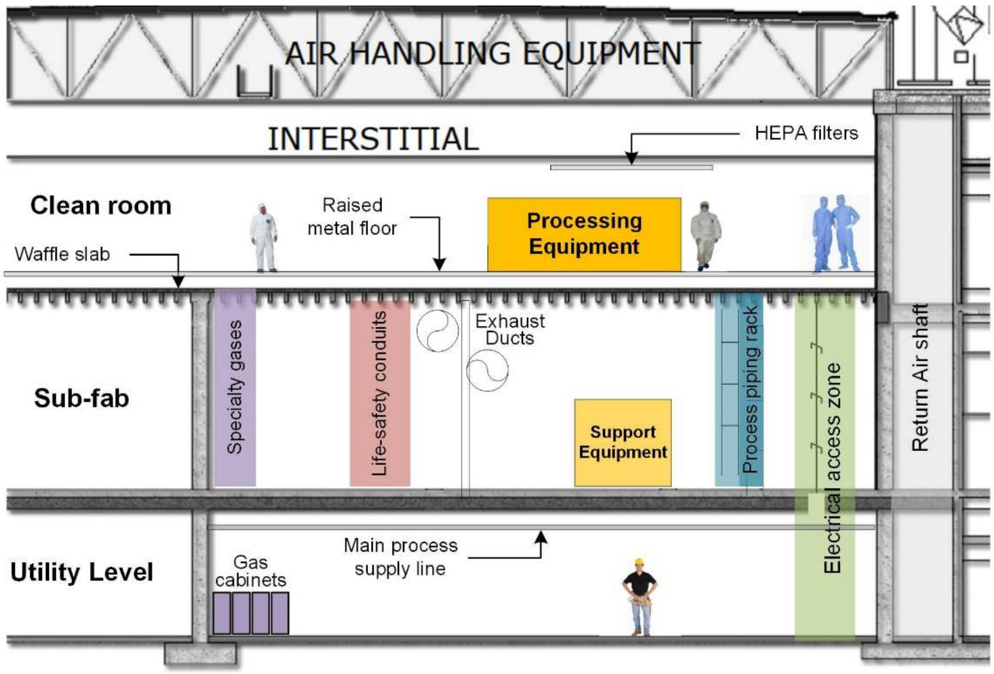


Figure 16. Cross-section of a Fab with Tools

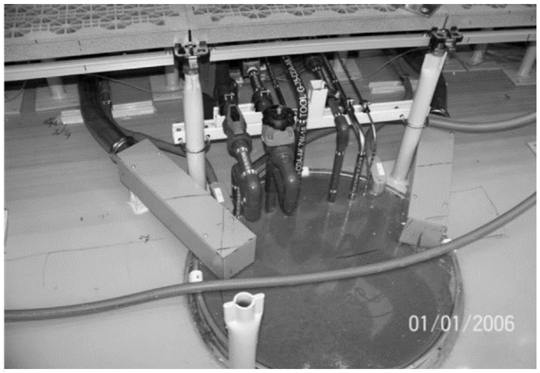
systems need to be redesigned to meet the new toolset's requirements (Pinho & Williamson, 2000). Other information pertaining to the tool regarding its footprint, interface with any automation systems, schedule information and clean installation protocol requirements need to be verified as well (Pindukuri, 2011).

The facility POC's and sub-fab support equipment such as Valve Manifold Boxes (VMB), electrical boxes, pipe racks and distribution racks, are installed during base-build construction and are hooked up to the tool POC's during tool install. Tool installation is usually separated into two phases: "pre-facilitation" before the tool arrives on site, and "hook up" once the tool and its support equipment move into their final positions (Gil et al., 2005). *Pre-facilitation* includes installing the pedestals (on which the process tools are placed so that they can be levelled) in the sub-fab and fab including structural and seismic verifications, the installation of hangers and the electrical, ductwork, exhaust and process piping runs from the facility POCs or support systems to approximately the last feet to the tool POC. The next step is the moving in of the process tools and positioning in their final locations on the pedestals. The *hook-up* includes connecting the pipe runs to the sub-fab tool POC and vertical pipe runs through pop outs in waffle slab, from the sub-fab tool to the corresponding tool in the cleanroom fab. Finally, the piping from underneath the RMF is connected to the tool POCs in the cleanroom.

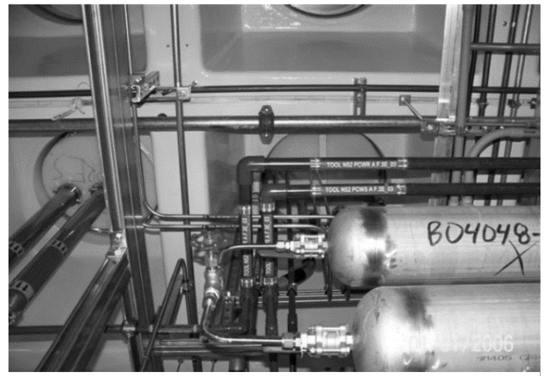
After the tools have been installed, the final phase is commissioning and start-up. Start-up procedures and punch lists are written up to fix critical issues to facilitate a soft start-up of the tool during the construction and installation phase. The system is then tested for function during a temporary run and critical issues are fixed (Pindukuri, 2011). During the final shakedown, critical issues are fixed and the tools are handed over to the facility owners/operators. Figure 17 shows some images from inside a fab and sub-fab.

Challenges and considerations. The construction of semiconductor fabs is a complex process with several fundamental challenges such as concurrent design and construction to keep up with frequent changes while meeting strict deadlines, fixed budgets, cleanroom codes and safety and finding skilled construction trades and personnel familiar with these complexities (Chasey & Merchant, 2000; Gil et al., 2005). The tool installation process is the focus of this research, which has its peculiar constraints affecting construction productivity, as described below:

- *Workspace constraints*: A typical 100,000 square feet cleanroom space can have up to 1000 tools with 300 to 500 different tool types organized in a very complex layout. As the wafer size increases, the tool size also increases with it, which results in even less space for construction workers (Kedem-Yemini et al., 2004).
- *Fast track:* Compared to other construction projects, tool install projects are typically fast-tracked from day one and have to comply with a strict schedule and budget. The goal in this case is to maximize parallel activities and reduce float in order to achieve the set schedule (Kedem-Yemini et al., 2004).



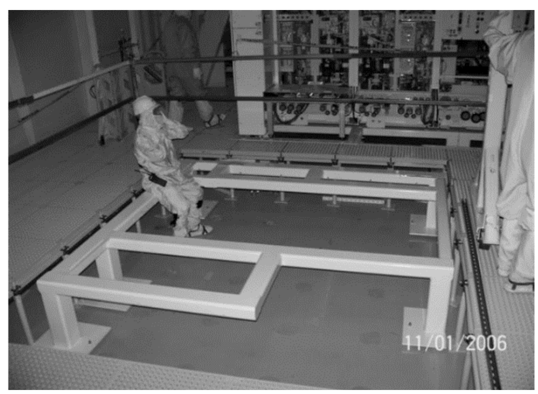
Utilities under the raised metal flooring (RMF) through the pop-out to the sub-fab



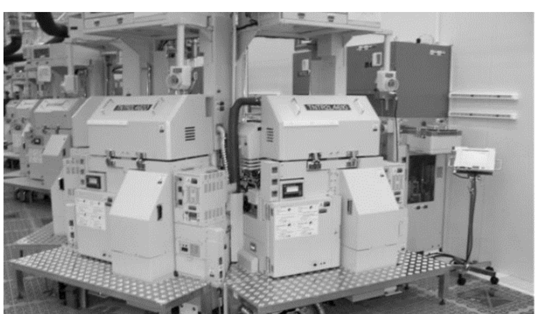
View of the Popouts in the waffle slab (viewed from the sub-fab)

Electrical and gas piping “highway”

VMB’s and distribution racks in sub-fab



A RMF under construction



A tool ready to be installed sitting on the RMF in the cleanroom

Figure 17. Images from Fab and Sub-Fab. Adapted from *Tool Accommodation* by M. Hansen, November 2011.

- *Frequent changes:* Process improvements, new technologies, engineering modifications and field requirements lead to frequent changes and hence high uncertainty (Chasey & Merchant, 2000; Gil et al., 2005; Kedem-Yemini et al., 2004).
- *Safety-quality standards:* Some gases and chemicals used for the processes can be extremely toxic and highly sensitive to temperatures and humidity, leading to strict protocols and guidelines. This naturally creates a high-risk area for construction and the need for stricter safety protocols once chemicals are introduced into the system.
- *Risk of rework:* Pre-facilitation of some of the utilities in the sub-fab before final design leads the risk of rework, which automatically increases the risk of material waste, reduced productivity and potentially contamination, which ultimately affects cost and schedule.

According to a research by Gil et al. (2005), most industry professionals agree that *product flexibility* (designing and building extra capacities, delay tool installation until all decisions are finalized, allow space for future expansion) is the most effective way of coping with such uncertainties while meeting all the goals of fab construction. However, they also present some of the challenges to that, such as anticipating performance requirements and excessive over-design. They advocate the concept of *process flexibility* through strategies such as pre-facilitation, off-site prefabrication and time based four-dimensional modeling.

Strategies and practices

- ***Retrofitting*****:** Traditionally, the semiconductor industry preferred commissioning green field sites for new fabs; however, recently owners are preferring refurbishment of existing facilities, partly due to reasons such as; re-use of old equipment, cost savings from not having to rebuild infrastructure and building envelope and move work-force and possible tax-savings (Greenhalgh, 1998). Refurbishment or retrofit results in overall project cost savings but also introduces certain complexities such as space congestion in the sub-fab and minimizing disruptions to current manufacturing operations.

- ***Prefabrication and standardization:*** A research study by Chasey & Ma (2001) found that total installation cost (labor and material) is directly affected by the number of POCs. They propose standardization and prefabrication with the use of an interface panel and a single point of connection to reduce installation costs. Another area for applying a prefabrication strategy is the off-site fabrication and assembly of support system equipment such as hangers, pipe racks, high-purity stainless steel piping, electrical wire-ways and electrical conduits. This will have a direct impact on simplifying pre-facilitation, hook-up and startup processes, procurement of materials, improved labor productivity and less congestion on site. However, as Chasey & Ma (2001) point out, standardization and prefabrication will make the design phase more critical, less flexibility will exist for changes, dimension co-ordination will be a major concern, structural, code issues will have to be reconsidered, and durations of certain construction activities will have to change.

- ***Use of Building Information Modeling:*** BIM is an enabler for prefabrication by allowing processes such as automatic generation of spool drawings from a 3D CAD model, computer aided manufacturing and rapid prototyping. BIM also enables 3D coordination for checking interferences, construction sequencing (4D) and a faster process for cost analysis (5D) through material and quantity take-offs. Additional technologies such as laser scanning and material tracking using bar codes is also a benefit realized through BIM.

2.3. Building Information Modeling

The significance of using BIM on a project is that if used correctly from the beginning of the projects lifecycle, BIM offers opportunity for the development of high performing facilities through sustainable building construction processes with fewer resources and lower risk than a traditional process (Eastman et al., 2011). While the benefits of using BIM and its applications are many, there are several conflicting viewpoints about what exactly is BIM. A literature review of the definitions provided by academics and practitioners reveals two understandings; one that refers to BIM as a representation, and the other defining it as a process. Table 5 highlights a few of these definitions.

Table 5

Varying Definitions of BIM

Building Information **Modeling** (Process)	Building Information **Model** (Representation)
Intelligent model based process	Digital representation of the physical and functional characteristics of a facility
Process improvement methodology	Complex database of intelligent objects
Development and use of a multi-faceted computer software data model	Data-rich, object-oriented, intelligent and parametric digital representation
Value creating collaboration through the entire life-cycle of an asset	Shared 3D models and intelligent, structured data attached to them
Interacting technologies, processes and policies	Intelligent elements that are the digital prototype of the physical building elements
Methodology to manage data	
Shared knowledge resource	

Note. Adapted from Autodesk, 2011; Azhar, 2011; Computer Integrated Construction Research Program, 2010; Eastman et al., 2011; NIBS, 2012; Penttilä, 2006; Reddy, 2012; Succar, 2009a; US General Services Administration, 2007

In all the definitions reviewed, three aspects of BIM become consistently more apparent; it's a 3D model with information attached to it and it is a process. Hence, as mentioned in Section 1.1.1, this study will address BIM as a function of those three aspects, namely:

- ***Geometric information**:* Defined as the three-dimensional parametric modeling of geometry representing physical and spatial building components, including factors such as local attributes, spatial attributes and dimensions.
- ***Descriptive information**:* This includes all functional characteristics and semantic data about the objects, including information such as the type, function, material, cost, to name a few. This constitutes the object, specifications, performance requirements and all the information required to build and maintain the building.
- ***Workflows*:** This aspect refers to the process of planning, implementing and using 3D CAD models with geometric and descriptive information; including, but not limited to acquiring, managing, modifying and updating information.

Despite the semantics, BIM has several uses and functions such as visualization, documentation, simulation, coordination and management, which can be applied during the design, construction and operations lifecycle as shown in Figure 18. Table 6 presents a non-exhaustive list of commercially available BIM software.

This next section will begin with a brief review of literature on BIM adoption, execution/implementation and considerations (Section 2.3.1). Research shows that BIM literature has primarily focused on its application for new buildings and most examples of case studies are from commercial construction, where BIM use is most popular. Hence, the following section (Section 2.3.2) will consider BIM use for existing facilities including retrofits and application in the semiconductor industry. The final section (Section 2.3.3) will provide an explanation of the concept of BIM value from a stakeholder perspective.

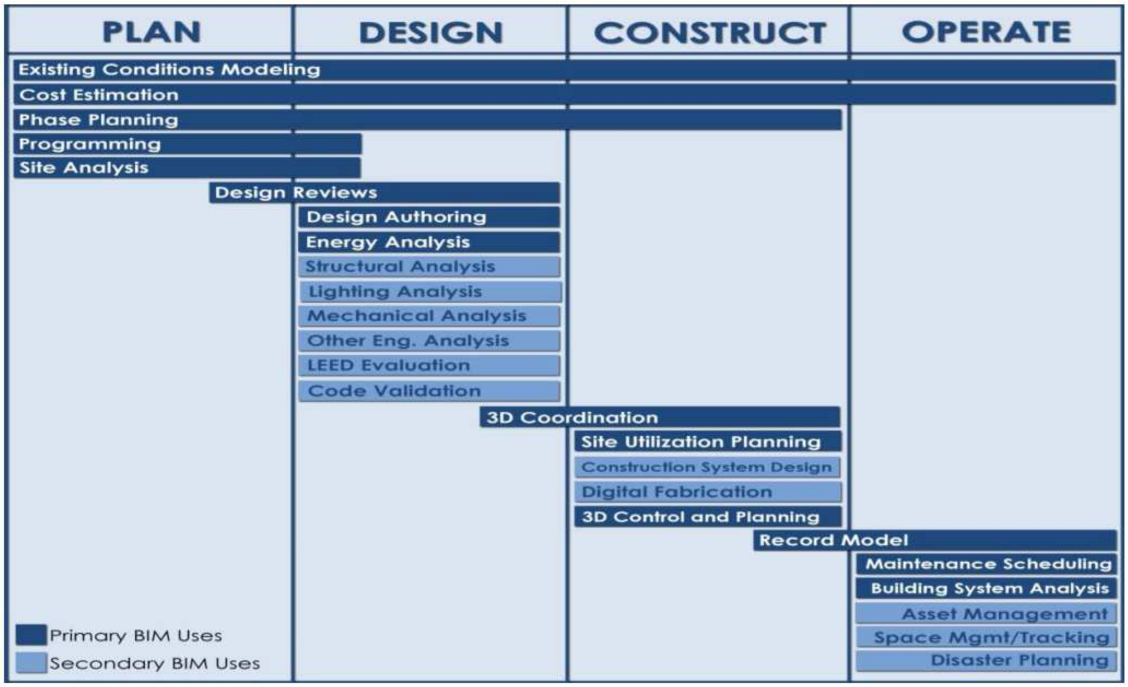


Figure 18. BIM uses During the Project Lifecycle. Reprinted from BIM Project Execution Planning Guide Version 2.0*,* Computer Integrated Construction Research Program*,* 2010

Table 6

Non-exhaustive List of Commercially Available BIM Software

Primary Function	**Commercially Available Software**
Model Authoring	Autodesk® Revit®, Autodesk® Fabrication CADmep, Graphisoft® ArchiCAD®, Tekla® Structures, Dassault Systemes® SolidWorks & Catia, Gehry Technologies etc.
Energy Modeling	Autodesk® Ecotect®, Autodesk® Green Build Analysis, Graphisoft® EcoDesigner® etc.
Construction (Coordination, Estimating, Scheduling, QAQC etc.)	Autodesk® Navisworks®, Trimble® VICO software, Tekla® BIMSight, Bentley® ConstruSIM, Synchro, Innovaya, Solibri etc.
Field Coordination	Autodesk® BIM360, Bluebeam, Plangrid etc.
Facility Management	YouBIM, FM:Systems, EcoDomus, Onuma Systems etc.

2.3.1. BIM Adoption, Execution and Considerations

Barriers to BIM adoption. Initial adoption of BIM is often met with several barriers such as high startup costs, lack of buy-in, learning curve, poor interoperability, limitation of the current software, lack of expertise, difficulty in measuring performance and so on (Bernstein & Pittman, 2007; Eastman et al., 2011; Gu et al., 2010; Won, Dossick, & Messner, 2013). According to Zhai (2010), even though improved use of Information Technology has led to productivity improvements in most industries, construction has consistently been slow in adopting and implementing new technologies. The slow adoption can be attributed to; (a) *technical tool functional requirements and needs* such as data organization, version management, validation, data integrity, standards, data security and lack of communication and information exchange and, (b) *non-technical strategic issues* such as changing roles and responsibilities and learning curve (Gu et al., 2010). Other barriers to adoption are attributed to the high investment costs and relatively slow return on the investment (Barlish & Sullivan, 2012; Giel & Issa, 2013). Information Technology investments are significantly different from capital investments, characterized by high risk, erratic timing of cash flows and significant intangible costs. Hence, the term “productivity paradox” has been used to describe the alleged inability of information systems and technology to deliver in practice the benefits they promise in theory (Irani & Love, 2008). The return on investment in BIM also depends on the stakeholders’ role in the project and their definition of BIM-value; project owners value improved project process and outcomes while designers value productivity and communication, and constructors list project costs and improved productivity as their top BIM benefits (Hoffer, 2014).

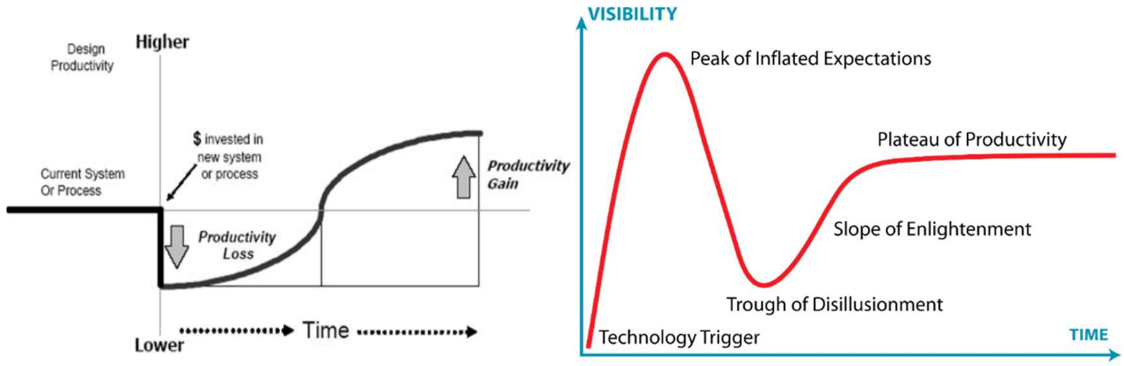


Figure 19. Design Productivity and Visibility of Emerging Technology vs. Time, reprinted from *BIM's Return on Investment,* Autodesk, 2007 and *Gartner Hype Cycle,* Gartner, 2015

According to Autodesk (2007), at the time of implementation of any new IT system, initially there is a productivity loss from the original and eventually, as personnel training progresses, productivity gains from the use of the system can be experienced (see Figure 19). We can study it in parallel to the Hype cycle developed and branded by the IT research and consulting firm Gartner (2015) to represent the maturity and adoption of specific technologies (see Figure 19). Several past studies have looked into the causes of the adoption barriers, developed frameworks for their resolution, benchmarks to measure BIM performance and reported on case studies with positive ROIs and indicators. We can infer from existing literature that the major criteria for successful implementation of BIM in an organization include; cultural change, re-engineering of existing workflows, training in collaborative practices, identifying stakeholder values, scope and expectations, technical development for multi-disciplinary collaboration, accurate capture of existing information and identification of business drivers for the evaluation of BIM (Gu et al., 2010; Khosrowshahi & Arayici, 2012; Singh, Gu & Wang, 2011; McGraw-Hill, 2012).

BIM adoption criteria. In adopting any new technology for a project, the organizational pillars of *people, process and technology*, are approximately balanced as 40-40-20 (Shelbourn, Bouchlaghem, Anumba, & Carrillo, 2007). Several studies have investigated strategies and developed frameworks to implement BIM based on these factors, addressing different aspects and strategies at various levels of granularity (see Table 7). According to Taylor & Bernstein (2009) BIM practice in an organization, typically follows a trajectory from visualization to coordination, to analysis and finally supply chain integration. The adoption to 100% BIM thus happens over time and over a few projects. Industry consortiums and government agencies have developed guidelines to initiate the process (see Table 7).

The level of maturity in BIM is a critical factor for determining the successful implementation of BIM. According to Succar (2009b), BIM capability is *"the basic ability to perform a task'* and BIM maturity is the *'degree of excellence in performing that task."* A method for benchmarking BIM capability and maturity of project participants replaces the anecdotal basis of knowledge evaluation with a measurable performance metric. Popular BIM evaluation frameworks include; (a) the Interactive Capability Maturity Model developed by the National Institute of Building Sciences (NIBS), (b) the BIM Maturity Matrix developed by Succar (2009a) and, (c) bimSCORE developed at Stanford University's Center for Integrated Facility Engineering (CIFE).

Succar (2009b) provides a systematic analysis of a user-based description of BIM implementation, depicted in three stages: Stage 1: object based modeling (referring to the migration from 2D to 3D), Stage 2: model based collaboration (integrated data sharing & communication) and Stage 3: network based integration (dissolution of project phases and the transition to real-time nD collaboration with intelligent models).

Table 7

BIM Frameworks and BIM Guidelines for Implementation

Source	Strategy	People	Process	Technology/ Product
(Eastman et al., 2011))	General considerations	●	●	●
(Khanzode, Fischer, & Reed, 2007)	MEP coordination	●	●	●
(Li et al., 2008)	Virtual prototyping	●	●	●
(Suermann, 2009)	Construction performance measurement		●	
(Succar, 2009a)	BIM implementation framework	●	●	●
(Succar, Sher, & Williams, 2013)	BIM competency & maturity measurement	●		●
(Gu et al., 2010)	Collaborative decision framework for implementation	●	●	●
(Dossick & Neff, 2010)	Organizational adoption, collaboration	●	●	
(Sacks, Dave, Koskela, & Owen, 2009)	Interaction of Lean and BIM		●	
(Singh et al., 2011)	Collaboration platform			●
(Jung & Joo, 2011)	BIM implementation framework		●	●
(Khosrowshahi & Arayici, 2012)	UK BIM implementation roadmap	●	●	
(Love, Simpson, Hill, & Standing, 2013)	Evaluation of benefits	●	●	
(Monteiro & Poças Martins, 2013)	Modeling guidelines for QTO		●	
(Won et al., 2013)	Critical success factors for early adoption	●	●	●
(Hoffer, 2014)	BIM value, Return on investment	●		●
(Kassem et al., 2014)	Collaborative modeling		●	●
(Lee & Kim, 2014)	Clash detection process		●	●
	Industry Guidelines			
(US General Services Administration, 2007)	BIM guide series	●	●	●
(CIC, 2010)	BIM Project Execution Plan	●	●	●
(NASA, 2011)	Scope of services	●	●	●
(NIBS, 2012)	National BIM standards US	●	●	●
(CIC, 2013)	BIM Protocol UK	●	●	●

The Interactive Capability Maturity Model (CMM) is a part of the National BIM Standards specified by the National Institute of Building Sciences. It defines the minimum BIM standards that should be exhibited by a project to specify that they are doing BIM. There are 11 areas of interest measured by capability levels ranging from 1-10. The National BIM Standard defines minimum BIM as having the following characteristics through associated areas of maturity as determined by the CMM: Spatial Capability, Roles or Disciplines, Data Richness, Delivery Method, Change Management, Information Accuracy, Lifecycle Views, Graphical Information, Timeliness and Response, Interoperability and Industry Foundation Class Support (NIBS, 2012). A minimum score of 40 is required for the organization/project to meet the minimum BIM maturity (NIBS 2012). *bimSCORE* is a project-based maturity ranking system also known as the Virtual Design and Construction (VDC) scorecard measures the degree of BIM innovation in planning, adoption, technology, and performance.

Successful adoption of BIM depends on the achievement of the goals for using the resource established at the beginning of the project. Although there are several uses of BIM, not all are applicable or applied to a project at a given time. With increased experience in implementing BIM, academics and industry consortiums have established a few factors that are critical for assuring the possibility of success in BIM implementation. These include the development of a BIM Execution Plan and a contract addendum for BIM, standards for the 3D CAD model and BIM development, management and deliverables, the Level of Development (LOD) of the model, interoperability and information exchange standards and the establishment of performance benchmarks to measure the effectiveness of BIM.

- ***Execution plan and contract:*** The Computer Integrated Construction Research Program at Pennsylvania State University developed the BIM Project Execution Planning (BIM PxP), which AEC firms across the United States have adopted by as a guide, and a template for execution plans for their projects and organizations. The BIM PxP provides a framework to identify BIM goals and uses, design a BIM project execution process identifying tasks, information content, information exchanges, level of detail and responsible parties and the supporting infrastructure required for BIM implementation (Computer Integrated Construction Research Program, 2010). The guide emphasizes early planning, owner involvement, improved collaboration and flexibility in work processes for greater success. Although, it is a widely held belief that BIM processes are more comprehensively adopted in integrated project delivery (IPD) approaches, the BIM PxP can be adapted in all contracting structures (Computer Integrated Construction Research Program, 2010).

The American Institute of Architects (AIA) published new BIM contract documents in 2013-14, the AIA E203: Building Information Modeling and Digital Data Exhibit and the AIA G203: Project Building Information Modeling protocol form (see Figure 20). These contract documents include the topics of; *project definition and planning* (BIM roles, maturity, and functions), *technical specifications* (file formats, information exchanges, level of detail and development), *implementation processes* (BIM management, process maps and workflows, QAQC protocols and handovers), *infrastructure support* (software, hardware, network) and *legal aspects* (procurement, contractual issues, liability issues and risks). The document also helps in associating model elements utilizing the CSI Uniformat by their Level of Development (LOD) in each phase of the project lifecycle (see Figure 20). Several organizations use these contracts but adoption is still in the initial stages. Other agencies such as the Association of General Contractors (AGC) ConsensusDOCS, the Mechanical Contractors Association of America (MCAA), Department of Veterans Affairs (VA), General Services Administration (GSA) also have their own guidelines for BIM implementation.

§ 4.3 Model Element Table

Identify (1) the LOD required for each Model Element at the end of each phase, and (2) the Model Element Author (MEA) responsible for developing the Model Element to the LOD identified.

Insert abbreviations for each MEA identified in the table below, such as "A – Architect," or "C – Contractor."

NOTE: LODs must be adapted for the unique characteristics of each Project.

Model Elements Utilizing CSI UniFormat™				Conceptualization LOD	Conceptualization MEA	Criteria Design LOD	Criteria Design MEA	Detailed Design LOD	Detailed Design MEA	Implementation Documents LOD	Implementation Documents MEA	Construction LOD	Construction MEA	LOD	MEA	Note Number (See 4.4)
A SUBSTRUCTURE	A10 Foundations	A1010	Standard Foundations	100		200		300		400		500				
		A1020	Special Foundations	100		100		300		400		500				
		A1030	Slab on Grade	100		200		300		400		500				
	A20 Basement Construction	A2010	Basement Excavation	100		200		300		300		500				
		A2020	Basement Walls	100		200		300		400		500				
B SHELL	B10 Superstructure	B1010	Floor Construction	100		200		300		300		500				
		B1020	Roof Construction	100		200		300		300		500				
	B20 Exterior Enclosure	B2010	Exterior Walls	100		200		300		400		500				
		B2020	Exterior Windows	100		200		300		400		500				
		B2030	Exterior Doors	100		200		300		400		500				
	B30 Roofing	B3010	Roof Coverings	100		200		300		300		500				
		B3020	Roof Openings	100		200		300		300		500				
C INTERIORS	C10 Interior Construction	C1010	Partitions	100		200		300		400		500				
		C1020	Interior Doors	100		200		300		400		500				

Figure 20. Model Element Table. Reprinted from *AIA Document G202-2013,* American Institute of Architects.

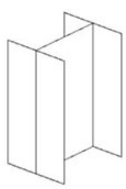
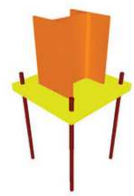
- ***BIM standards:*** The National BIM Standard – United States (NBIMS-US) provides consensus based standards through referencing existing standards, documenting information exchanges and delivering best business practices for the built environment. Since design and construction drawings as well as CAD models are the typical products of BIM techniques, the National CAD Standards (NCS) are an important standard for drawings and model outputs from the BIM process. The NCS defines standards for many aspects of digital design data including CAD layers, organization of drawing sets, drawing sheets and schedules, drafting conventions, terms and abbreviations, graphic symbols, notations etc. BIM is a way of gathering building information and the NCS is a way of graphically documenting the building information. Although BIM authoring software such as Revit are object-based CAD software and not a layer-based CAD software like AutoCAD or Vectorworx, when documents are exported from Revit as 2D or 3D CAD drawings, the standards become critical in maintaining uniformity for information exchanges. This is considering that the information exchanges are in drawing-based deliverables and not model-based deliverables.

- ***Level of Development (LOD):*** The Level of Development (LOD) Specification is a reference that enables practitioners in the AEC Industry to specify and articulate with a high level of clarity the content and reliability of BIM at various stages in the design and construction process (BIMForum, 2013). Table 8 outlines the fundamental definitions for the various LODs. Level of *Development* and *Detail* are often considered similar in meaning, however, the difference is in the amount of detail added to the model versus the degree to which the element's geometry and attached information is developed. Level of Detail can be thought of as input to the element, while Level of Development is the reliable output (BIMForum, 2013). Higher precision in the modeling effort can lead to better decision making during the projects lifecycle, but that does not necessarily imply a proportional increase in modeling work (Leite, Akcamete, Akinci, Atasoy, & Kiziltas, 2011). Rather, a higher LOD can provide increased accuracy for BIM functions such as clash detection. For example, the research conducted by (Leite et al., 2011) found that BIM at a higher LOD for automatic clash detection resulted in a complete identification of clashes, but at the cost of having to deal with many false positives. A manual process, on the other hand, resulted in higher precision rates. Nonetheless, it was more expensive to deal with field-detected clashes than with virtual false positive clashes. It is thus important to relate the LOD requirements with the design and construction activities in order to drive a more objective determination of LODs to be used in supporting those activities. The Model Element Table (as seen in Figure 20) begins to develop a model progression supported by the relevant LOD requirement.

Table 8

Level of Development Definitions

Model element is graphically represented as a…

LOD 100	**LOD 200**	**LOD 300**	**LOD 350**	**LOD 400**	**LOD 500**
symbol or other generic representation	generic system, object, or assembly with approximate quantities, size, shape, location, and orientation	specific system, object or assembly in terms of quantity, size, shape, location, and orientation	specific system, object, or assembly in terms of quantity, size, shape, orientation, and interfaces with other building systems	specific system, object or assembly in terms of size, shape, location, quantity, and orientation with detailing, fabrication, assembly, and installation information	field verified representation in terms of size, shape, location, quantity, and orientation
					

Note. Adapted from *Level of development specification,* by BIMForum, 2013.

- ***Interoperability and information exchange:*** In 2004, the National Institute of Standards and Technology (NIST) commissioned a study to identify and estimate the efficiency losses in the US capital facilities industry resulting from inadequate interoperability among CAD, engineering, and software systems. The study concluded that interoperability problems in the capital facilities industry stem from *"the highly fragmented nature of the industry, the continued paper based business practices, a lack of standardization, and inconsistent technology adoption among stakeholders"* (Gallaher, Connor, Dettbarn, & Gilday, 2004). The study showed that in 2002, the industry as a whole spent $15.8 billion on interoperability, 67% of which was borne by owners. Of the $10.6 billion spent by owners and operators in a year, $9.03 billion (or 85%) was spent in the O&M phase itself, of which $4.8 billion or 53.1% was the cost of information verification and validation. This research effort by NIST led to several efforts by academics and research consortiums such as the building SMART alliance (bSa) and the development of the Industry Foundation Class (IFC) and Construction Operations Building Information Exchange (COBie) as open information exchange standards for improving interoperability.

IFC is an ISO Standard (ISO 26739) vendor neutral data format used to describe exchange and share information. It is a data schema based on class definitions representing objects such as building elements, spaces, properties etc. It is able to link alphanumeric information such as properties to the physical geometry of an object such as a door or a wall while preserving their semantic relationships. IFC model information is typically exchanged through an information exchange format called STEP (ISO 10303). Most BIM authoring tools now provide an export function for converting the model geometry to an .ifc format that can be read by any other non-compatible software application.

COBie is an information exchange model that helps capture information at the point of origin and assures a smooth transfer of information through the stages of the facility lifecycle without losing its context. It contains three types of information; information created by designers, information created by contractors and supporting information created by both. This process is based on the assumption that the data will be provided by the party contractually required to create the information. It is then translated to an Excel spreadsheet format, which enables the capture of the data in its simplest format. COBie attributes can be added to a BIM authoring tool and can be exported as a function of BIM.

- ***Performance benchmarks:*** According to Succar, Sher, & Williams (2012), BIM use needs to be assessable if the productivity improvements that result from its implementation are to be made apparent. They propose a framework for benchmarking BIM performance of BIM users based on five factors;

- BIM capability (ability to perform a task or deliver a BIM product),
- BIM maturity (quality, repeatability ad degree of excellence),
- BIM competency (hierarchical collection of individual competencies for implementing BIM),
- BIM organizational scales (individual, project, organization and industry) and,
- BIM granularity levels (for assessment and measurement).

On the other hand, how well BIM is performing on a project or for an organization is slightly more difficult to measure. This is because BIM does not act alone. The use of BIM with strategies such as lean construction, good project management, collaborative contracting, open standards and information sharing; together improve the performance of BIM and add value to the project. We can classify the benefits received from BIM use as; *qualitative factors* (subjective benefits that improve the process but cannot be quantified) and *quantitative factors* (which can be measured by collecting project data). Some of the qualitative benefits are increased visualization, coordination and validation, benefit to client (client satisfaction), quality of communication and information flow, better conformance to original project scope, risk analysis, improved safety and improved quality of As-Built drawings. Although these factors contribute to the over project success and can be measured as a contributing factor to reduced schedule, cost and improved safety and quality; it is difficult to ascertain what percentage of that success factor is due to BIM. The more easily quantifiable factors of BIM performance metrics for a project are:

- CAD modeling time and compliance
- Performance against schedule
- Number of Request for Information (RFI)
- Number of change orders
- Number of clashes detected through 3D coordination and the cost avoided on site
- Labor hour savings through prefabrication
- Safety incidents detected by BIM
- Risk impact assessment from the use of 4D

Table 9, Table 10, and Table 11 identifies 22 factors considered for BIM implementation (unranked) classified by people, process and technology.

Table 9

People-factors for BIM Implementation

Factor	Definition	Source
1. Cultural change & flexibility	Organizational readiness to adopt BIM	(Gu et al., 2010), (Won et al., 2013), (Dossick & Neff, 2010)
2. BIM capability & maturity	The basic ability to perform a task & the degree of excellence in performing that task.	(Succar et al., 2012, 2013), (Kam, Senaratna, Xiao, & McKinney, 2013)
3. Workforce training & onboarding	Training support and awareness building to align people on the use & benefits of BIM	(Gu et al., 2010), (Eastman et al., 2011)
4. Learning curve of project team	Rate of progress of people and project team in learning & adopting BIM	(Autodesk, 2007),(Won et al., 2013), (Eastman et al., 2011)
5. Collaboration	Willingness & technical support for collaboration between people & teams	(Kassem et al., 2014), (Singh et al., 2011), (Eastman et al., 2011)
6. Communication	Willingness & technical support for communication between people & teams	(Gu et al., 2010)
7. Project team alignment	Willingness to share information and work together towards, organizational and cultural alignment on a common project goal	(Won et al., 2013), (Dossick & Neff, 2010), (Eastman et al., 2011)
8. Performance measurement	Performance measurement of BIM and people using BIM against a known project metric.	(Suermann, 2009), (Love et al., 2013), (Coates et al., 2010)

Table 10

Process-factors for BIM Implementation

Factor	Definition	Source
9. BIM contract & legal considerations	Legal framework to support BIM benefits, uses, information exchange, deliverables and deployment of digital innovations.	(CIC, 2010), (Oluwole Alfred, 2011), (AIA, 2013)
10. BIM strategic planning objectives	Value of BIM adoption and requirements from a company and clients strategy, with clear objectives, goals and expected outcomes.	(Won et al., 2013), (CIC, 2010), (Reddy, 2012), (Eastman et al., 2011), (CURT, 2010)
11. Investment in BIM and related strategies	Allocation and justification of funds for investment in BIM and other support technologies, training & development.	(Won et al., 2013), (Love, Simpson, Hill, & Standing, 2013), (Giel & Issa, 2013)
12. BIM execution plan	Guideline and standards development for the deployment of BIM and team alignment	(Won et al., 2013), (CIC, 2010), (CIC, 2013b), (NASA, 2011)
13. BIM/CAD standards & specifications	Standards & specifications for BIM/CAD drawings and models	
14. Workflow evolution	"The definition of the sequence in which activities should be executed within a process (flow structure) for the modification & management of existing workflows while they are operational" (Casati, Ceri, Pernici, & Pozzi, 1998) when applied to the migration to BIM from CAD or other manual documentation processes.	(Tsai, Md, Kang, & Hsieh, 2014)
15. Supply chain integration	BIM use for material tracking, logistics management and supply chain integration	(Grau, Caldas, Haas, Goodrum, & Gong, 2009), (Vrijhoef & Koskela, 2000)
16. Risk management	Analyzing the risks and impacts of the BIM process	(CIC, 2010)
17. Version control	Tracking and synchronization of changes and modifications across various platforms.	(Doboˇs, 2015), (Gu et al., 2010)

Table 11

Technology-factors for BIM Implementation

Factor	Definition	Source
18. Existing geometry & semantic data capture (As-Built)	Creation of As-Built 3D models of existing buildings from laser scans	(Gu et al., 2010), (Xiong, Adan, Akinci, & Huber, 2013), (Tang et al., 2010), (Gao, 2014)
19. Legacy data migration	"Selection, preparation, extraction, transformation and permanent movement of appropriate data that is of the right quality to the right place at the right time and the decommissioning of legacy data stores" (Morris, 2012) when migrating from CAD to BIM.	
20. Interoperability and information exchange	Exchange of data in the form of drawings, models and information seamlessly between different software platforms	(Gu et al., 2010), (Won et al., 2013), (East & Brodt, 2007), (Gallaher et al., 2004)
21. Software/Hardware/ Network compatibility	The software, hardware and network capability requirements for managing large file sizes and graphics.	(Won et al., 2013), (Eastman et al., 2011)
22. BIM to VDC	Use of technology such as robotic total stations for layout, RFID tags for material tracking, CNC for CAD to CAM, such that BIM can be effectively used for construction in the field.	

The next section provides a commentary on BIM use in facilities which were built without a pre-existing 3D CAD model or utilization of BIM functionalities and the application of BIM for retrofit construction.

2.3.2. BIM for Retrofit Construction

Sanvido & Riggs (1991) define a *"retrofit project"* as the modification or conversion of an existing process, facility, or structure that may alter the kind, quantity, cost or quality of the products or services being produced by the facility. Retrofit projects differ from green field projects in the intensity of the constraints posed by the project types. Table 12 outlines some of the constraints common to retrofit construction projects. Intensity of these issues is also dependent on factors such as the facility type and its operation during construction. For example, an office renovation and semiconductor tool-install project will have the same constraints of safety, schedule, cost and information, but much more exaggerated for tool-install. The commonality exists in challenges which are technical (*e.g.* capturing & maintaining accurate As-Built data, lack of interoperability, high data volumes), organizational (*e.g.* stakeholder collaboration, new workflows), cultural (*e.g.* learning curve, increased effort) (Volk et al., 2014), and in some cases, operational in nature. We can discuss the use of BIM for retrofits in two sections; the technical considerations for BIM development and the non-technical or organizational considerations.

Technical considerations. In order to effectively prefabricate and install building components in retrofits, reliable capture and accurate representation of As-Built conditions is necessary. Rojas et al. (2009) emphasize the importance of determining the LOD required for the purpose of its use (*e.g.* facility maintenance, facility upgrades etc.), and then identifying the method of data capture whether it is 2D geometry, COBie or LIDAR. They present the argument that COBIE data can be produced from the extrapolation of information from traditional drawings. This information can be maintained for long-term use, even if 3D models become redundant. Significant findings from their study are the practical challenges in capturing existing As-Built data, which are; logistical issues (*e.g.* limited access to certain areas of the facility), operational issues (*e.g.* non-standardized data collection methods) and user interface issues (*e.g.* technology and workflow for data capture). Although LIDAR technology through commercially available high-

Table 12

Constraints in Retrofit Projects

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

resolution laser scanners is popular in capturing existing data, some workflow issues need to be addressed. For example, complex designs and obstacles make it difficult to rely on the data capture from standard vantage points, addition of more data creates large file sizes slowing down systems and the mismatch of point cloud and model geometry make the data unreliable.

This approach is different from the more automated approach to capturing conditions using laser scanning. Although there are certain difficulties in data capture such as, complex designs and obstacles of existing conditions, repetitive manual task of capturing multiple angles of a scene and large file sizes due to the addition of more data, several advantages have made laser-scanning indispensable. Point clouds can be converted to surface models in one of two ways; manually drafting in the CAD software or the use of automatic surface generation algorithms. According to Tang et al. (2010), this process is fundamentally manual and time consuming and there are several technology gaps in the automatic model generation process such as; modeling of more complex structures and non-ideal realistic geometries, handling realistic environments with clutter and occlusion, representing models using volumetric primitives rather than surface representations and developing quantitative performance measures for tracking the progress of the field. Volk et al. (2014) summarize the lack of overall implementation of BIM in a retrofit scenario as; identifying challenges such as capturing structural, concealed or semantic building information under changing environmental conditions and of transforming the captured data into unambiguous semantic BIM objects and relationships.

Non-technical considerations. BIM application in a retrofit project naturally requires a 3D CAD model of the existing conditions. If an outdated or no model is available, processes begin with auditing, documenting and analyses of previous and current building properties as shown in Figure 21. Some of the modeling considerations include the accuracy and reliability of data, the LOD and information exchange and interoperability. Other factors outlined by Volk et al. (2014) are the same issues as BIM implementation in a new building which are stakeholder collaboration, responsibility, liability and model ownership and education, training and culture.

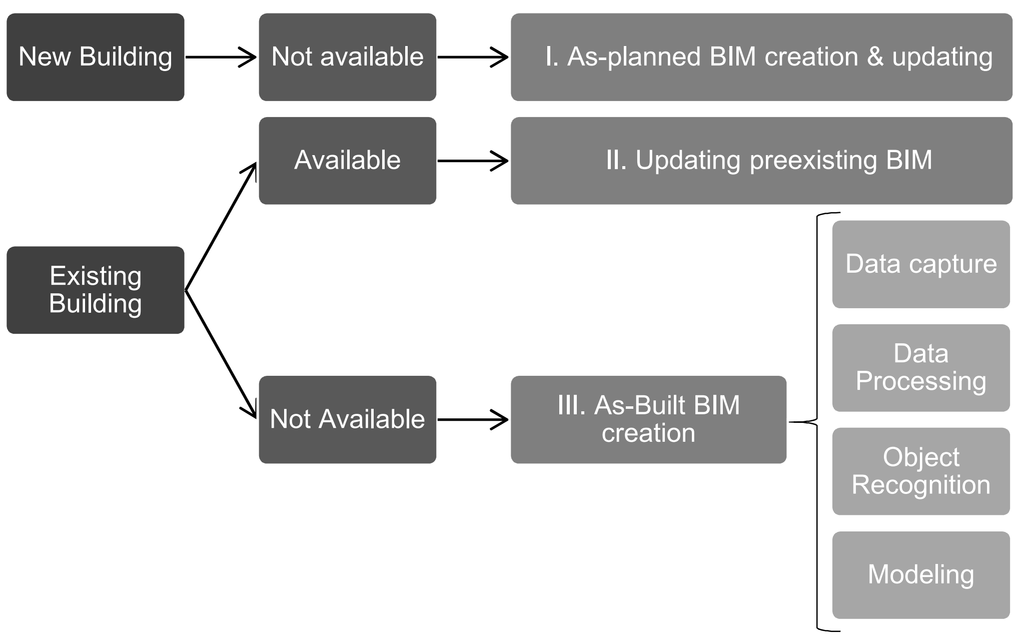


Figure 21. Model Creation Process in New and Existing Buildings. Adapted from *Building Information Modeling (BIM) for existing buildings — Literature review and future needs* by R.Volk, J. Stengel & F. Schultmann, 2014.

2.3.3. Stakeholder Value of BIM

Construction project stakeholders seek different utilities from BIM as a product and a process. As a product, design disciplines see BIM as an extension to CAD, while contractors and project managers expect BIM to be an intelligent database management system that can extract data from CAD packages for analysis, time sequence and cash flow modelling and simulation and risk scenario planning (Gu et al., 2010). As a process, all project stakeholders seek greater collaboration and communication across disciplines from BIM. A more detailed survey based study conducted by Hoffer (2014) found that the economic value of BIM is driven by the stakeholder utility for BIM. For example, owners tend to recognize multiparty communication and improved project process and outcomes as top benefits, while architects and engineers prioritize productivity and communication and contractor's list productivity and lower project cost as their top benefits from BIM (Hoffer, 2014).

Stakeholders are defined as *"any group or individual who can affect or is affected by the achievement of the organizations objectives"* (Freeman, 1984). In the case of construction, the project is the temporary organization and the stakeholders include the prime beneficiary of the project *i.e.* the owner, the project participants *i.e.* the architect, engineer, construction manager, contractors and their supply chain partners *i.e.,* subcontractors and material and equipment vendors and also the larger community and environment who will be affected by the project. All stakeholders have a vested interest or stake in the success or failure of the project. Moreover, stakeholders must add value to the project to meet the primary goals of cost, schedule, quality and safety.

Harrison & Wicks (2013) propose extending the meaning of the term "value" beyond the immediate notion of economic returns, and to include *"anything that has the potential to be of worth to stakeholders."* In addition, they use the term "utility" to mean the *"value a stakeholder receives, which is actually of some merit to the stakeholder."* They propose that a stakeholder-based perspective of value is important for management to examine more broadly, value-creation from the perspective of the stakeholders who are involved in creating it. This is critical for measuring firm performance, which they define as *"the total value created by a firm through its activities which is the sum of the utility created for each of the firms' legitimate stakeholders."* The stakeholder based perspective of value postulates that the "*utility created for one stakeholder is dependent in part on the behavior of the other stakeholders and the amount of utility they receive influences their transactions with the organization and the other stakeholders"* (Harrison & Wicks, 2013).

Borrowing from this theory, we can understand a construction project and its participants in a similar way. It is known in construction literature and practice that most stakeholders are often in conflict, although they frequently depend on each other to satisfy their interests and contribute to the goals of the project. This is especially true when creating and sharing *information* in a construction project. The success of using BIM for information creation and sharing and ultimately for effective application in the field depends on the reliability, accuracy and timelines of the data. It is also critical to know whether the information created in BIM by one stakeholder (say the architect) has utility for another stakeholder perusing it for a purpose down the line (*e.g.* the process piping contractor using BIM for prefabrication). Moreover, the value of the information created by the architect depends on data received from other sources (*e.g.* owner, surveyor, etc.). Thus, we can say that the quality (reliability, accuracy, and timeliness) of information received, created and shared by the stakeholders will determine the overall success of using BIM on a project. While there are several concepts of stakeholder value which are important for a construction project, this research will consider the *stakeholder utility associated with BIM,* and the value they seek from it.

2.3.4. Summary

We can summarize the literature reviewed for BIM in the form of the following questions:

- ***What is BIM?*** Building Information Modeling is a tool and a process comprising of three primary aspects; geometric information in the 3D CAD model, descriptive information linked to the model elements and workflows for acquiring, managing, modifying and updating information.

- ***What are the <u>requirements</u> for successful BIM implementation?*** Cultural change, re-engineering of existing workflows, collaborative practices, identifying stakeholder values, scope and expectations, technical development for multi-disciplinary collaboration, accurate capture of existing information and identification of business drivers for the evaluation of BIM etc.
- ***What are the <u>major steps</u> in BIM implementation?*** The development of a BIM execution plan, contract, standards, a model progression based on the Level of Development required for a BIM use, interoperability and information exchange standards and the establishment of performance benchmarks to measure the effectiveness of BIM.
- ***What are the <u>major challenges</u> in implementing BIM for retrofits?*** Accurate capture of structural, concealed or semantic building information under changing environmental conditions and transforming it into unambiguous semantic BIM objects and relationships, and non-technical concerns such as disrupting the existing workflows and the organizational adaption to the new processes.
- ***What are the <u>driving factors</u> for successful BIM implementation?*** Reliability, accuracy and timelines of the data or the quality of information received, created and shared by the stakeholders and the *stakeholder utility associated with BIM.*

The literature on BIM presented several factors and theories for BIM implementation, improvement and advancement, but there was an evident gap in documented case studies quantifying the impact of BIM use at its current maturity level on labor productivity and retrofit projects. The case study of tool installation at a semiconductor manufacturing facility provides an environment to explore both these phenomena. The next section is a literature review on labor productivity, the factors causing productivity loss and the factors for regarding BIM and prefabrication as processes for improving labor productivity.

2.4. Construction Labor Performance

Construction faces criticism because of its poor labor productivity. As explained in Section 1.2.1 – State of the AEC industry, there is a difference in labor productivity trends when measured at the aggregate level versus the activity level. However, while the manufacturing industry has embraced organizational discipline and developed various models for effective design, production and management, a similar trend in construction has been considerably slow. This section will examine some of the metrics for measuring productivity, the reasons for productivity loss and conclude with how BIM and prefabrication are methods for countering some of those loss factors.

2.4.1. Labor Productivity Definitions and Metrics

Tangen (2005) postulates that despite the popularity of their usage, the terms productivity, performance, effectiveness and efficiency are often confused because of lack of definitions. Productivity as defined by Tangen (2005) is the physical phenomenon identifying the relationship between an output quantity (*i.e.* correctly produced products that fulfill their specifications) and the input quantity (*i.e.* all resources that are consumed in the transformation process). Performance, on the other hand, is an umbrella term for excellence, which includes productivity and profitability as well as non-cost factors such as quality, speed, dependability and flexibility (Tangen, 2005).

Construction productivity is measured at three levels: the activity or task, the project and as an industry or economy (Huang et al., 2009; Thomas et al., 1990). Since construction is a labor-intensive industry, human effort plays a critical role in determining construction performance, thus making the activity or task-level labor productivity an important index. At the most basic level, it is a measure of outputs for a combination of inputs, as shown in Table 13. Project managers use a productivity ratio (actual productivity/planned or estimated productivity) to assess construction performance.

Table 13

Metrics for Measuring Task-level Labor Productivity

Metric	Measure	Parameters		
		Economic	Project	Task
Production rate	Amount of output produced per unit of input *= Output/Input*	O = Total Output in dollars or functional units I = Labor + Materials + Equipment + Energy + Capital (in dollars)	O = Functional Unit I = Labor + Material + Equipment (in dollars)	O = Functional Unit or Value-added I = Labor-hours or Labor-cost
Unit rate	Amount of input required for a fixed amount of output *= Input/ Fixed output*	N/A	N/A	I = Labor-hours or Labor-cost O = Functional Unit

Productivity at the task level can be measured using a single factor or discrete approach (*i.e.* quantification of how much a specific factor affects productivity) or as a multi-factor or cumulative approach (*i.e.* quantification of multiple factors using statistical tools). At the task-level, factors such as the amount of work, crew size, constructability, environmental conditions and learning curve influence the production rate. Even though the factors may have a similar impacts on productivity, their level of influence will vary from task to task (Yi & Chan, 2014). For example, retrofit and renovations have considerations of congestion and limited space availability for work. Semiconductor manufacturing environments have to consider additional regulatory and environmental factors that may impact productivity such as clean room environment, air particulate matter control, sanitization of equipment, gowning and de-gowning and the complexity of the sub-fab level.

Comparing the baseline productivity; *i.e.* the actual, representative unimpacted productivity; with productivity observed during certain disrupted time-periods estimates productivity loss. Three methods from literature offer ways to determine baseline productivity; baseline method by Thomas & Zavrski (1999), statistical process control method by Gulezian & Samelian (2003) and statistical clustering method (K-means method) by Ibbs & Liu (2005). Fundamental differences in the models regarding the assumption of the baseline factor as being the best productivity or normal productivity of the contractor may provide conflicting results. More commonly in the industry, contractor and owner groups refer the industry standards provided in the MCAA (Mechanical Contractors Association of America) manual, NECA (National Electrical Contractors Association) Job Factor Check List, and US Army Corps of Engineering's Modification Impact Evaluation Guide, to calculate the baseline productivity. These standards provide percentage values for productivity loss due to various internal and external factors, which may or may not reflect actual conditions of a particular project or construction sector.

Value-add and Non-Value add as a measure of productivity. Research shows that the available work hours and effective work hours differ because of certain unavoidable time delays that occur during a work day, such as breaks, weather conditions, cleanup times etc. (Hanna, 2010). A "work-study" method analyzes labor-time utilization at the task-level. The objective is to observe the work-method and work-time in order to determine the amount of time spent by labor on productive versus non-productive work and hence identify site or management constraints that hinder efficiency (Yi & Chan, 2014). Common data-collection techniques used for work-study are video photography, stopwatch timing, and work sampling. The techniques rely on collecting large amounts of data to establish average values, and few attempts determine the causes of variations (Thomas et al., 1990). Lean concepts of value-added versus non-value added work also contribute to the interest in labor-time utilization. Hanna (2010) found that value-added activities make up only 41% of a construction workday. The remaining 59% of the time can be attributed to non-value adding activities (ineffective and essential contributory). However, labor-time utilization alone is not a measure of productivity (Thomas et al., 1990). This is because even though work-study records the method in which a task is completed, it does not capture the total

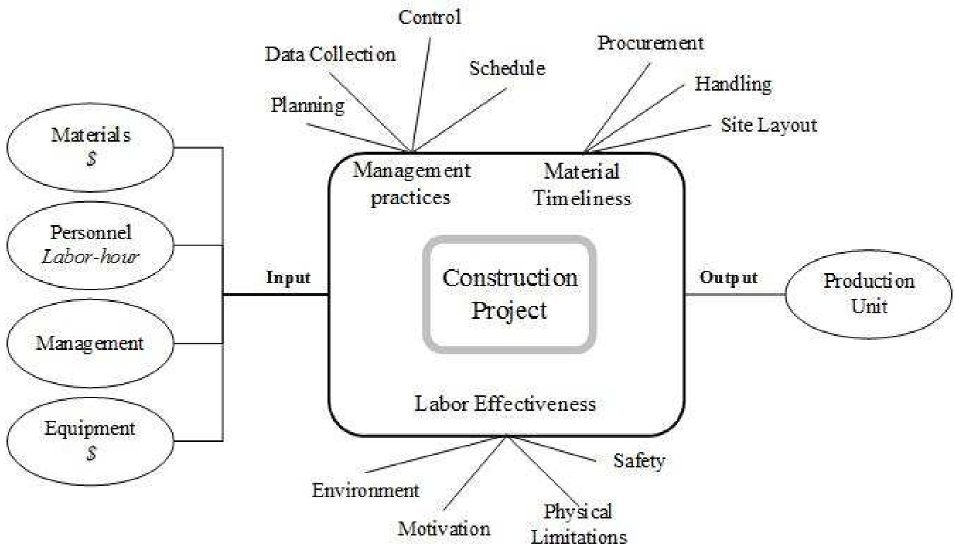


Figure 22. Construction Project as a System for Productivity Improvements. Adapted from *Productivity in Construction,* Dozzi & AbouRizk,1993

output from the day. It is crucial to measure the output, labor-time utilization and the factors that influence the production rate, in order to develop a clear picture of labor performance.

2.4.2. Factors Causing Productivity Loss

Dozzi & AbouRizk (1993) suggest viewing the construction process as a complete system as shown in Figure 22. The factors affecting labor productivity are grouped in three categories: management practices, material availability and labor effectiveness. Since the process is viewed as a complete system, all three factors including labor effectiveness play a role in determining the labor performance (Kriel, 2013).

Changes cause disruptions. Disruptions lead to deviations from the original sequence of work, which in turn leads to productivity loss. Hester & Kuprenas (1987) report a productivity loss of 70% for a frequency of three or more interruptions per day for pipe installation. Thomas & Napolitan (1995) found a productivity loss of 29% for electrical and mechanical trades when change work exists. They also found that change work is highly correlated with disruption (R=0.000) and rework (R=0.0017). Ibbs (2005) on studying the timing of change found that a late

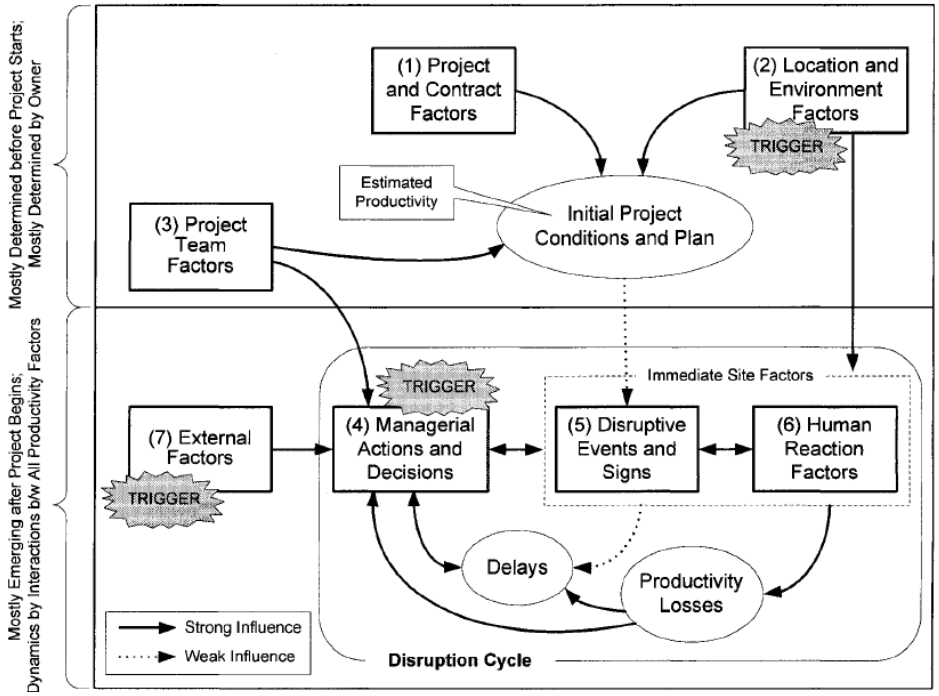


Figure 23. The 'Disruption Cycle'; Project as a System of Productivity Factors. Reprinted from, *Understanding and Quantifying the Impact of Changes on Construction Labor Productivity: Integration of Productivity Factors and Quantification Methods, by* Lee, 2007.

change is about twice as detrimental to productivity as a normal or early change (20% productivity loss for a 10% change if the change is later in the project). Lee (2007) in his seminal work presents a "disruption cycle," which is a generalization of the dynamics introduced by a change or a trigger and the corresponding management intervention. According to Lee (2007*),* *"every participant in a project usually has different and conflicting interests, knowledge, background and experience. They foresee and interpret the possible impacts and ramifications of a change with different perspectives, usually without full understanding."* In response to this problem, Lee developed a comprehensive map representing a project as a system of productivity factors: (1) Project and contract factors, (2) location and environment factors, (3) project team factors, (4) managerial actions and decisions, (5) disruptive events and signs, (6) human reaction factors and, (7) external factors (see Figure 23). Several sub-categories for the productivity factors are defined in an expanded version of the system map. The purpose of this map is to represent the interrelated triggers of productivity loss and reduce redundancy when considering loss due to multiple factors.

2.4.3. BIM and Prefabrication as Methods for Improving Productivity

Productivity is best optimized by modifying those factors which management can control. Several methods for improving labor productivity have been proposed and validated through past research. The methods proposed are concerned with either controlling the factors that cause productivity loss or the introduction of a new process, which replaces the existing methods. We can classify some of the proposed methods from literature as management strategies, technology innovations or production models. These solutions are not mutually exclusive; rather it is possible to see the adoption of more than one solution on a project:

- Management strategies
    - Last Planner System for production control (Ballard & Howell, 1998)
    - Reliable labor-flows and labor management by addressing issues such as trade stacking, insufficient work to perform and overstaffing (Thomas, Horman Jr, & Chen, 2003)
    - Predictable work-flows to match available work load with capacity (Liu et al., 2011)
    - Integrated project delivery (IPD) method for collaborative work processes, lesser design changes, less number of RFI's, reduced RFI processing time and superior labor reliability (Asmar, 2012)
- Technology innovations
    - Building Information Modeling and photogrammetry (Eastman et al., 2011; Huang et al., 2009; Teicholz, 2013)
    - Wireless technology and visual analysis (Kriel, 2013)
    - Material tracking using radio-frequency identification devices (RFID) and global positioning systems (GPS) (CII, 2008; Grau et al., 2009)

    - Head Mounted Devices (HMD) using Augmented Reality
    - Model based layouts using robotic total stations (Kramer & Searle, 2013)
- Production models
    - Prefabrication, pre-assembly, modularization and off-site fabrication (Eastman & Sacks, 2008; Huang et al., 2009; Mikhail, 2014)
    - Rapid prototyping using 3D printing technology
    - Computer aided design (CAD) to Computer aided Manufacturing (CAM)

BIM improves task-level labor productivity by; streamlining CAD information exchange and rapid-prototyping for off-site prefabrication and pre-assembly, avoiding rework through early detection of errors, providing the project team accurate and reliable information using a co-developed model, enabling model based layouts, tracking material and equipment and enabling faster communication between field and the office. A case-study research conducted by Azambuja, Alves, Leite, & Gong (2012) provides examples for the different applications of BIM in context of the four roles of supply chain management (SCM) in construction (as proposed by Vrijhoef & Koskela (2000)) discussed in Table 3). As indicated in Table 14, one of the ways of transferring activities from the site to the supply chain is with the use of prefabrication using a computer-aided-manufacturing (CAM) approach. Other applications include material tracking using bar codes, development of online model repositories and real-time tracking of components using RFID tags. Azambuja et al. (2012) conclude that the implementation of BIM adds value in the form of schedule savings, cost savings, reduced variability and increased reliability for the entire supply chain by enabling prefabrication.

According to a survey conducted by Cowles & Warner (2013), the focus for prefabrication efforts in the construction industry is to improve productivity and promote lean construction, specifically for mechanical and electrical contractors. Research by Haas et al. (2000) found that while prefabrication offers benefits of reduced project duration, project cost and improved craft productivity, there are several impediments in the adoption such as added amount of preplanning, project coordination, transportation difficulties, greater inflexibility and more advanced

Table 14

BIM uses for the Four Roles of SCM in Construction (adapted from Azambuja et al., 2012)

	Role of SCM	BIM use	Collaborative partners
1	Interface between supply chain and site	Material tracking using bar-codes linked to information to BIM	Contractor, software developer and vendor
2	Improving the supply chain	Development of online repositories of building element models enabling engineering integration, saving fabrication time and engineering costs	Suppliers or critical components and software developer
3	Transferring activities from site to supply chain	Prefabrication of MEP components using a CAD-CAM approach	MEP trade contractor
4	Integrated management of supply chain and site	Use of BIM and RFID tags to track materials and components from fabrication shop to site installation	Contractor and fabricator

procurement requirements. The use of prefabrication is expected to nearly triple over the next five years (Cowles & Warner, 2013). As we approach this increase in production, a more coordinated cross-trade collaboration is expected to arise, particularly under alternative project delivery methods such as Integrated Project Delivery (IPD).

In another study (mentioned earlier in Chapter 1), Eastman and Sacks (2008) compared the relative productivity of construction industry with significant off-site fabrication with more traditional on-site sectors. Used the data from the Census of Manufacturing and the Census of Construction, the labor productivity in this article was defined as value added per employee. The economic data is presented and comparisons between off-site and on-site activity were drawn in two ways: (1) within sectors that have both significant on-site and off-site labor components (curtain walls, structural steel, and precast concrete; and (2) between wholly on-site sectors (drywall and insulation, cast-in-place concrete) and sectors that are predominantly off site (elevators and moving stairways). The off-site production of building components was observed to be significantly more labor productive in contrast to related on-site activities. Not only did they have a higher level of labor productivity, but also their rate of overall productivity growth was greater than comparable on-site sectors. Typically, the off-site productivity grew by 2.32% annually, while the on-site productivity grew by 1.43%.

2.4.4. Summary

The discussion on labor productivity highlighted:

- The need for measuring labor-time utilization, daily output and productivity loss factors in order to draw a complete picture of labor performance,
- The importance of viewing the construction process as a system and,
- Identifying the disruptions in workflow and their causes to understand the factors causing productivity loss.

Further, the discussion on BIM and prefabrication showed that:

- Off-site prefabrication has shown relative productivity improvements by reducing the variability of field conditions and BIM is the facilitator,
- The effectiveness of BIM at the labor work-face is extended beyond 3D by using other technologies such as photogrammetry, robotic total stations, bar codes, CNC and 3D printing.

It is evident from past literature that BIM has the potential to improve labor productivity, however there are limited studies examining this theory in the context of retrofit construction. This presents another gap in knowledge, which is explored in this research project. The next section summarizes the literature review and develops the connections between these topics to inform the development of the theoretical constructs for the current research study.

2.5. Summary of Literature Review

The literature review presented in this chapter has two purposes. First, it articulates the unique characteristics of construction and manufacturing and presents a thorough background of the facility type chosen for the case study, which is a semiconductor manufacturing facility. This discussion frames the research within its context and helps establish the necessity for productivity improvements at the task-level or labor workface. It also helps develop an understanding of the complexities, which are apparent in retrofit construction. Even though semiconductor manufacturing is a highly complex and expensive process with multiple processes, there is still a semblance of standardization. Moreover the value-add functions are automated, removing any human interaction with the delivery of the final product. On the other hand, construction of semiconductor manufacturing facilities is an added capital cost with several productivity issues and high amounts of waste. Design standardization is challenging because of the simultaneous nature of technology change and the requirement for installing new process tools in an operational facility to keep up with the pace of production. BIM provides the ability to prefabricate components off-site with the hope of improving construction productivity and thus, reduce waste and improve delivery of projects. A mature use of BIM can also fulfill the vision of concurrent design and construction, real-time change management and eliminating waste from the construction process. However, the use of BIM is in its nascent stage and it is important to document and analyze its current use in order to develop better processes to improve its further adoption and use.

The second purpose of this chapter was to develop knowledge about BIM, its implementation in an organization, identify its utility for stakeholders and find its relation with labor productivity. Towards this objective, the author identifies 22 factors from past literature which are essential for the implementation of BIM at an organization. At the outset, we realize that literature on BIM use for retrofit construction is limited (gap 1). In addition, while BIM is enabling project management improvements, very few studies have developed around its impact on labor productivity (gap 2). The semiconductor manufacturing facility provides an environment for analyzing both these gaps (gap 1 and gap 2) in knowledge. Figure 24 summarizes the literature review identifying the benefits of BIM in retrofit construction and its potential for improving labor productivity.

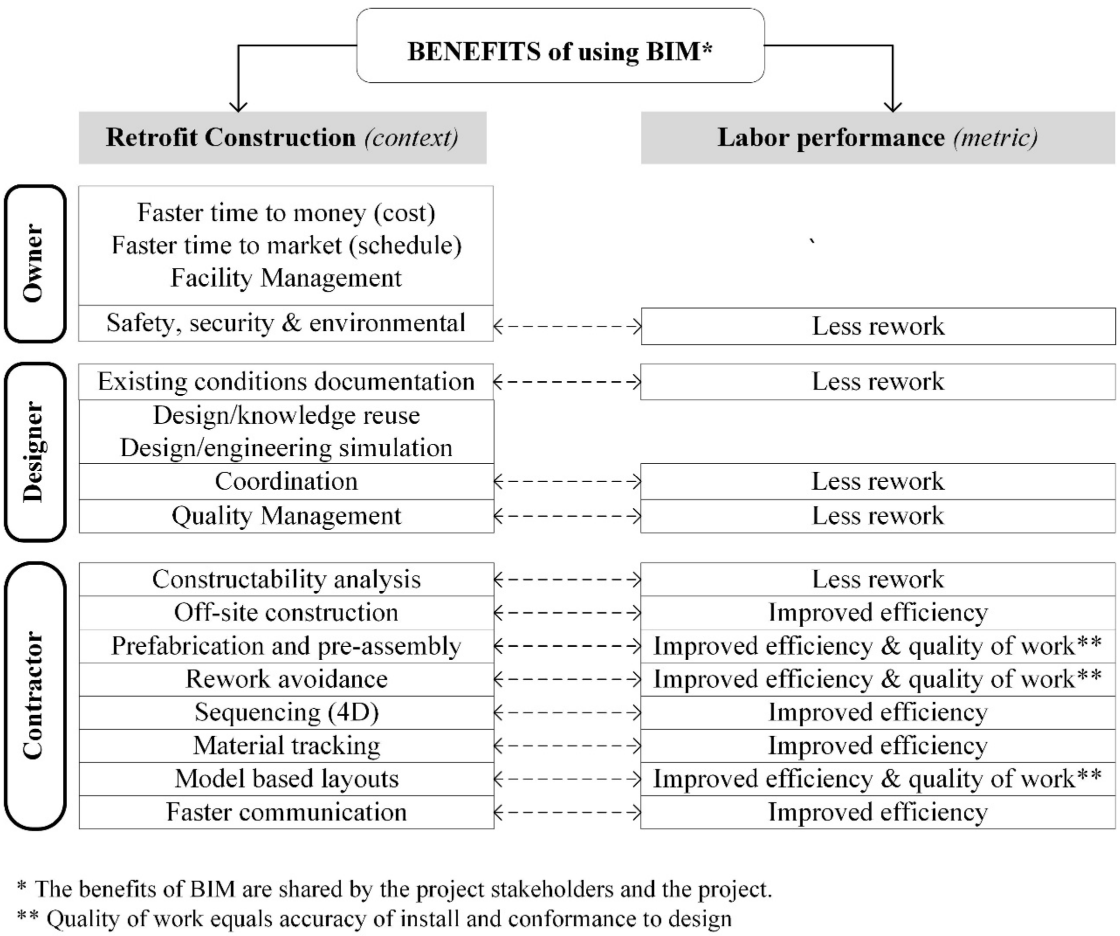


Figure 24. Benefits of BIM for Retrofit and its Impact on Labor Productivity

CHAPTER 3

CASE STUDY: "BIM" PRACTICE AT A SEMICONDUCTOR MANUFACTURING FACILITY

This chapter describes the planning, management and implementation of BIM for process tool installation at a semiconductor manufacturing facility. Section 3.1 - Case Study Background provides an overview of the project, describes the construction supply chain, and identifies some of the inherent risks in the project. Analysis of the BIM planning by the owner, identification of stakeholders of the BIM process, and the BIM & prefabrication maturity levels of the trade contractors, follows in Section 3.2 - Planning for BIM. Next, Section 3.3 - Process mapping BIM workflows, discusses the process mapping effort led by the author for an in-depth analysis of current workflows for BIM management and modeling. This chapter utilizes the research method described in Figure 25 to answer research questions R1a and R1b, which are:

R1a: Who are the decision-makers involved in the planning, management and implementation of BIM and what is their expected value from BIM?

R1b: What are the decision-factors (*i.e.* factors considered during decision-making), identified during the planning, management and implementation of BIM?

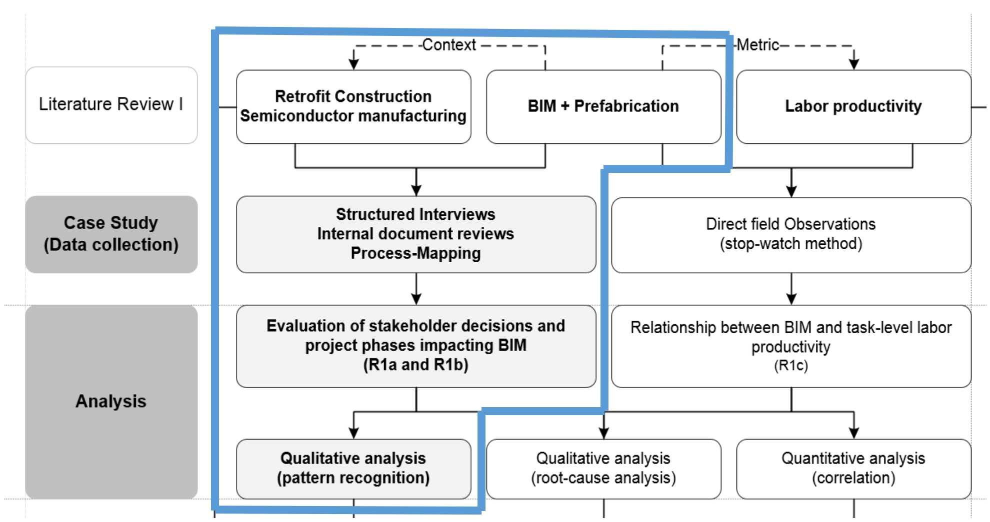


Figure 25. Research Method for BIM Case Study

3.1. Case Study Background

The author conducted the case study at a semiconductor manufacturing facility located on a 700-acre site occupying approximately four million square feet of conditioned space consisting of wafer fabrication plants, central utility plants, office buildings and a sort manufacturing building. The owner is an integrated design manufacturer (IDM) *i.e.* they design and manufacture their own integrated chips. This particular facility is a high-volume manufacturing site. The scope of the retrofit construction project includes pre-facilitation, tool install and hook-up of approximately 790 new process tools and approximately 300 convert-in-place tools in 12 functional areas distributed in two existing base build structures. The base build structures were originally constructed in 1996 (19 years ago) and 2007 (8 years ago). The construction phase of this project started in January 2013 and the date of substantial completion for most tools was set for June 2014. Tool install includes multi-level complexities of designs, identified by the owner as minimum complex, medium complex and super complex. The super complex tools can include up to 1000 small projects (architectural, electrical, mechanical, plumbing and piping) and take up to 7,000 labor-hours to install. Each tool occupies anywhere between 50 to 400 square feet of space. The original estimate for the total cost of construction was approximately $400 million (excluding the cost of the processing equipment), and the estimate for the cost of BIM was about 4% of the total project cost. The manufacturing operations were continuing during the retrofitting process of the tools.

In Phase 1 of the project (Jan 2013 – Dec 2013), all subcontractors (17 trade contractors, A/E and BIM coordinator) were organized through a multiple-prime unit-price contract directly with the owner. In a multi-prime model, the owner establishes competitively bid prime contracts with a general contractor and major specialty contractors on the project. This is a preferred contracting strategy used by an owner when the project is large and highly complex and a single party cannot assume the entire risk of the project. Research conducted by Rojas (2008) shows that public construction projects organized as multi-prime have 5% less direct costs than projects using a single prime contractor. However, multi-prime contracts suffer due to the lack of expertise of the

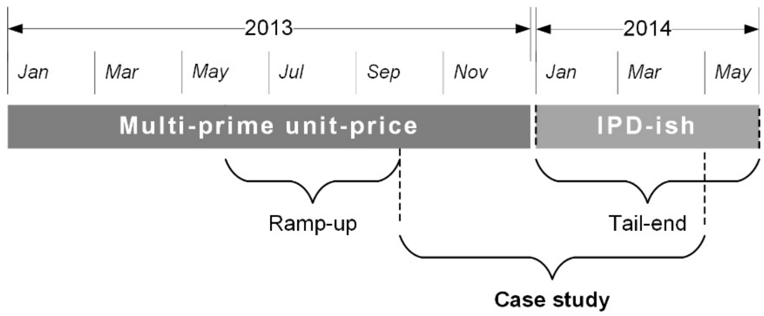


Figure 26. Research Timeline

owner in managing and coordinating construction projects, hence accumulating a larger number of change orders (Rojas, 2008).

In Phase 2 (Jan 2014 – June 2014), at the tail-end of the project, the owner initiated an integrated project delivery (IPD) method through an integrated form of agreement (IFoA) in order to reduce costs, encourage collaboration and ensure the project is delivered on time for all remaining tools. The central feature of IPD is a single multiparty contract with the "*goal of creating a project where all participants benefit by its success and are equally motivated to avoid its failure"* (Ashcraft, 2011). Asmar (2012) defines IPD as *"a project delivery system distinguished by a multiparty agreement and the very early involvement of the key participants, ideally at 0% design but definitely before 10% design complete."* If a delivery system does not meet the above two criteria, it is termed as IPD-ish. In this particular case study, each functional area (such as Lithography, Dry Etch, and Wet Etch etc.) was a "small project," with an IPD team consisting of the owner, A/E, mechanical contractor, piping contractor and electrical contractor. At the scale of a "small project," the project teams followed the tenets of IPD. However, at a meta-level, we cannot classify the project as IPD because there is no front-end collaboration between the parties nor a multi-party contract. Hence, this study refers to this phase as *IPD-ish.* The IPD-ish effort resulted in positive trends in project performance; 23% cost reduction and a consistent 70% percent plan complete despite increase in activities per week. We conducted this case study between October 2013 and May 2014. Hence, the observations are from both phases (see Figure 26).

The stakeholders of this project include the owner, who is the financial beneficiary from the project, and the subcontractors, who benefit from securing repeat projects with the same owner. The organizational structure includes multiple lines of communication as depicted in Figure 27. The owner engaged a general contractor as the BIM coordinator to manage the BIM planning, management and execution process for this project.

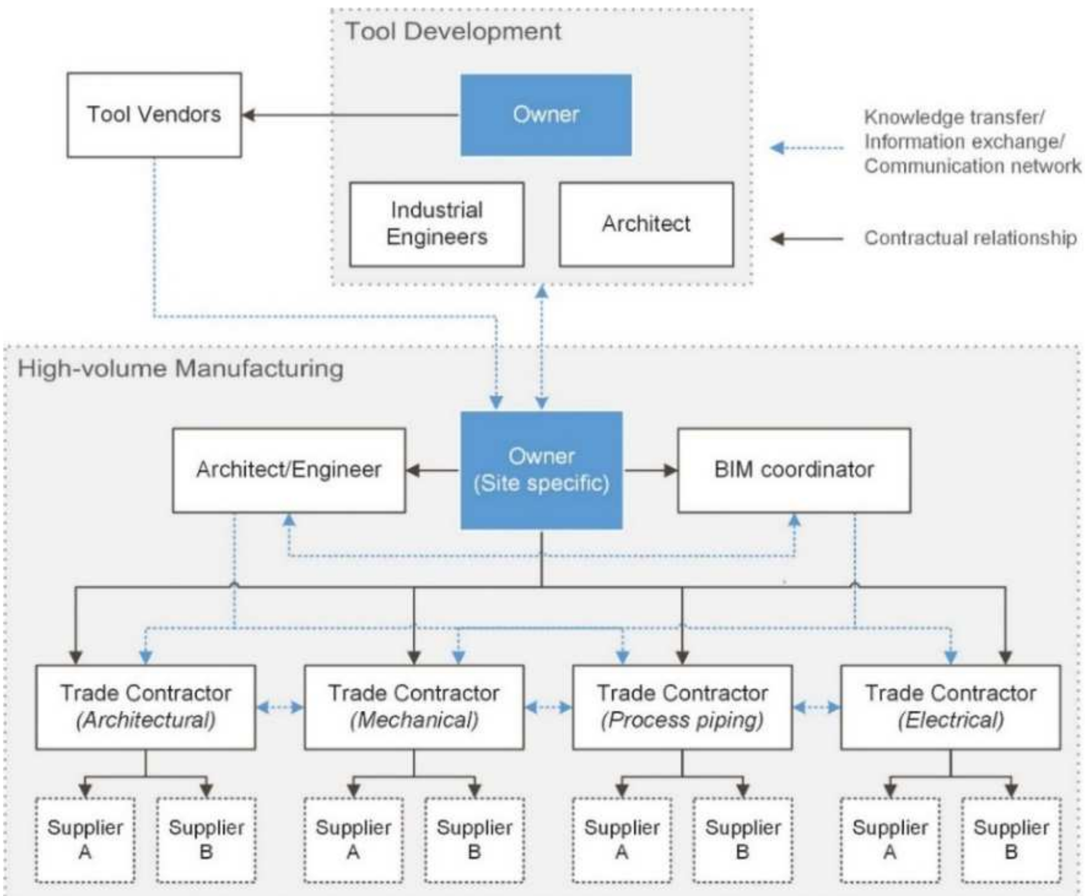


Figure 27. Project Stakeholders and Relationships

Project Risks. Construction projects constrained by timelines driven by manufacturing needs are susceptible to frequent uncertainties. According to Gil et al. (2005) the sources of internal uncertainty in semiconductor facility tool installation projects include: "*(1) unexpected design iterations when initial assumptions on design parameters do not hold after design information that is more complete becomes available; and (2) design and construction rework due to design choices that are hard to implement on site."* The concurrent nature of design and installation and lack of constructability analysis makes change management a critical factor. The author identified the risks in the project using the Project Definition Rating Index (PDRI) developed by the Construction Industry Institute (CII) under the three categories of; (1) Basis of Project Design, (2) Basis of Design and (3) Execution Approach. The PDRI is a front-end planning tool, which evaluates the completeness of scope definition at any point before detail design and construction (Construction Industry Institute, 2013). The "Basis of Project Design" identifies criteria such as manufacturing and business objectives, project scope and value engineering; "Basis of Design" identifies the site information and scope for process/mechanical, civil, infrastructure, electrical and equipment; and the "Execution Approach" outlines the procurement strategy, deliverables, project controls and project execution plan. CII recommends using the PDRI version 3 at a stage when the project team has identified the risk issues and is in the process of developing mitigation plans (Construction Industry Institute, 2013). The author used the PDRI version 3 to conduct a retrospective analysis of the project. Results of the analysis are included in Appendix B. The analysis shows that the major risks in the project are concentrated in a poorly defined execution approach, attributed to the lack of subcontractor involvement in front end planning. Some of the findings from the PDRI analysis are as follows.

- *Business Objectives:* The time to market is the most critical objective for the owner, with cost and quality in that order. However, the project is subject to frequent internal (design changes) and external (market forces) changes.

- *Project Scope:* A unit-price contract provides the flexibility to allow modifications at any stage of the project. This led the owner to add to the scope of the trade contractors as the project ramped-up.
- *Value Engineering:* The trade contractors perform value analysis through alternative design and material suggestions during the construction phase.
- *Process/Mechanical Design:* As explained in Chapter 2, the owners' Industrial Engineer provides the layout for tool locations as a template based on optimal manufacturing processes. The A/E incorporates the suggested routing into Process & Instrumentation Diagrams (P&ID) based on the local information of the facility. The trade contractors' scope includes routing design in 3D (based on the 2D P&ID provided by the A/E). Based on the feasibility of field conditions, the contractors often request alternative Points of Connections (POCs) which are more feasible to reach and construct.
- *Deliverables:* The owner decided to use BIM on this project after the successful implementation of 3D CAD on a previous project. The owner developed a BIM specification document, a BIM execution plan and BIM-CAD standards. However, before the design & construction phase began, these documents were missing critical information such as administration of servers, handling of life-cycle data and quality management requirements.
- *Project Controls:* Although the owner has an established method for measuring cost, schedule and cash flow, a change management process was not in existence at the time of this study.

The next section discusses BIM planning process followed by the owner.

3.2. Planning for BIM

Chapter 2 (Figure 24, pg. 98) provides an analysis from past literature identifying the benefits of using BIM in retrofit construction projects. According to the BIM contract, the owner identified three objectives for using BIM on their projects:

1. Improve space and installation coordination by optimizing resources, including people, material and time (3D BIM: clash coordination)
2. Improve base build and tool install coordination by providing early visibility to scope of work and simulating 'what if' scenarios (4D BIM: sequencing)
3. Enable off-site prefabrication to support shorter install durations by providing cost predictability, reducing laydown space requirement and ordering long lead items earlier

Although the project saw the application of 3D BIM, the use of 4D BIM applications was absent. The lack of 4D BIM was largely due to the manual updates required for the continuous changes in the drawings, models and schedule, and the absence of personnel with relevant experience in 4D. The following section will first discuss the factors considered in BIM planning (3.2.1) including the role of the stakeholders (3.2.2) and then focus on the capability and maturity of the trade contractors (3.2.3).

3.2.1. BIM Planning Documents

The owner developed the following documents to articulate the BIM process;

- *BIM contract specification (for A/E and trade contractors)* including definitions, scope of work, roles and responsibilities, BIM execution plan, performance indicators and components of the models. The owner chose to remain "software agnostic" and let the project team choose their application of choice as long as it complied with the standards and specifications outlined in the contract documents.
- *BIM contract specification (for BIM coordinator)* including procedure for managing (storing, sharing, revision control) project data, managing a clash detection meeting, alignment on process and timing for incorporating design changes and RFIs.

- *Model attributes standards* including CAD standards (naming, attribute definitions, units, layers, file formats) and deliverable milestones.
- *Laser scanning specifications* including tolerances, quality control, field execution procedures and information storage and exchange.

The author reviewed the above-mentioned documents to compare them with the factors of BIM implementation in retrofit construction identified from the literature review (see Table 15). The analysis shows that the BIM documents address only eight out of the twenty-two factors critical for successful BIM adoption recommended in academic literature and by industry standards. This analysis reveals that in this case, the emphasis was on *process* integration and less on the integration of people and technology. The expectation was on the project team (A/E and contractors) to address the technology implementation factors (*e.g.* interoperability, hardware/software requirements, legacy data management). As the project progressed, the project team made collaborative efforts to address factors such as cultural change, project team alignment and streamlined communication.

In addition to the factors presented in Table 15, the owner also defined *specifications and standards for model versus physical construction tolerance* in their documents. The specification identifies the quality assurance of the installed content versus the 3D model. The intent of the specification is to encourage conformance to the model and hence improve the accuracy and reliability (geometric tolerance) of As-Builts for future use. As will be seen in the analysis presented in Section 3.3.3, this specification created a loophole, causing a process colloquially termed as "As-Bimming." Rather than installing to the coordinated 3D model, the trade contractors were creating 3D models from the installed content.

Table 15

Analysis of BIM Decision Factors Addressed in Case Study

	BIM Decision Factor	Addressed in BIM Documents	Finding(s) from Case Study
PEOPLE	1. Cultural change & flexibility	No	
	2. BIM capability & maturity	No	No formal assessment method
	3. Workforce training & onboarding	No	
	4. Learning curve of project team	No	
	5. Collaboration	**Yes**	Use of a collaboration platform to share files
	6. Communication	No	To be determined by project team
	7. Project team alignment	No	
	8. Performance measurement	**Yes**	Project Indicators: design & construction duration, model conflicts/clashes, CAD compliance, cost avoidance (RFI & change orders), material prefabricated off site, man-hours associated with offsite prefabrication, on-site labor headcount
PROCESS	9. BIM contract & legal considerations	**Yes**	Addressed as a part of the BIM execution plan
	10. BIM strategic planning objectives	No	
	11. Investment in BIM and related strategies	**Yes**	ROI analysis only, no other formal method established
	12. BIM execution plan	**Yes**	BIM milestone schedule, roles and responsibilities, process for management of project data, process and timing for incorporating changes, BIM deliverable
	13. BIM/CAD standards	**Yes**	File format, attribute name and property, model tolerance, Level of Detail, file/folder name structure, line weight, color, building survey control points.
	14. Workflow evolution	No	
	15. Supply chain integration	No	
	16. Risk management process	No	
	17. Version control	No	To be determined by project team
TECHNOLOGY	18. Existing geometry & semantic data capture (As-Built)	**Yes**	Laser scanning specifications
	19. Legacy data migration	No	
	20. Interoperability & Information exchange	No	To be determined by project team
	21. Software/Hardware/ Network requirements	No	To be determined by project team
	22. BIM to VDC	**Yes**	Use of robotic total station for horizontal & vertical layout

3.2.2. Stakeholders in the BIM Process

A construction project is a temporary organization and the stakeholders include the owner, the project participants and their supply chain partners. All stakeholders have a vested interest or “stake” in the success or failure of the project. When creating and sharing information in a construction project, the stakeholders depend on each other to satisfy their requirements in order to effectively contribute to the shared goals of the project. Thus, all stakeholders have a role in the BIM process. For the purpose of this research and case study, the author defines the stakeholders in the BIM process as

> *“any group or individual directly or indirectly involved in supplying, creating, managing and using information in any form or format, which is included in BIM for the ultimate purpose of meeting the objectives of BIM use as defined by the owner”.*

Using this definition, we identify the stakeholders in the BIM process as:

1. The Industrial Engineers (IEs) responsible for designing the conceptual layout of the fab level with exact locations of the processing equipment and the support equipment according to the required manufacturing process steps.
2. Tool Vendors, supplying the physical product (the process tool) and the 3D models (if available) of the tools during design. The 3D model of the tool identifies the exact coordinates (x, y and z) of the tool POCs.
3. Site-specific facility owners managing the construction process. The owners’ representatives for HVM site included a project management team as well individuals responsible for every tool, also known as the tool owners. The owner designated an individual as the Owner - BIM Manager who was responsible for coordinating the BIM process from their end.
4. Architect Engineer (A/E) responsible for adapting the IE’s layout to the local factory site, specifying utility requirements and developing P&IDs.

5. The GC - BIM coordinator (general contractor team engaged by owner) responsible for implementing and managing the BIM process and the 3D models authored by the trade contractors, quality management of installed component and delivering the record model to the owner.
6. Trade contractors, classified as:
   a. Trade BIM Manager, typically responsible for coordination and communication between the trade modelers and the project team. Responsible for receiving and verifying information and ensuring the implementation of BIM as per contract.
   b. Fabrication shop manager, responsible for the operations and management of the off-site prefabrication facility.
   c. BIM modeler, responsible for model authoring, creating shop drawings and coordinating with installers to ensure installation is as per the model
   d. Installers, who are the final users in the BIM process. The primary scope of the installers is to accurately install the components and prefabricated assemblies as per the model in a safe and timely manner. The installers rely on the coordinated 3D models and accurately prefabricated assemblies, both of which are outcomes of the BIM process, to perform their work.

Beside the above-mentioned stakeholders, other individuals involved in the construction process include the owners' project manager, the design project manager, trade detailer, trade site manager, superintendent, safety manager, project engineer etc., who are all responsible for the success of the project. Although the entire project team and project benefits from the use of BIM, the purpose of this study is to identify the decision-makers involved in the planning, management and implementation of BIM.

Analysis of stakeholder input/output. The author conducted structured interviews (standardized open-ended) with the following project stakeholders. Please note that in order to protect the identity of the organizations, the author will here on refer to the stakeholder either by their scope (A/E, BIM coordinator) or by a fictitious name (P1 pipe, P2 pipe, E1 electrical, E2 electrical and A1 architectural):

1. Site specific facility owner (Owner - BIM Manager),
2. Architect/Engineer,
3. BIM coordinator and,
4. Trade contractor (BIM Manager):
    a. Piping (P1 pipe)
    b. Piping (P2 pipe)
    c. Electrical (E1 electrical)
    d. Electrical (E2 electrical) and,
    e. Architectural (A1 architectural)

These interviews were one-on-one face-to-face interviews using a list of structured questions (see Appendix A for meeting dates). The author recorded responses from the participants anonymously. Standardized open-ended interviews are the most popular form of interviewing utilized in qualitative research studies because of the nature of the open-ended questions, allowing the participants to fully express their viewpoints and experiences (Turner, 2010). Appendix C documents the list of questions. The author transcribed the responses and undertook a diligent process to meet the following objectives:

1. Validate the stakeholders' *BIM scope of work* with the definition provided in the BIM contract,
2. Identify the utility for using BIM or *BIM-value* as described by the stakeholder,
3. Identify their *expected outcome* from the BIM process,
4. Discuss *challenges* faced in the current process and potential methods for process improvement and,
5. Verify, validate and refine a *BIM process map* developed by the author

The author coded and transcribed the responses from the interviews in an Excel file. Table 16 captures the common themes in the responses received from the structured interview (bullet points no.1, 2 and 3). Comparing the information found in the BIM planning documents (Section 3.2.1) with the qualitative data collected through the interviews, the author developed a process map showing the overall BIM process (see Figure 28). The BIM process map shows the major steps involved from the creation of an As-Built 3D model of the existing conditions to the installation of the prefabricated assemblies on site. The map also shows the information input and document outputs in the steps highlighting the interaction between the various stakeholders involved in this process. The analysis reveals an extra step for the trade contractors, which is unique to a retrofit condition *i.e.* *"field verification of existing conditions."* This step existed in the process despite the development of an As-Built model from the laser scan of the facility indicating a lack of trust in the information provided. In addition, for the question about *"challenges in the current process (point no. 4);"* similar responses were received from all the interviewees. The author identified the following themes:

- *Collaboration*: Lack of early involvement of subcontractors in the planning process
- *Information*: Mistrust in the reliability of information in As-Built model, geometrical accuracy of the model, interoperability of software, validation and verification of existing conditions, new design and constructability
- *Communication*: Lack of timely communication of changes and frequent addition of new information.

From the analysis presented in Figure 28 and Table 16, it is evident that although the owner and BIM coordinator plan and execute most BIM related decisions, the trade contractors are largely the authors and users of the information. The author concluded that in a retrofit project such as this case study, the verification and validation of existing conditions is a critical but redundant step. The interviews with the stakeholders revealed that some of the BIM factors not addressed in the BIM planning documents prepared by the owner (*e.g.* Communication standards, Interoperability, Software/Hardware/Network) were gaps in the process that required clarifications. The next section focusses on the trade contractors and their capability and maturity levels as it relates with BIM and prefabrication.

Table 16

Analysis of BIM Scope, Expected Outcome and BIM-Value

Stakeholder	BIM Scope	Expected Outcome from BIM Use	BIM Value for Stakeholder (from interview)
1. IE (owner)	• Provide exact locations and layout of tools as 2D CAD	N/A	N/A
2. Tool Vendor	• Provide tool 3D CAD blocks	N/A	N/A
3. Owner (fab)	• Approves the process tools facilitation & construction. • Manages the trades & BIM coordinator to their deliverables. • Enforces construction plans per models.	• Reduce cost • Compress schedule • Reduce RFIs and change orders	*Financial* (using BIM to reduce installation cost, reduce headcount & enable faster time to market)
4. A/E	• Develop P&IDs in 2D CAD • Provides 3D CAD for the tool pedestals & tool blocks • Provide a utility matrix	• Compress design schedule • Manage design change	Communication & documentation (using 2D/3D CAD for construction documents only)
5. BIM Coordinator	• Develop the federated model • Manages collaboration • Coordinate meetings • Tracks 3D deliverables aligned with project schedule • Run clash detection • Federated model quality control • Manage tool install	• Effective communication, coordination & collaboration; • Ensure quality of models to meet the owners objectives	Efficiency, risk management, predictability (using BIM for collaboration, coordination & communication)
6. Trade Contractors (BIM manager)	• 3D model authoring • Develop fabrication details • Execute field construction activities	• Reduced rework • Deliver project on schedule	Improve productivity & efficiency (using BIM for prefabrication, BOM, coordination)

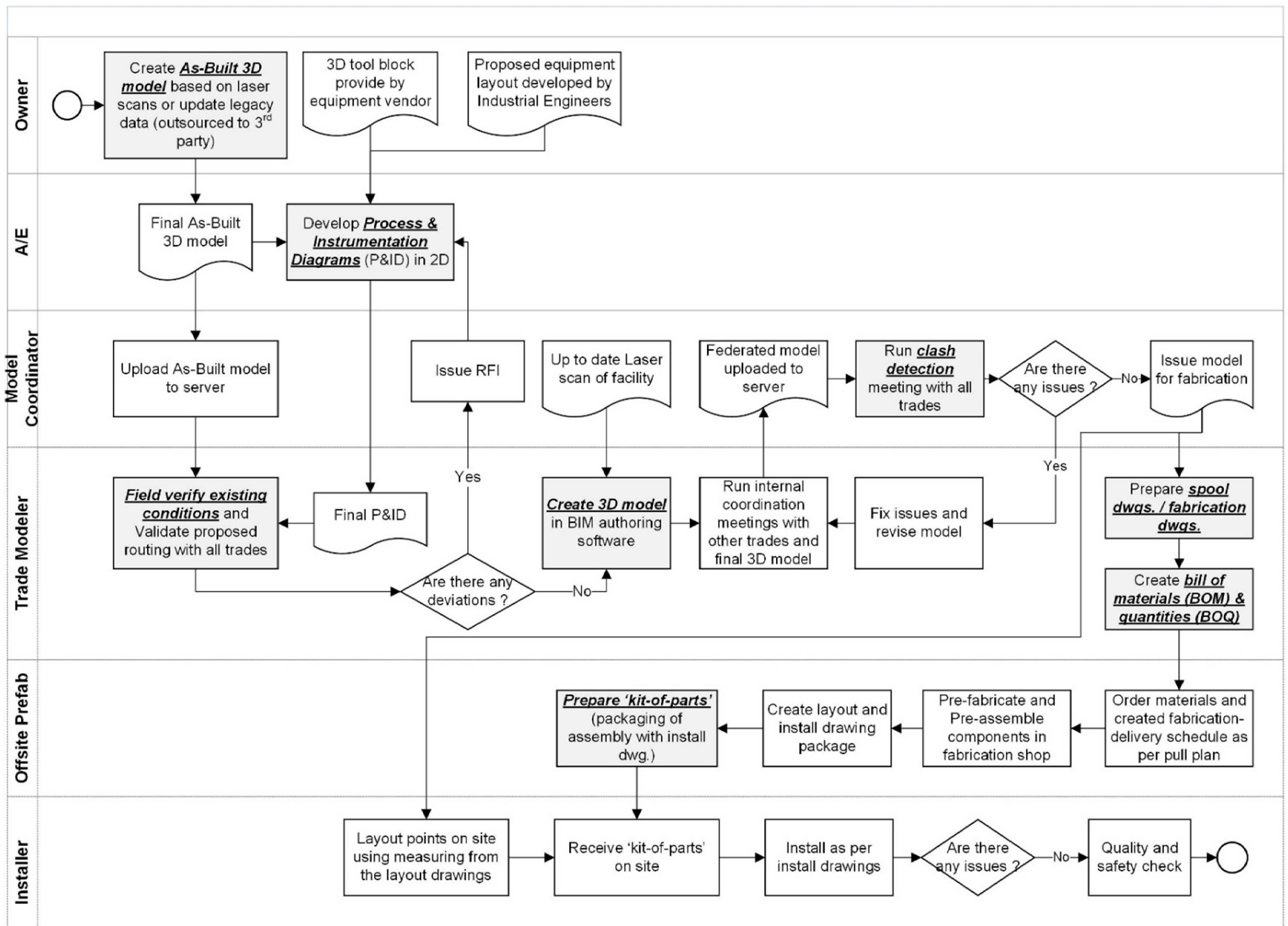


Figure 28. Overall BIM Process from Design to Install

Analysis of BIM capability and maturity of the trade contractors. Four type of trade contractors were involved in this project; process piping, mechanical, electrical and architectural. Considering the scope of the project, the owner procured at least two or three subcontractors per trade for the tool install project. As is common in such situations, each subcontractor had a different level of maturity and capability with BIM and prefabrication. As mentioned in Chapter 2 Literature Review Section 2.3.1., at the time of procurement of services, the BIM capability and maturity of the subcontractor is a critical driver for successful BIM implementation. According to Succar (2009), BIM capability is *'the basic ability to perform a task'* and BIM maturity is the *'degree of excellence in performing that task'*. A method for benchmarking BIM capability and maturity of project participants replaces the anecdotal basis of knowledge evaluation with a measurable performance metric. Past literature identifies three models of maturity assessment:

1. The Interactive Capability Maturity Model (i-CMM) (NIBS, 2012).
2. bimSCORE also known as the VDC Scorecard (Kam et al., 2013)
3. The BIM Maturity Matrix developed by Succar (2009).

Table 17 compares the three maturity models. The Capability Maturity Model and bimSCORE evaluate the performance of a team on their BIM use for an on-going or completed project. To validate the bimSCORE, Kam et al. (2013) conducted a survey of 108 projects. Findings from their survey reveal that there is a weak correlation of *"project performance"* (*i.e.* actual performance versus original objectives) with *"planning, adoption and technology;"* implying that although AEC firms are investing on BIM planning and technologies, they are yet unable to convert these practices into a definite change in the projects overall performance (Kam et al., 2013). They also found that performance wise, the top 25% of projects had 84% of their stakeholders involved in BIM/VDC compared to just 35% for the bottom 25%. Also 83% of the top 25% had established quantifiable objectives compared to 3% for the bottom 25%.

Due to the sensitive nature of the project and the willingness of each company to share information relating to their competitive advantage, the author had limited access to quantitative data related to the project performance and qualitative data related to individual competencies.

Hence, the author identified indicators (collected from structured interviews and informal discussion with the trade contractors), to categorize them based on their experience with BIM and prefabrication. Table 18 identifies those factors describing a typical contractor at two ends of the spectrum of capability and maturity levels. Most trade contractors are positioned somewhere between these extremities.

Table 17

Comparison of Maturity Models

	Capability Maturity Model (NIBS 2012)	**bimSCORE** (Kam et al., 2013)	**BIM Maturity Matrix** (Succar, 2009)
Purpose	Tool for stakeholders to plot their current capability with BIM	Evaluate, track and assess the BIM maturity of the project against an industry rating framework	Assess the competency of individuals and capability of systems based on current strengths and challenges.
Categories of measurement	Data richness, lifecycle views, roles or disciplines, change management, business process, timeliness of response, delivery method, graphical information, spatial capability, information accuracy, interoperability Total = 11 categories	Planning (objective, standard, preparation), Adoption (organization, process), Technology (maturity, coverage, integration), Performance (quantity, quality) Total = 56 categories	Individuals, Organizations, Projects Teams
Category data type	Qualitative	Qualitative & quantitative	Qualitative
Factors addressed	BIM workflows and models	BIM workflows and models, project performance	Skill, knowledge, ability & understanding of BIM (model & processes)
Maturity levels	1 to 10	Based on a percentile ranking system	Not specified
Scoring	Minimum BIM = 40 points	Typical practice (25-50%) Advanced practice (50-75%) Best practice (75-90%) Innovative practice (90-100%)	Customized capability and maturity map
Availability/ access	Free to use (available through NIBS)	Fee-based consultancy	Fee-based consultancy

Table 18

BIM and Prefabrication Experience Level of Trade Contractors

BIM & Prefabrication features	Experience level	
	More experienced	**Less experienced**
BIM capabilities explored	• 3D model authoring, • 3D coordination, • Quantity take-offs, • Automatic spool drawings, • Fabrication using computer numerical control (CNC) machines • Material tracking • Schedule control	• 3D model authoring, • 3D coordination
Company experience w/ BIM	> 10 years	< 5 years (first BIM project)
Benefits of BIM use evidenced (quantitative metrics measured)	• Time savings (design & detailing), • Improved communication between field & office, • Improved quality of design & constructability, • Reduced labor man-hours (improved construction productivity)	• No significant return on investment. Disrupted current workflows.
Professional experience of modeler	• Experience in field as a pipe fitter, electrical worker or detailer. Trained in BIM authoring software by company	• No past field experience. Trained in CAD drafting only.
Fabrication facility details	• Company owned fabrication shop with Class 100-1000 cleanroom and CNC equipment. Lean factory principles of waste reduction adopted (5S, visibility, tracking)	• Fabrication outsourced to 3rd party facility
Material tracking & transportation	• Prefabricated material and assembly assigned unique identifier for schedule controlled digital tracking • Material packaged as a ‘kit’ and shipped to site once a day. • Minimal inventory stored on site	• Prefabricated material and assembly tracked manually or as per demand. • Shipments transported to site as required; not coordinated with schedule.
Benefits received from prefabrication	• Improved labor productivity (greater throughput of assemblies/parts built in fabrication shop versus site, reduced man-hours per tool), • Reduced waste (material, equipment & time), • Reduced labor and material costs, • Effective business strategy for securing future jobs, • Cost of fabrication facility and logistics amortized over time	• Benefits diminished due to inability to manage design change, improve accuracy of prefabricated assembly, reduce rework on site and manage inventory

3.3. Process Mapping BIM Workflows

The author uses a method of flowcharting known as the Business Process Diagram (BPD) to represent the BIM process workflows based on the data collected through the structured interviews, document reviews and field observations. A BPD is a network of graphical objects, representing activities and the flow controls that define their order of performance (White, 2004). It is the primary representation for the Business Process Modeling Notation (BPMN) initiative. The goal of BPMN is to create a simple mechanism for creating business process models, while at the same time being able to handle the complexity inherent to business processes (White, 2004). A BPMN diagram uses four basic objects for representation: flow objects, connecting objects, swim lanes and artifacts (see Figure 29).

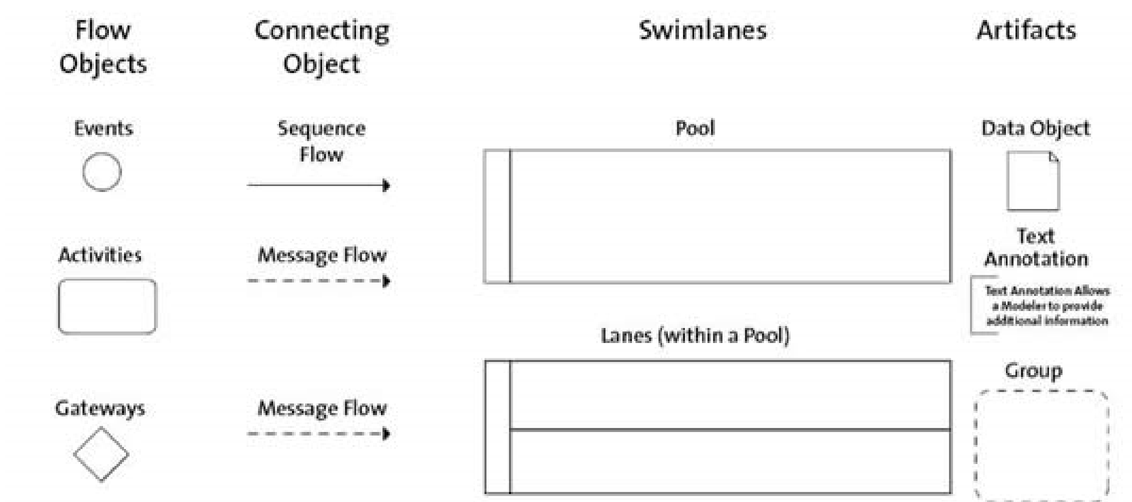


Figure 29. BPMN Basic Categories

The next section will analyze three BIM processes encompassing the role of all BIM stakeholders identified in the previous section. They are:

1. BIM Planning (Owner, Tool Vendor)
2. BIM Management & Implementation (A/E, BIM Coordinator, Trade Contractors)
3. 2D & 3D CAD drawing & modeling (Trade Contractors)

3.3.1. Analysis of BIM Planning Workflow

The BIM Planning process begins with feasibility studies, procurement and the development of BIM execution plan and standards. It also includes the documentation of the existing conditions to create As-Builts. The As-Built model then serves as the base model. Figure 30 outlines this process.

Inference. The objectives during the BIM Planning process include:

1. Justification of the investment in BIM,
2. Strategic business planning objectives for using BIM,
3. Procuring the project team which can meet these objectives and
4. Developing standards and documents for aligning the project team.

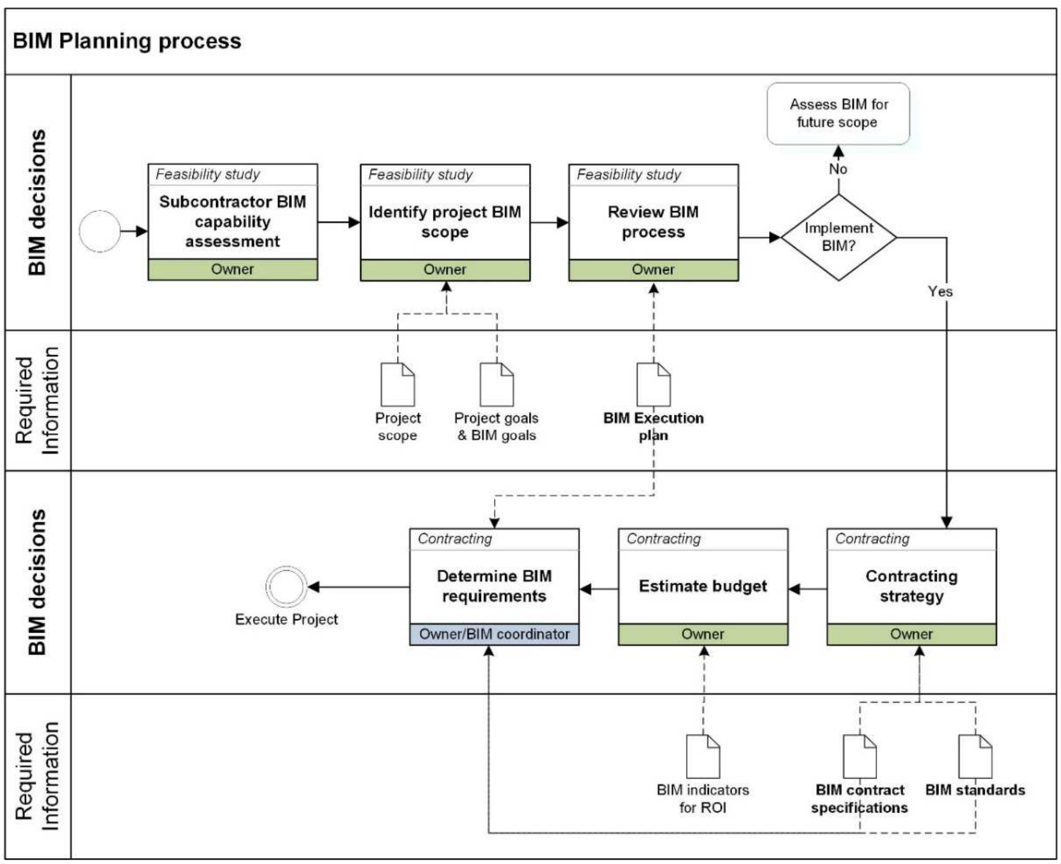


Figure 30. BIM Planning Workflow for Owner

The value of BIM for the owner in this case is an *"economic."* Procuring the project team, which has the capability and maturity to deliver the objectives of the owner, is thus a critical aspect driving the success of the implementation phase. Planning also includes the development of standards and a BIM Execution Plan. The core implementation team (A/E, BIM coordinator and trade contractors) in this case study was not involved in the planning phase leaving gaps in the process. Finally, in the case of retrofits, As-Built documentation serves as the basis for all design decisions and development. Early focus on the Level of Accuracy and the Level of Development of the existing conditions model (As-Built model) may prevent future cascading errors and eliminate the need for constant validations during design and detailing.

3.3.2. Analysis of BIM Management / Implementation Workflow

The author performed the documentation and analysis of the BIM management and implementation workflow through a two-day process mapping effort led by the author, the Owner - BIM Manager of the facility and the Owner - Lean Manager, who was the facilitator of this effort. This event saw the participation of personnel from four trade contractors (P1 pipe, P2 pipe, E1 electrical, M1 mechanical) and the BIM coordinator (see Appendix D for details). The part of the BIM process documented includes the role of the trade contractors in receiving and reviewing information, model authoring and creation of spool drawings for fabrication.

The participants identified the phases, tasks, sub-tasks, milestones and outputs on the process map. Four primary phases in the BIM implementation process were identified as; (a) Receive Information, (b) Review Information, (c) Model Authoring and, (d) Generate package for fabrication & install (see Figure 31). The step for "review information" is a unique condition for retrofit situations and a direct result of the team not trusting the information provided, hence the need for constant validation. The author found that in a typical scenario, the total time from receiving information to issue of final drawings requires *33 days* if there are no changes to the design.

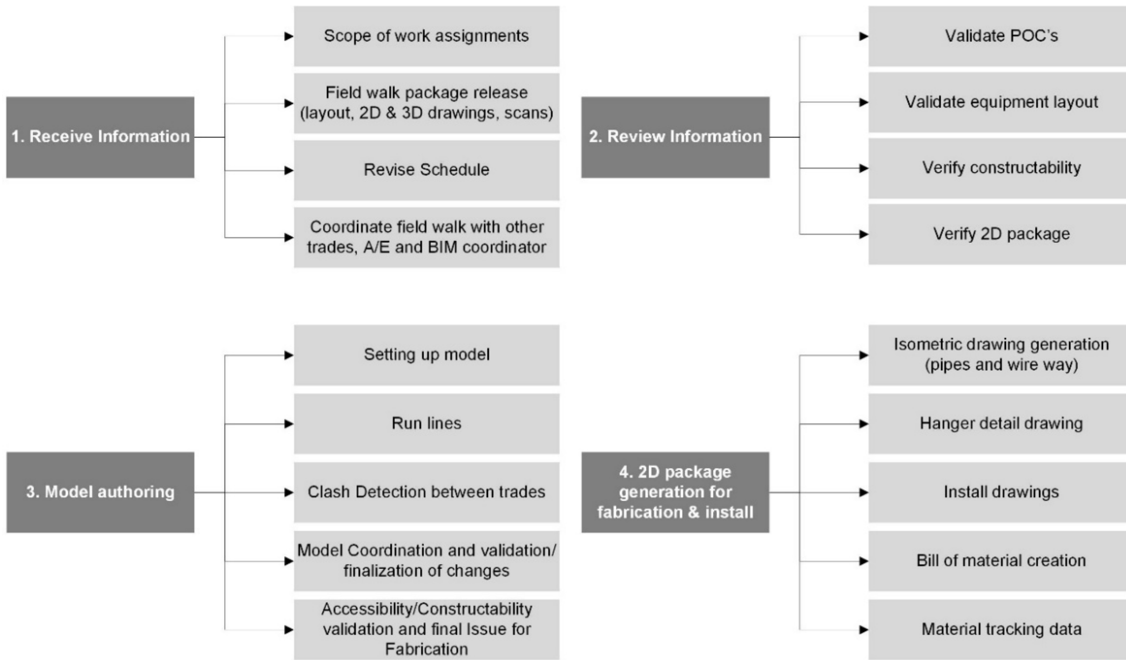


Figure 31. BIM Management/Implementation Phases and Tasks Creation

Value-add is any activity, which changes the product, the customer is willing to pay for and is done right the first time. The total number of activities identified was 169 and the team agreed upon 5% of the total steps as value-adding activities. Figure 32 presents a condensed version of the full implementation workflow.

Inference. The process had at least three instances of recurring problems/issues, which required escalation to the A/E or the owner:

1. Discrepancies in information provided in field walk package versus existing field conditions identified during "*Review Information"* phase such as; missing POCs, incorrectly placed tool blocks and undocumented existing conditions.
2. Means and methods issues identified by contractor during 3D modeling at time of *"Model Authoring"* such as; accessibility to POC, restricted space for routing and undocumented field condition in As-Built model.

3. Severe conditions identified during *'Model Authoring'*, which would require a change order such as obstruction to POC and/or relocation of tool.

This exercise presented the value of the BIM process from the perspective of the facilitators and users of the information in BIM. The author found that in retrofit conditions, there is a continuous need for reviewing and validating the information received against the existing conditions before the BIM modeler can begin detailing and modeling. This step is important for the availability of accurate and relevant information to ensure accurate results and reduced rework during installation. This is despite the availability and use of laser scanning for capturing the existing conditions. The major findings from the BIM implementation workflow are:

1. In retrofit conditions, the project team requires verification and validation of the information received from the owner and A/E against the actual and current conditions. This is because:
    a. They do not trust the information.
    b. There is a lack of transparency to the schedule, coordination of changing conditions and communication of decisions to all parties, hence making it difficult to accurately know the exact condition of the facility at any given time during construction.
    c. Although the BIM use of clash-detection is identified as a critical step in the process, specific *"construction-method"* related concerns such as accessibility to work area, obstruction to the POC, restricted space for routing and hanger install and safety analysis are often overlooked in a purely 3D visual exercise. A restricted space further exaggerates such concerns in performing basic functions; such as lifting, maneuvering, positioning and adjusting for final connections; when installing prefabricated assemblies
2. In this particular case, the total time for the BIM implementation phase was 33 days, of which the trade contractor - BIM managers spend 60% of their time verifying the information while the trade contractor - BIM modelers spend the remaining 40% time on model authoring and performing functions such as clash-detection, bill of material creation and spool drawing creation. Since, the information received is in the form of 2D CAD drawings, the modelers

have to develop the BIM to LOD500 (for prefabrication) within this short period. A research conducted by Leite et al. (2011) found that the modeling time increases from doubling the effort to eleven times when moving from an approximate geometry to precise geometry and detail required for fabrication. This finding requires further research on the relationship between modeling time per object in MEP versus accuracy versus clashes identified in the clash detection process and the field.

3.3.3. Analysis of Modeling Workflow

The author conducted the analysis of the modeling workflow after conducting the productivity studies documented in Chapter 4. The analysis of the productivity study justified a closer look at the process of modeling for a complete understanding of the BIM process at the case study facility. The author used a method of *"job shadow"* to record the role and perspectives in detail. Job shadowing is a qualitative research technique, popular in the social sciences, that involves a researcher closely following a member of an organization over an extended period to observe the actions and to reveal purpose (Mcdonald, 2005). This technique provides a first-hand report of actual actions performed by the individual rather than rely on the second-hand conjectural information. The advantages of shadowing are that the data is more detailed and it solicits opinions and behaviors concurrently, linking actions and purpose (Mcdonald, 2005). The problems are in access-negotiation, data management and the influence of the researcher on the situation they are researching (Mcdonald, 2005).

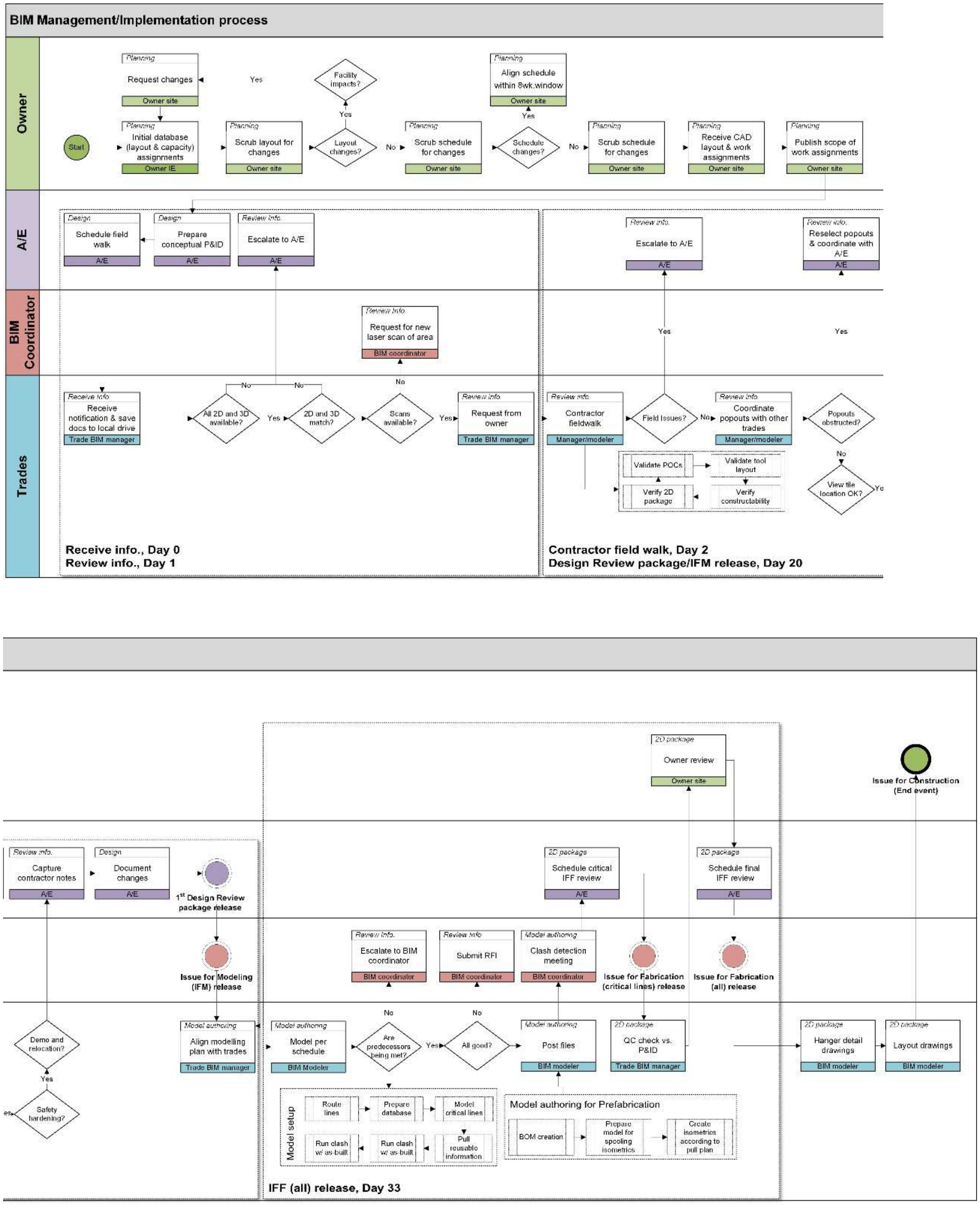


Figure 32. BIM Management/Implementation Workflow (Critical Steps)

For this case study, the author obtained permission from three trade contractors to shadow their modelers; (1) piping contractor (P2 pipe), (2) electrical contractor (E1 electrical) and, (3) mechanical contractor (M1 mechanical). The author shadowed the modelers on three workdays (see Appendix A for dates). The typical workday for each trade contractors was 9 hours long including breaks (with a varying start time from 5.00am to 8.00am). The author used a set of structured interview questions (compiled in Appendix E) to first develop a general idea of their background, experience and method of working. Simultaneously, she took notes on a laptop to identify their workflow. The author did not take time measurements since that was outside the scope of this research. Table 19 captures some of the major characteristics identified during the job-shadow. We can infer that all three have different backgrounds and slightly different methods of working. The more experienced a modeler is in the field (M1 mechanical), they prefer working directly on site. The more experienced a modeler is in CAD (P2 pipe), the greater responsibility he/she has and can recognize limitations beyond the technical capabilities of the software and appreciate the importance of communication. Figure 33 captures the modeling workflow for all three contractors compiled in to one business process diagram. While most of the steps are similar, it is the method and time of execution that differs.

Table 19

BIM Modeler Job-Shadow Notes

	P2 pipe	E1 electrical	M1 mechanical
Experience	CAD: 10 years Other: 3 yrs. (installer, detailer & modeler)	CAD: 5 years Other: none	CAD: 2 years Other: 10 yrs. (installer)
Software	AutoCAD MEP + fabrication database	Autodesk Revit	CADworks
Current project	Detail design of new tool	Preparation for clash detection meeting	Pipe routing
Location	Job-trailer	Job-trailer	Sub-fab (field-modeling)
Responsibilities	• Contractor field walk review meeting, • Detail design and modeling, • Coordination with federated model, • Create isometrics, • Make model updates	• Detail design and modeling, • Coordination with federated model • Make model updates • As-Bimming	• Contractor field walk review meeting, • Detail design and modeling, • Coordination with federated model, • Make model updates
Benefits	• Work ahead and make changes • Minimal time on the field (concentrate on accurate modeling)	• Automated spool drawing creation • Model based layout using Trimble robotic total station	• Benefits of field-modeling: • Accurate • Easy to identify pre-assignments • Receive field input for constructability
Limitations	• Lack of inter-trade modeler communication • (People-Process)	• Inaccuracies in laser scan and federated model • Electrical expected to be flexible • Too much workload • (Process-Technology)	• Slow network connections • Frequent changes • Lack of training & software troubleshooting • (Technology-Process)

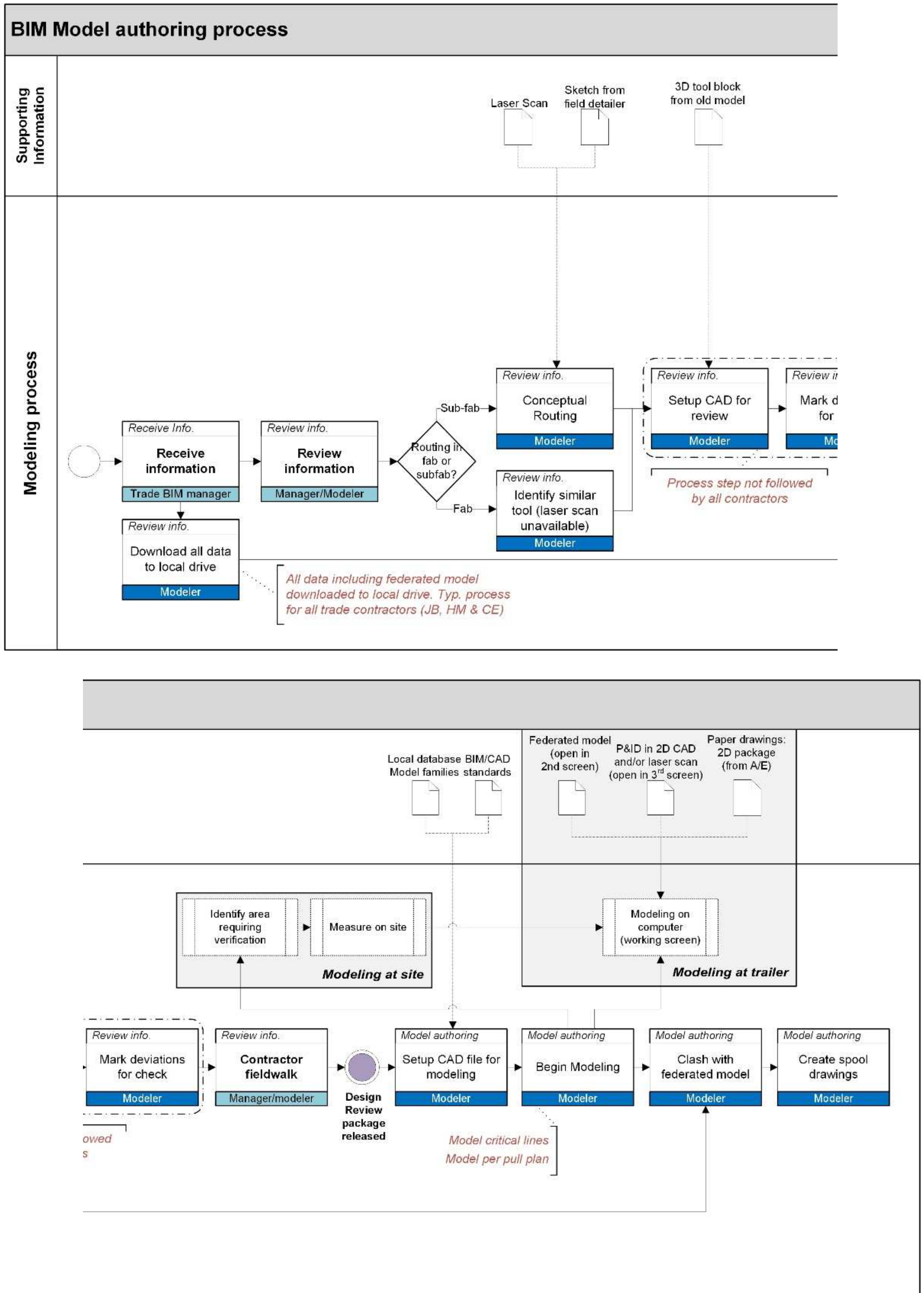


Figure 33. BIM Modeling Workflow

Inference. The job-shadow methodology revealed several anomalies in the process followed for the particular process of model authoring. They are:

1. *Non-collaborative BIM*: The BIM coordinator had set up a common collaboration platform for uploading and sharing the latest versions of the files. However, due to technical issues in accessing the network, the trade contractors preferred downloading and saving the files to their desktops. Hence, at any given time, if there were updates posted to the federated model, they would have to download the new files and manually update instead of enabling automatic updates. Automatic updates, use of a central sharing file and collaborative modeling is a hallmark of a true BIM process.
2. *Modeling for BIM vs. "As-Bimming"*: A benefit of the BIM enabled process is the ability to visualize spatially and simulate errors before construction to avoid rework. To ensure the information is accurate and reliable, the trade contractors would spend 60% of their design detailing and modeling time on verification and validation. Despite these efforts, some trade contractors gave preference to "As-Bimming" or modeling after-the-fact in the field to have the flexibility to measure a certain space manually for increased accuracy. Although this process would guarantee accuracy in the model geometry, it was a redundant step and counter-productive to the BIM process.
3. *Non-interactive non-immersive modeling*: 2D CAD and 3D models are essentially non-immersive environments, thus reducing their utility for accurate high-quality modeling. Using these tools in a workflow analogous to manual drafting, without leveraging the in-built parametric capabilities, further reduces their potential. In this case study, the modelers would setup their interface to open the primary model authoring software (AutoCAD MEP, Revit) on one screen and the reference drawings (point cloud, federated model and P&ID) on different screens. Instead of using the federated model and the point cloud as a background or an external reference (xref) to which the "new information" was progressively added, they were using the reference drawings just for visual clarifications.

Their reasoning for such a counterproductive workflow was the inability of their local systems to handle the size of the files.

4. *Spool drawing creation*: The modelers created spool drawings for fabrication after eliminating potential errors through clash detection. In order to make-it-ready for field installation, they added additional detail to the 3D model after clash detection. This was a “setup for failure” and a wasted effort of the clash-detection process, since the addition of new elements to a clash free model might create more clashes, which would go undetected.

3.4. Conclusions

This chapter described the planning, management and implementation of BIM for process tool installation at a semiconductor manufacturing facility. At the outset, the author identified through a PDRI analysis that the major risks of the project were concentrated in a poorly defined execution approach, due to the lack of subcontractor involvement in front end planning. With this premise, the author adopted a rigorous methodology for identifying the stakeholders of the BIM process, their defining characteristics, workflows and the decisions made during the planning, management and implementation of BIM (as shown in Figure 34).

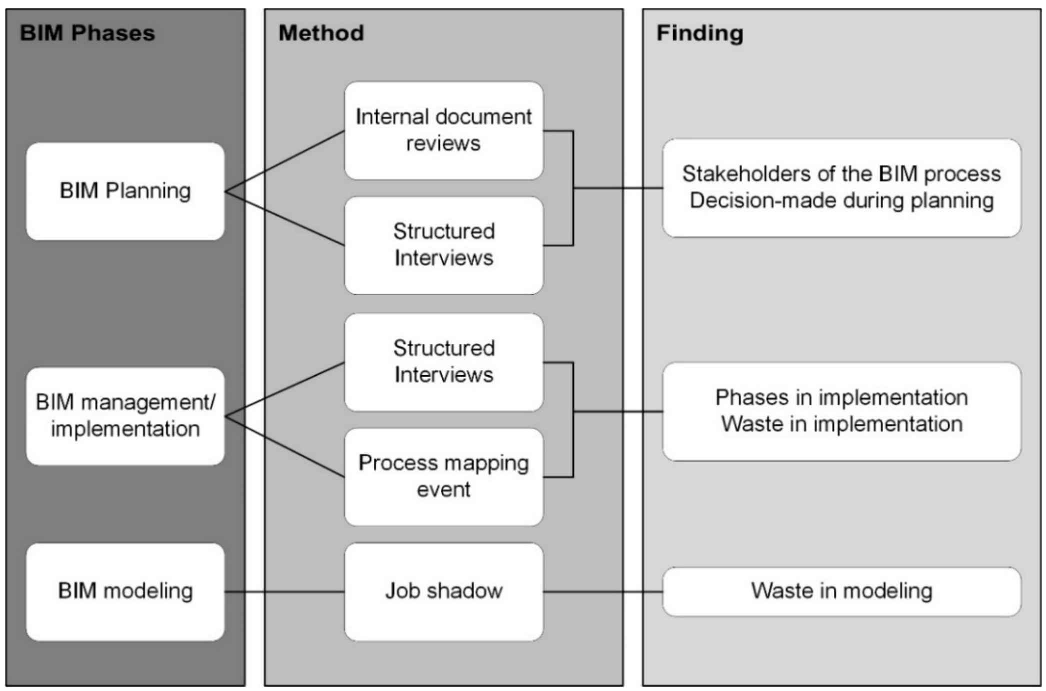


Figure 34. Research Method and Findings to Identify the BIM Practice

The owner identified three uses for BIM; clash coordination, simulate ‘what if’ scenarios and enable off-site prefabrication to support the goals of time to market and time to cost, established by the owner. In preparation to implement BIM, the owner developed four major planning documents including; a BIM contract specification for the A/E and trade contractors, a BIM contract specification for the BIM Coordinator, model attribute / CAD standards and laser scanning specifications. A comparative analysis of the owners' BIM planning documents with the findings from the Literature Review indicated that the owner considered factors, which emphasized *process* integration and considered less the integration of people and technology in the established work-processes. However, as the project progressed, the project team made collaborative efforts to address factors such as cultural change, project team alignment and revision control. We can thus conclude that the planning for BIM was at the beginning stage and the owner was not experienced in BIM processes. An important consideration is the lack of precedents of retrofit construction in the process piping and advanced technology manufacturing industries to serve as a guideline.

The first research question (R1a) asks: Who are the decision-makers involved with the planning, management and implementation of BIM and what is their expected value from the BIM process? In order to answer this question, the author considered the primary source of the case study. Table 16 presents the findings from the analysis. The author found that information exchange and knowledge sharing in BIM happened even outside the contractual boundaries thus making every process a "customer" of the previous process. The author also found that although the owner and BIM coordinator plan and execute most BIM related decisions, the trade contractors are largely the authors and users of the information. The final customers of the process, however, are the installers in the field who rely on the information in BIM and the prefabricated assembly (constructed from a BIM) for accurate and reliable installation.

The second research question (R1b) asks: *What are the decision-factors (i.e. factors considered during decision making) identified during the planning, management and implementation of BIM?* In order to answer this question, the author considered two sources; (1) implementation factors identified from an extensive literature review and (2) factors identified from the case study, within the context of retrofit construction. Table 20 identifies the decision factors. The author found, in this particular case study, the decision makers in the BIM process relied on

Table 20

Decision Factors for BIM Planning, Management & Implementation

	Decision Factors	Literature Review	Case Study
Planning	P1. Investment in BIM and related strategies	ref. Table1 #11	✓
	P2. BIM strategic planning objectives	ref. Table1 #10	✓
	P3. Contractor selection (BIM capability & maturity)	ref. Table 1, #2	
	P4. Standards and specifications development		
	a. *Contract documents* (scope of work, roles and responsibilities, performance metrics, deliverables, legal, CAD standards)	ref. Table 1, #8, #9, and #13	✓
	b. *Execution plan* (information exchange, Level of Development/Detail of model, software compatibility, , collaboration & communication, existing conditions data capture & processing, legacy data management & integration, cultural acceptance/change)	ref. Table 1, #1, #5, #6, #12, #13, #17, #18, #19, #20, #21	✓
	c. *Quality management plan* (model vs. physical conditions tolerance)		✓
Management	M1. Workforce training & onboarding	ref. Table 1, #3, #4	
	M2. Project team alignment	ref. Table 1, #5, #6	
	M3. Multiparty communication/collaboration platform	ref. Table 1, #7	✓
	M4. Technical requirements (software, hardware, network)	ref. Table 1, #21	
	M5. Risk identification & management process	ref. Table 1, #15	
Implementation	I1. Existing conditions data capture	ref. Table 1, #17, #18	✓
	I2. Verification & validation of data		✓
	I3. Legacy data migration	ref. Table 1, #19	
	I4. Workflow evolution	ref. Table 1, #14	
	I5. BIM schedule		✓
	I6. Model authoring workflow		✓
	I7. Resource forecasting (material, labor, equipment) from BIM	Typ. BIM use	
	I8. Project controls (cost, schedule, safety, material tracking) from BIM using functions such as 4D, 5D & GPS tracking	BIM to VDC	
	I9. Coordination using multi-trade clash detection	Typ. BIM use	
	I10. Fabrication drawing creation from BIM (auto)	BIM to VDC	✓
	I11. Revision control/change management process	ref. Table 1, #16	✓
	I12. Technology use in field (CNC, total station, VR, AR, cloud computing, RFID)	ref. Table 1, #22	
	I13. Quality management using laser scanning/total station		✓

✓ Identified from case study

standards adopted from related implementation processes in general construction without adapting them with additional constraints found in a retrofit construction project. The author considers the *decisions* made in BIM planning, management and implementation to be “complex and difficult.” Bellman & Zadeh (1970) define a *decision* as a fuzzy set (class of objects with no defined boundary, *e.g*. class of objects defined by adjectives such as small, large, accurate, approximately etc.) of alternatives resulting from the intersection of goals and constraints. A decision is complex and difficult, when there are multiple criteria (both qualitative and quantitative), multiple participants, uncertainty and risk, incomplete information and imprecise data for decision-making (Hipel, Radford, & Fang, 1993). The inherent characteristics of the construction supply chain (unique products, multiple stakeholders, variability) in retrofit construction thus lead to *decision-making in a fuzzy environment* i.e. an environment in which the goals, constraints and consequences of actions are not precisely known (Bellman & Zadeh, 1970). In the case of BIM use for retrofits especially when the experience with BIM is new and without established precedents to learn from, the knowledge of possible constraints is a *“best-guess”* at the start of the project. It is thus important to establish clear strategic goals, identify constraints and their impact and define performance metrics to measure outcomes based on the strategic goals.

Analysis of the “expected outcome from BIM” and “BIM-value” (through structured interviews) and the observations from the process mapping reveals that the stakeholders of the BIM process have different requirements/utility from BIM, based on their scope of work and their objectives. Table 21 summarizes this theory as the stakeholder value of BIM. Future chapters will elaborate on the value system, specifically in relation with labor productivity.

Table 21

Stakeholder Value of BIM

Stakeholder of BIM	**Value**
Tier 1: Owner	Financial gain (cost, schedule, performance, quality)
Tier 2: Design (Architecture/Engineering)	Quality of design Analysis of design Improved design schedule Improved communication Documentation
Tier 3: Construction Management	Improved const. schedule Multiparty communication Predictability (cost, time, performance, risk) Spatial coordination Efficient management process
Tier 4a: Implementation (Trade contractor - Modeler)	Efficient modeling process Accurate, reliable and timely availability of information
Tier 4b: Implementation (Trade Contractor - Installer)	Improved productivity Reduced rework

CHAPTER 4

BIM IMPACT ON LABOR PRODUCTIVITY IN RETROFIT CONSTRUCTION

Chapter 4 presents the observations and analysis from the field, discusses the productivity analysis and investigates the relationship between labor productivity and BIM. The author follows the method described in Figure 35 to develop a framework to answer the research question:

R1c: How does BIM use impact activity-level labor productivity in retrofit construction?

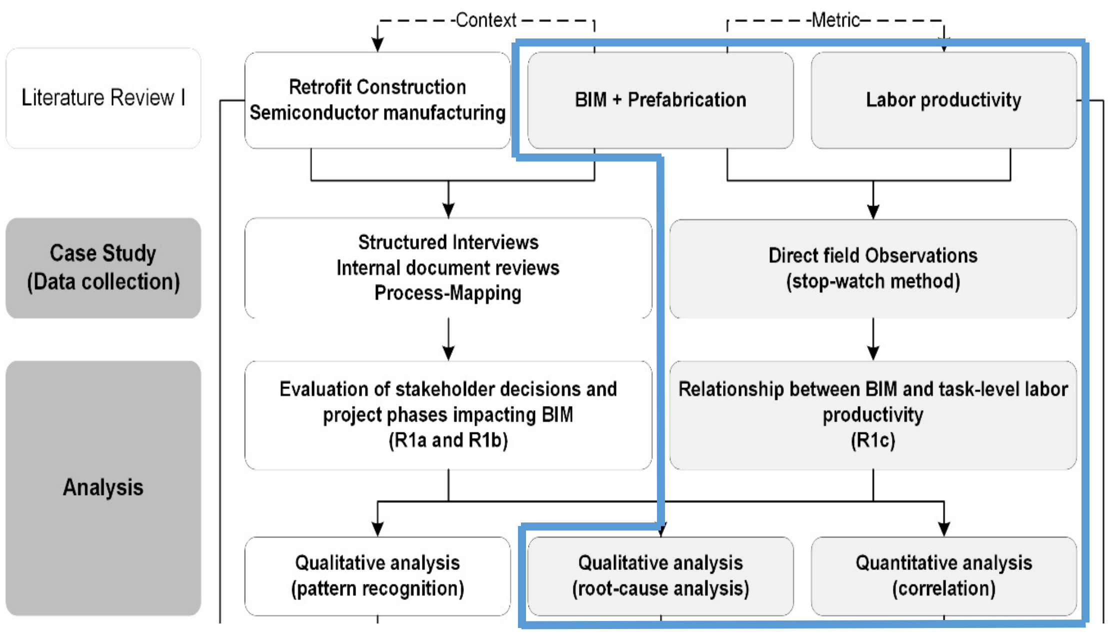


Figure 35. Research Method for Case Study (Productivity Study)

4.1. Background

As defined in Chapter 2 (Literature Review), *productivity* is the physical phenomenon identifying the relationship between an output quantity and an input quantity while *performance* is an umbrella term for excellence which includes productivity, profitability as well as non-cost factors such as quality, speed, dependability and flexibility (Tangen, 2005). Data from past studies' suggest that BIM and prefabrication are effective management and production methods to improve labor productivity and performance (ref. Chapter 1). Therefore, the goal of this study is to explore how *BIM use at its current maturity level influences labor productivity in a retrofit construction project*.

During Phase I of the project (multi-prime contracting), only a single trade contractor had a formal method of activity-level measurement of productivity *i.e.* the labor-hour per unit (feet of pipe or no. of hangers) installed. The rest of the trade contractors relied on a project-level measurement of productivity *i.e.* actual billed hours to the owner per estimated billed hours for the project. This indicates less control on the site activities, potential wastes in the process and an un-optimized labor headcount per task. During Phase II of the project, as the trade contractors' felt the pressure of measuring, benchmarking and improving labor productivity for their collective gain, they adopted a "*work-study"* method to measure the activity times and the delay times. According to research done by Thomas et al. (1990) and sources cited by Thomas, productive time (or value-added time) is linearly related to output only if the productivity during that time remains constant. Productivity (input/output) can remain constant if the activity is high volume and repetitive, similar to a manufacturing or production environment. In this case, although the activity types were repetitive (*e.g.* hanger install, pipe install), the constraints posed by the existing conditions made every activity unique and thus labor-intensive. The owners' hypothesis was that prefabricating assemblies such as hangers, wireways and pipe fittings, conforming to a clash-free model (BIM), would eliminate non-value added time in the construction activities, thereby improving labor productivity (more units installed per labor-hour) and reduce labor headcount.

Measurement of labor-time utilization helps identify the non-value added activities in the process. The objective is to observe the work-method and work-time in order to determine the amount of time spent by labor on value-added versus non-value added work and hence identify site or management constraints that hinder efficiency (Yi & Chan, 2014). The owner and project team gave the author access to the activity time data as well as access to the site to observe construction crews on particular days. This section will provide an explanation and justification of the data collection method, followed by a description of the observed construction activities and workflows to establish a background prior to discussing the productivity analysis.

4.1.1. Data Collection

The author along with an observation team of three personnel engaged by the owner conducted direct field observations for six weeks from March to May 2014 (see Appendix A for dates) collecting the following three types of data:

1. **Value-added Time (VAT) and Non-Value Added Time (NVAT):** There are eight forms of waste according to the tenets of lean production; transport, inventory, motion, waiting, over-production, over-processing, defects and skills. Waste, according to Howell (1999), is *"defined by the performance criteria for the production system*." Alternatively, any activity, which does not add value to the product from the perspective of the *customer* (facility owner), is a waste or a non-value adding activity. Time spent on any non-value added activity is by association defined as non-value added time or NVAT. In this case study, the facility owner classified the following activities as non-value added activities, based on their initial objectives for using BIM enabled prefabrication:
    a. Rework: Fayek, Dissanayake, & Campero (2003) define rework as *"activities in the field that have to be done more than once in the field, or activities which remove work previously installed as part of the project regardless of source, where no change order has been issued and no change of scope has been identified by the owner".*

For this research, we also consider rework as the modifications made to a prefabricated assembly, if it did not fit as designed and fabricated.

b. <u>Movement:</u> A typical workday involves the arrival of the prefabricated assemblies on site by the end of the previous day. The crew receives the material, gathers any additional materials & equipment, locates the work-area and spends the rest of the workday installing the assemblies. Any unnecessary movement not contributing to the final product; such as looking for missing or extra materials, walking to a different location to find for a supervisor or other personnel; is considered waste.

c. <u>Breaks:</u> In a workday, there are three official owner-contractor negotiated breaks;

   - AM break (15 min. break + 2x10 min. travel time to/from break)
   - Lunch break (30 min. break + 2x10 min. travel time to/from lunch tent)
   - PM break (15 min. break + 2x10 min. travel time to/from break)

   Any break apart from these negotiated breaks is a waste.

d. <u>Consulting Drawings</u>: A survey of nearly 2000 craft workers across the United States by Dai et al. (2009) found *“engineering drawings management”* as one of the top factors affecting labor productivity from the perspective of the craft worker irrespective of their trade. This includes factors such as missing or incorrect information in the drawings and lag in communication for clarifications when needed. In an ideal situation, when using BIM enabled prefabrication, there should not be a need to spend unnecessary time consulting drawings.

e. <u>Discussion</u>: Although discussions are unavoidable, we measure it, as a category of NVAT to account for the time spent not doing productive work.

f. <u>Measurement</u>: In an ideal situation, a prefabricated assembly should fit-as-designed, reducing the need for measurement on site. However, in reality, the labor workforce spends a considerable amount of time measuring, validating locations, and horizontal, vertical and spatial dimensions before finalizing the fittings.

g. <u>Waiting or idle time</u>: Time spent not working, waiting or idling is by definition a waste.

Other than the seven factors mentioned above, some unavoidable activities are non-value added but necessary (NNVAT); such as setup time, safety considerations and cleaning (especially in a semiconductor manufacturing facility).

2. **Workflow Disruptions and Potential Causes:** *"Disruption is a result of a loss in efficiency and a reduction of productivity"* (Baldwin & Bordoli, 2014). Disruption of activities on non-critical paths may not result in a delay; however, inefficiencies can lead to wastes and cost inflation. Typically there is more than a single factor causing disruption and isolating the disrupting causes requires comprehensive documentation (Baldwin & Bordoli, 2014). The objective of this research is to consider the impact of BIM only. During informal discussions with trade contractors: modelers and installers, prior to the productivity studies, the author noted a few anecdotal comments about BIM (outlined in Table 22).

    Even though these comments are conjecture, they are indicative of the craft workers' perceptions about BIM and prefabrication, which are mostly negative (movement, rework, inaccuracy, non-conformance, incomplete) and disruptive (workflow disruption). This contradicts the feedback received from BIM managers (trade contractor) and past literature reviews espousing the benefits of BIM at the labor workface. The goal of using BIM functionalities such as clash-detection is to reduce conflicts at the activity-level and improve reliability. Instead of relying on subjective feedback, we adopt an empirical approach through direct observations to investigate the reasons for this negative perception for BIM and prefabrication. During the direct observations, we identified the potential *causes* related to the NVAT categories of rework, movement, consulting drawings, discussion, measurement and waiting. Several interrelated factors can trigger productivity loss and NVAT such as project and contract factors, location and environment factors, project team factors, managerial actions and decisions, disruptive events and signs, human reaction factors and external factors (Lee, 2007). The scope of this study is limited to identifying factors immediately related to BIM and prefabrication that contribute to the NVAT activities and thus hinder efficiency.

Table 22

Trade Contractor (Installer) Comments on BIM

Comments	Coding
"BIM takes the craft out of the craftsmen's hands"	BIM: non-conformance, workflow disruption
"Electrical modeling is a formality. Trades are bending conduits on site so why spend time modeling?"	BIM: non-conformance, BIM: incomplete
"Gravity does not exist in the cyberspace. Stuff is not held up by anything in the model. They (fabrication shop) give us 10 bolts to hang so much stuff when we actually need 100"	BIM: incomplete, prefab: incomplete
"Every time we (installer) have to cut something or drill a hole we have to step outside (the clean sub-fab or fab) which takes up a lot of time"	Movement, rework, BIM: inaccuracy
"We need visibility to the 3D model earlier on or on the field while we are installing, without disrupting work"	Consult drawing, workflow disruption

3. **Total output:** The third dataset includes the quantitative measurement of the total output from the workday. This data was critical for arriving at a unit rate, *i.e.* input/output or labor-hour/feet. However, it was difficult for the observers to accurately measure the output due to the variation in the daily activities performed in the six-week period and their levels of complexity. In total, we collected 27 data points to measure the total output from the workday as total units installed. This included 5 data points for hanger install (each), 5 data points for pipe install (linear feet), 9 data points for wireway install (linear feet) and 8 data points for conduit install (linear feet). Since the hanger install is a comparatively different type of job

function measured in units different from the rest three activities (number of hangers installed by type), we are not considering the five data points in this analysis.

4.1.2. Construction Activities

The four construction activities observed for the on-site productivity studies include:

- Hanger (1' to 4' trapeze) installation by electrical and piping contractors
- Piping (1-1/2", 2" and 2-1/2" high purity stainless steel) installation by piping contractors
- Electric Wireway (4" x 4" or 6" x 6" prefabricated sections) installation by electrical contractors
- Conduit (3/4" to 2-1/2" rigid metal conduit) installation by electrical contractors including the installation of rigid metal conduit elbows.

Figure 36 outlines the systematic workflow for the daily construction activities. Activities common to all trades include a daily job talk during which the Superintendent provides a schedule update, reminds the installer of the safety concerns in a semiconductor-manufacturing environment, assigns tasks to the crew and the entire group spends a few minutes on stretching and flexing before beginning their day. The installers perform each task as a crew of two to comply with the safety requirements, which requires a "buddy-system" or a spotter for each worker working above the catwalk or below the raised metal floor (RMF).

After the job talk, the crew retrieves the prefabricated material and all other tools required to perform the task from the material storage area, which is located on either the sub-fab level or the utility level, and arrives at the location of the process tool. The installers transport the material on either a "cart" or a pipe rack. The 100% prefabricated assemblies such as unistruts hangers and high purity stainless steel pipes are packed and sealed in plastic wrapping to maintain the required level of cleanliness. The 50% prefabricated assemblies arrive at site as a "kit-of-parts" in large 4-6 cubic yard bins, which can be rolled over to the job site depending on the congestion at the particular location.

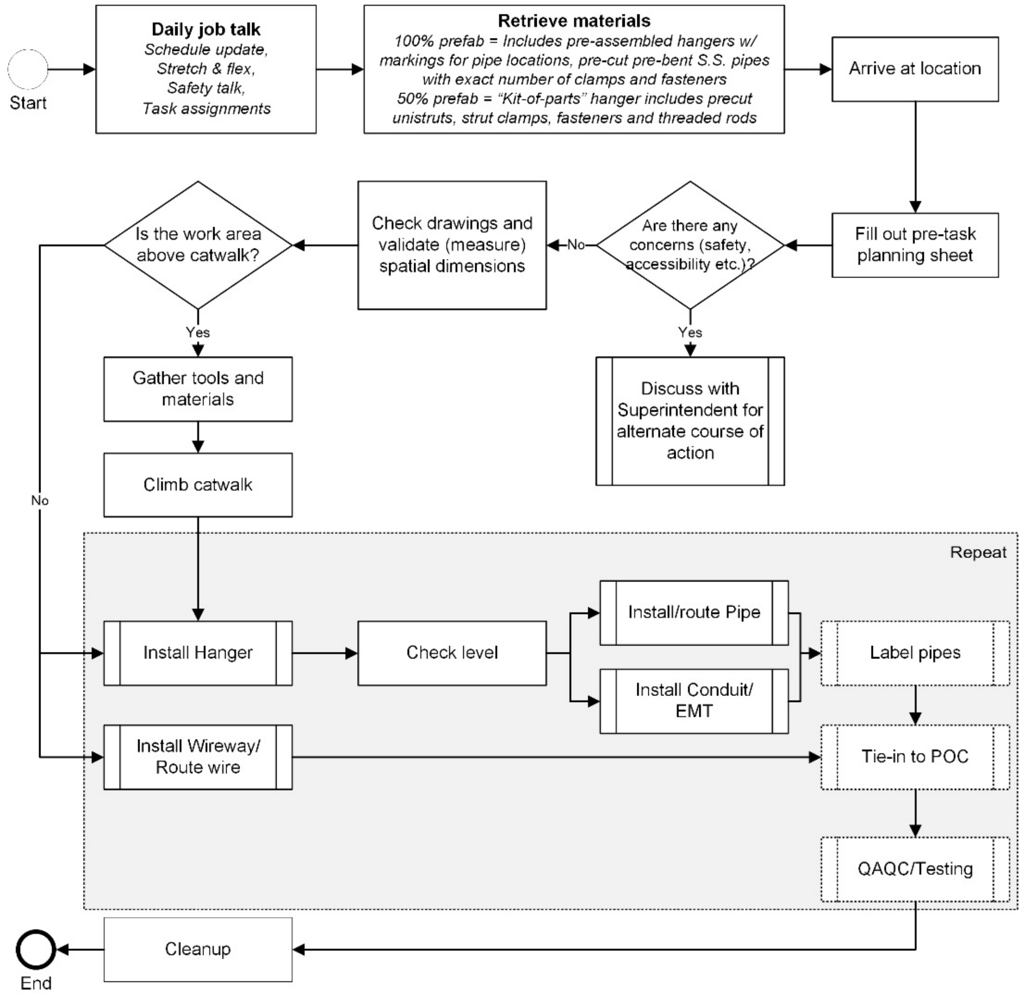


Figure 36. Daily Construction Activities

At location, before beginning work, the installers have to fill out a Pre-task Planning (PTP) worksheet, which identifies safety issues, accessibility concerns, material unavailability and any other factors that are of immediate concern to them. If there are no major issues, the installers proceed with the activity and if not, the Superintendent evaluates the situation. A separate crew, before the pipe fitters, typically performs the layout for the hangers. At the time of this case study, the process followed for layout included a "layout crew" marking the locations using tape or markers on the floor of the sub-fab. These markings became the reference to install the hangers from the ceiling, which is at least 12-15 feet high. The vertical datum for all measurements was pre-established using a laser level and marked on the column faces. The installers use these marking to install the hangers, after which they route the pipes and conduits. The wireways do not require hangers and can be installed independently in sections. At the end of the workday, the installers clean the site and return the tools to the toolbox located in the material storage area. Some contractors have a debriefing at the end of the day.

A workday is 10 hours (or 600 minutes), of which 63.5% or 6.35 hours is available for effective value added work after subtracting the daily wastes or the necessary but non-value added activities (see Table 23). The NNVA activities occupy 24.47 % or 2.45 hours of a workday. The data collected through the daily observations indicate that the NNVA times have a standard deviation of 10.57% for the sample of 47 data points. This means that on an average the NNVAT data varies by +/- 60 minutes from the mean.

Table 23

Daily Necessary Non-Value Added Time (NNVAT) Percentages

Activity	**Time (min)**	**%age of total work-day**	**Data source**
Total workday	600*	100%	
Daily job talk (set-up)	30	5%	Contractor adjusted
Pre-task planning (safety)	15	3%	Owner requirement
Breaks (negotiated)	120	20%	Contractor/Owner negotiated
Cleaning	24	4%	Avg. of daily observations
Safety	30	5%	Avg. of daily observations
Total Daily NNVAT	219	36.5%	
Effective available workday	*(600-219) = 381*	*63.5%*	

Note. * = Contract hours, can vary from day to day

4.1.3. Productivity Rates

The owner used a unit-price or schedule of rates contract for the project. In a unit-price contract, the contractor includes unit rates in the bid for each item such as labor, material and equipment. As the work is completed, the quantities are measured and the owner pays the contractor accordingly. Owners prefer this contracting strategy when there is a defined scope of work but uncertainty in the quantities. It offers the owner some flexibility to make changes without contract variations and fast-track the project when needed (Carmichael, 2000). The disadvantage is the lack of control on cost, time, quality and the possibility of disputes over measurements of quantities and the method of measurement if not defined prior to execution. Measuring the actual versus planned scope determines the effectiveness of this contracting strategy. Absence of a productivity metric can lead to inflated billed hours by the contractors, lack of control and overall waste in the process. We will use the bid value for the base labor rate as the planned or estimated productivity rate in our calculations.

The contractors establish the labor unit rates based on data published by the Mechanical Contractors Association (MCA) and the National Electrical Contractors Association (NECA). These associations represent majority of the mechanical and electrical contractors in the US. They develop productivity rates and suggest productivity loss factors from historical data and surveys. Estimators use this data for arriving at a realistic value based on the project type and constraints. MCA and NECA define a labor unit as *"labor-hours to install a unit of material (such as a foot of pipe) an individual item (such as a fitting or valve), or perform a specific task (such as welding a joint)".* The productivity factor includes base labor, handling and erection, fitting and joining and hydrostatic testing. The suggested loss factors include three levels of impact; minor, average and severe. They can be used for estimating bid values, modified forward pricing for change orders, impacting the project schedule and retroactively pricing losses of labor productivity. Table 24 identifies the factors.

Table 24

Productivity Loss Factors Defined by MCA and NECA

Factor	**Percent loss per factor**		
	Minor	**Average**	**Severe**
1. Stacking of trades	10%	20%	30%
2. Morale and attitude	5%	15%	30%
3. Reassignment of manpower	5%	10%	15%
4. Crew Size Inefficiency	10%	20%	30%
5. Concurrent Operation	5%	15%	25%
6. Dilution of Supervision	10%	15%	25%
7. Learning Curve	5%	15%	30%
8. Errors and Omissions	1%	3%	6%
9. Beneficial Occupancy	15%	25%	40%
10. Joint Occupancy	5%	12%	20%
11. Site Access	5%	12%	30%
12. Logistics	10%	25%	50%
13. Fatigue	8%	10%	12%
14. Ripple	10%	15%	20%
15. Overtime	10%	15%	20%
16. Season and Weather Change	10%	20%	30%

The next section will discuss the findings from the productivity analysis, which includes labor time utilizations, correlations and finally, the impact of BIM on task-level labor productivity.

4.2. Productivity Analysis

4.2.1. Labor-Time Utilization

For this particular study, the NNVAT categories include; breaks, cleaning, safety, setup and the NVAT categories include; consulting diagrams, discussion, measuring, moving, observation, retrieving materials, rework and waiting. An average of 47 data points indicate that VAT is 26.27% ($\sigma = 15.8\%$), NNVAT is 24.47% ($\sigma = 10.57\%$), and NVAT is 49.26% ($\sigma = 17.37\%$) of a labor day. *Figure 37* represents the average values of the subcategories. Each of these categories (VAT, NNVAT and NVAT) has a large range indicating a high variation in daily work activities (see Figure 38). A study of four types of construction activities shows that irrespective of the type of task (hanger install, pipe install, wireway install and conduit install) there is still a large spread in the data (see Figure 39). This large spread is indicative of certain external factors, such as site conditions (retrofit), management practices, project and contract factors, human reaction factors and disruptive events, which are causing this variation. The data also shows that in all four cases, the NVAT is typically greater than the VAT in a workday. The next section will analyze the relationship between the subcategories.

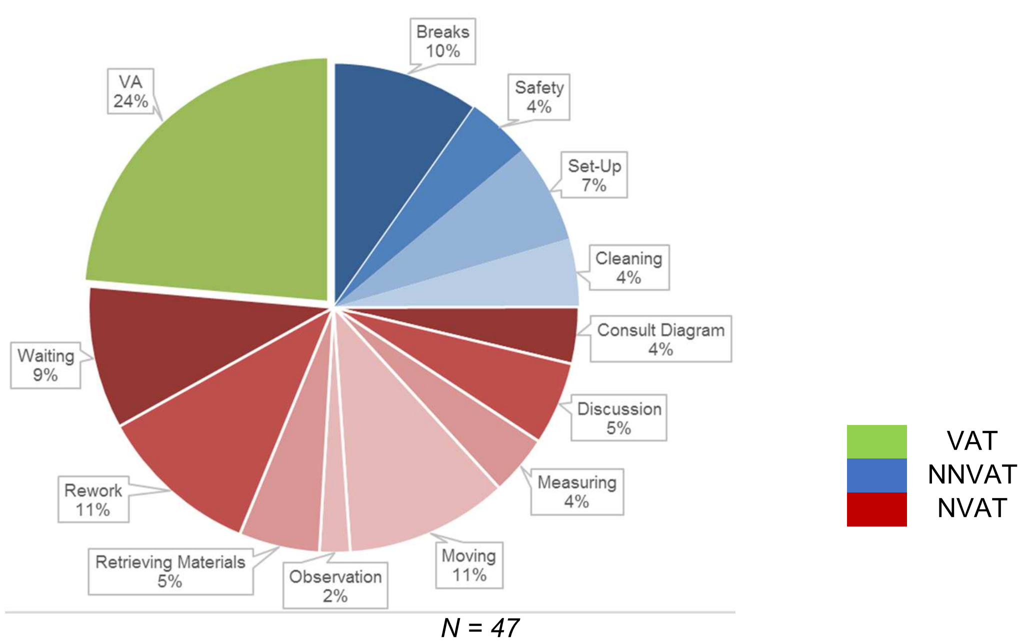
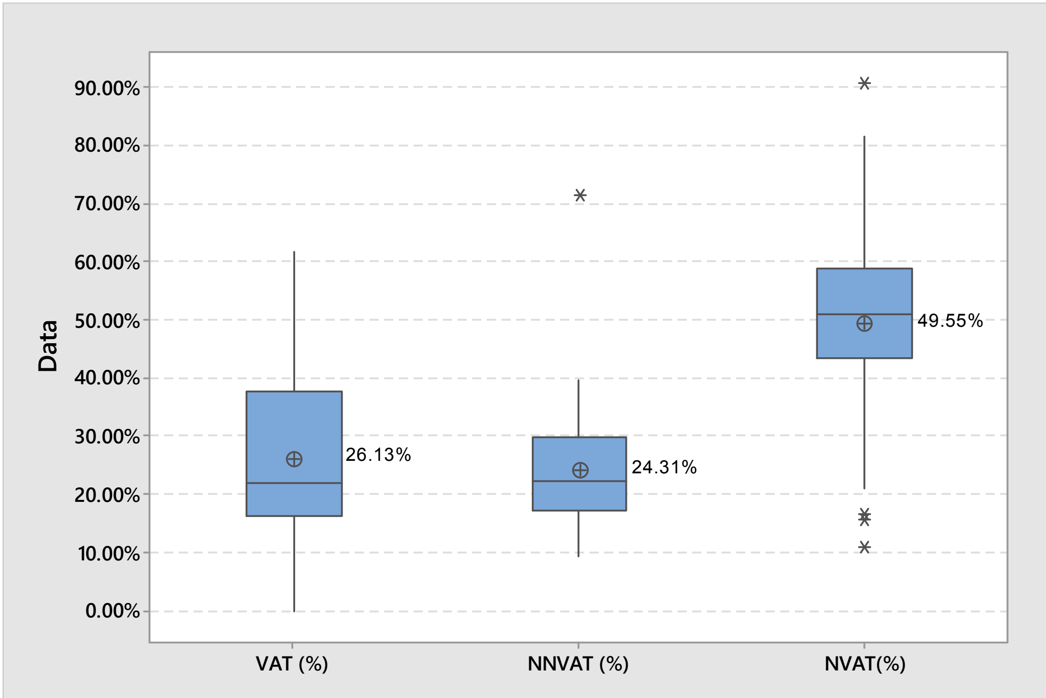
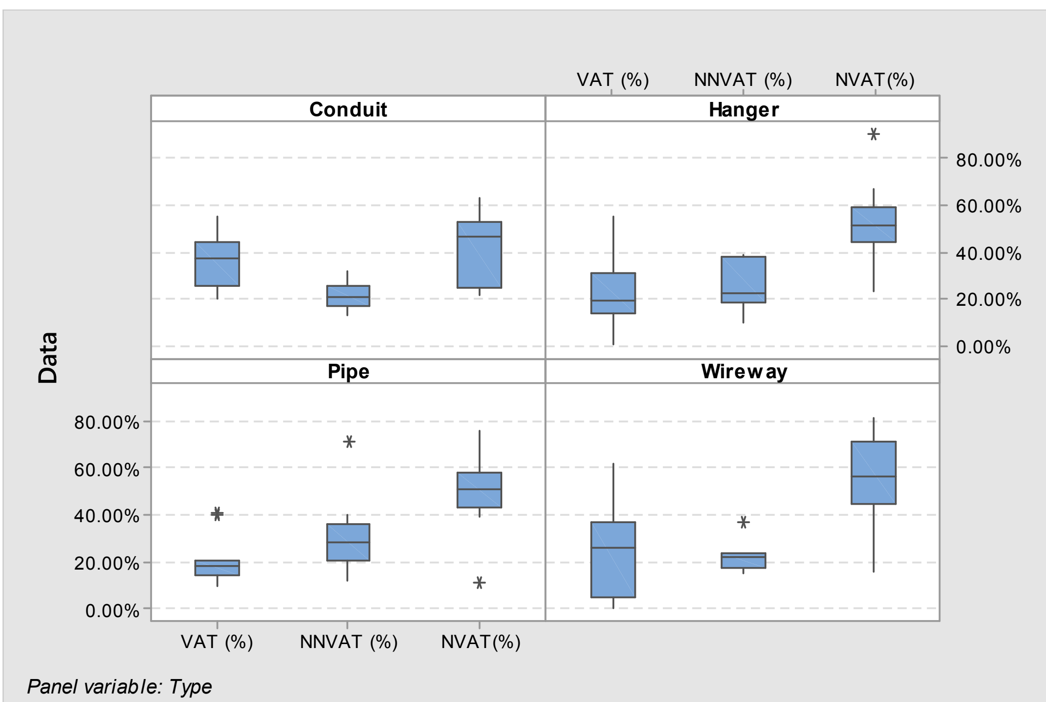


Figure 37. VAT, NNVAT, NVAT Categories in a Workday



n = 47

Figure 38. VAT, NNVAT, NVAT Spread (Overall)



Conduit (n = 12), Hanger (n = 11), Pipe (n = 12), Wireway (n = 12)

Figure 39. VAT, NNVAT, NVAT Spread by Construction Activity Type

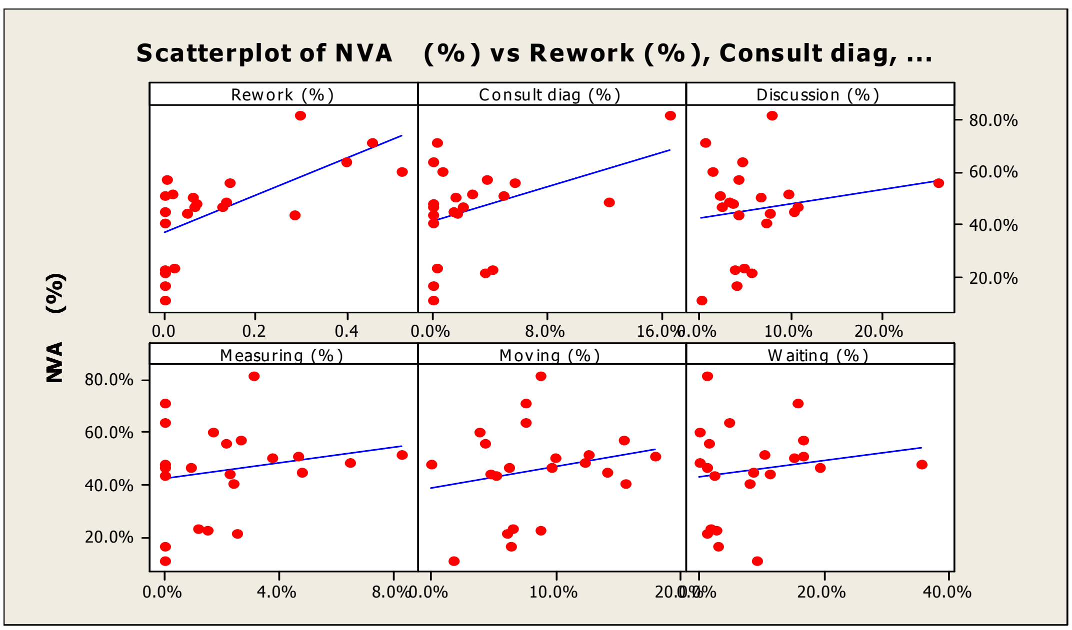
4.2.2. Analyzing Relationships

In this section, we explore the relationships between VAT, NVAT and productivity by using the statistical method of correlation. The correlation coefficient (*r*) measures the strength of the linear relationship between two variables and the sign indicates the type of linear relationship. A value of *r* closer to +1 suggests that the variables are positively linearly correlated and value of *r* closer to -1 suggests that the variables are negatively linearly correlated (Weiss, 2011).

Although the author was able to collect 47 observations during the case study, only 22 data points out of the 47 included the three measurements; (1) labor time utilization, (2) value added output per day and (3) workflow disruptions attributed to BIM (ref. Section 4.2.3). For all subsequent analysis, we will consider this reduced data set. At the outset, we acknowledge the limitation in the predictability of results posed by a small data set. However, we use the results as a foundation for further investigation.

NVAT Subcategories: The author first plotted scatter plots between total NVAT (%) and the individual subcategories of rework, consult diagram, discussion, measuring, moving and waiting, to investigate their relationships. The scatter plots created do not suggest any correlation (see *Figure 40*). To validate this, a Pearson correlation analysis was performed which suggests a positive association but no correlation between NVAT and each of the subcategories for NVAT when analyzed individually and a moderate positive correlation with "Rework" (see *Figure 40*). Therefore, we explore the relationship between Rework, NVAT, and VAT in more detail in the next section.

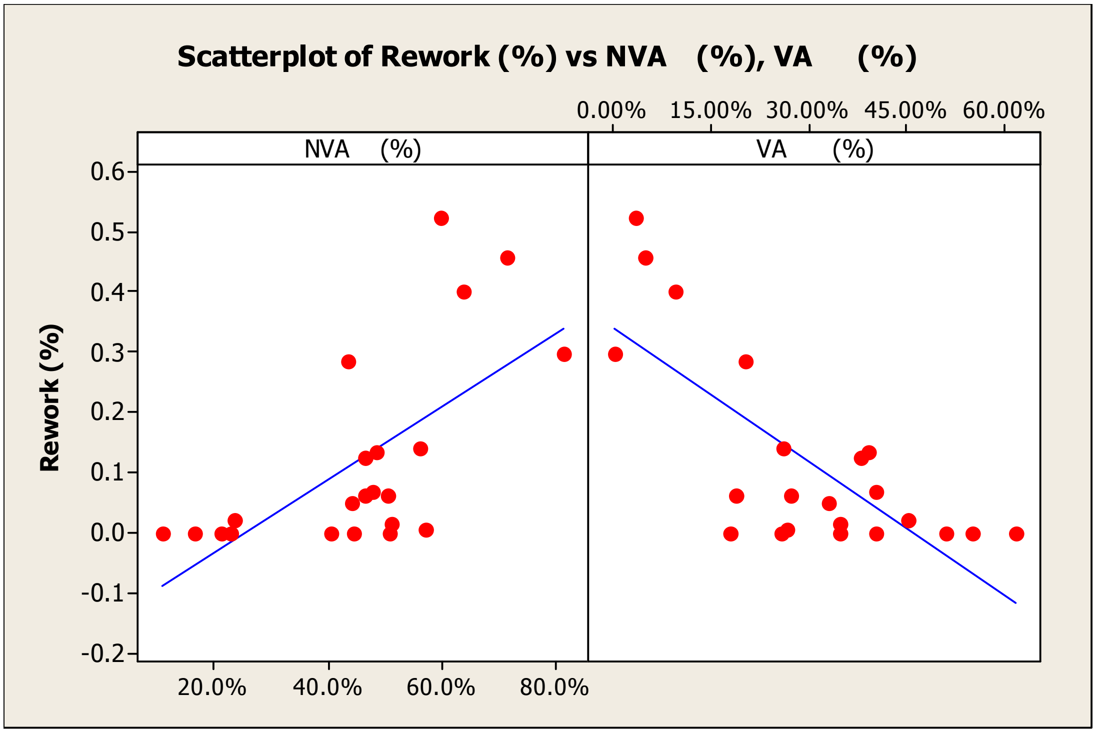
Rework vs. NVAT and VAT: The Pearson coefficient of correlation (r) between Rework (%) and NVAT (%) is +0.650 (p-value = 0.001) and represents a positive relationship between the variables, which means as rework increases, NVAT increases and vice versa. The p-value is 0.001 (< 0.05) indicating that there is not enough evidence to dismiss correlation. The Pearson coefficient of correlation between Rework (%) and VAT (%) is -0.745 (p-value = 0.000) and represents a negative relationship between the variables, which means as rework decreases, VAT increases and vice versa. In observing the data in detail, we find a few data-points, which skew the line of best fit. Further investigation of these specific points reveals that the NVAT activities other than rework, such as measuring, moving and waiting were particularly high on these specific days. Thomas et al. (1990) classify work-study as an unsuitable productivity model for labor-intensive operations because; *"they do not model the important external and management factors affecting productivity, output is not an element of the model, and various assumptions about the relationship between delay time, productive time, and output are unsupportable, except in isolated situations."* Thus, the next section explores the relationship between productivity and the labor time utilization to explore this statement.



n = 22

	Pearson correlation	P-Value
NVAT (%), Rework %	0.650	0.001
NVAT (%), Consult diagram (%)	0.395	0.069
NVAT (%), Discussion (%)	0.171	0.447
NVAT (%), Measuring (%)	0.192	0.391
NVAT (%), Moving (%)	0.213	0.341
NVAT (%), Waiting (%)	0.151	0.503

Figure 40. Scatter Plot and Correlation of NVAT Categories



n = 22

Figure 41. Scatterplot of Rework % vs. NVAT %, VAT %

Table 25

Productivity Data (n =22)

	Type*	Week Number	Output (feet)	Productivity				BIM disruption *frequency/ day*	Labor-time utilization								
				Actual Productivity (labor-hour/ft.)	**Estimated Productivity** (labor-hr/feet)	**Baseline** (labor-hr/feet)	**Performance Ratio** (Estimated/Actual)		**VA** (%)	**NNVA** (%)	**NVA** (%)	**Rework** (%)	**Consult diag** (%)	**Discussi on** (%)	**Measuri ng** (%)	**Moving** (%)	**Waiting** (%)
1	Conduit	13	40	0.27	0.21	0.10	0.77	1	25.7%	23.5%	50.9%	0.0%	5.0%	2.0%	4.7%	18.0%	16.6%
2	Conduit	13	100	0.15	0.21	0.10	1.37	1	34.8%	20.7%	44.5%	0.0%	1.4%	10.3%	4.8%	14.0%	8.6%
3	Conduit	14	60	0.23	0.21	0.10	0.88	2	34.8%	14.0%	51.2%	1.6%	2.7%	9.6%	8.3%	12.6%	10.5%
4	Conduit	16	60	0.21	0.21	0.10	1.00	0	50.9%	27.9%	21.2%	0.0%	3.6%	5.7%	2.6%	6.1%	1.3%
5	Conduit	17	50	0.39	0.21	0.10	0.53	0	40.2%	19.3%	40.5%	0.0%	0.0%	7.3%	2.4%	15.6%	7.8%
6	Conduit	18	250	0.06	0.21	0.10	3.32	1	54.9%	22.3%	22.8%	0.0%	4.2%	3.8%	1.5%	8.8%	2.6%
7	Conduit	18	290	0.06	0.21	0.10	3.21	0	45.3%	31.3%	23.4%	2.2%	0.3%	4.8%	1.2%	6.5%	1.8%
8	Conduit	18	100	0.19	0.21	0.10	1.10	2	39.2%	12.3%	48.5%	13.5%	12.3%	3.0%	6.5%	12.2%	0.0%
9	Pipe	13	10	1.72	0.34	0.12	0.20	1	9.3%	26.9%	63.8%	40.2%	0.0%	4.5%	0.0%	7.6%	4.8%
10	Pipe	15	40	0.33	0.34	0.12	1.03	4	20.0%	36.5%	43.5%	28.5%	0.0%	4.3%	0.0%	5.1%	2.3%
11	Pipe	16	120	0.09	0.34	0.12	3.94	1	40.2%	11.9%	47.9%	7.0%	0.0%	3.5%	0.0%	0.0%	35.7%
12	Pipe	17	20	0.96	0.34	0.12	0.36	1	17.7%	71.5%	10.8%	0.0%	0.0%	0.0%	0.0%	1.8%	9.0%
13	Pipe	17	40	0.77	0.34	0.12	0.44	0	18.7%	34.7%	46.6%	6.4%	0.0%	2.3%	0.0%	9.7%	19.2%
14	Wireway	13	9	1.78	0.38	0.45	0.21	2	25.9%	18.1%	56.0%	14.2%	5.7%	26.3%	2.1%	4.2%	1.4%
15	Wireway	14	10	1.58	0.38	0.45	0.24	1	37.9%	15.5%	46.5%	12.6%	2.1%	10.6%	0.9%	6.2%	1.3%
16	Wireway	14	40	0.41	0.38	0.45	0.93	1	27.1%	22.6%	50.3%	6.2%	1.5%	6.5%	3.8%	10.0%	15.0%
17	Wireway	15	0	0.00	0.38	0.45	N/A	5	0.0%	18.6%	81.4%	30.0%	16.6%	7.8%	3.1%	8.8%	1.1%
18	Wireway	15	100	0.29	0.38	0.45	1.32	1	26.4%	16.6%	57.0%	0.6%	3.8%	4.1%	2.7%	15.5%	16.5%
19	Wireway	16	120	0.09	0.38	0.45	4.32	0	61.8%	21.6%	16.6%	0.0%	0.0%	3.9%	0.0%	6.4%	3.1%
20	Wireway	16	3	6.64	0.38	0.45	0.06	4	3.3%	36.9%	59.8%	52.3%	0.7%	1.3%	1.7%	3.8%	0.0%
21	Wireway	16	2	8.66	0.38	0.45	0.04	3	4.9%	23.7%	71.5%	45.9%	0.3%	0.4%	0.0%	7.6%	15.8%
22	Wireway	18	30	0.68	0.38	0.45	0.56	0	32.9%	23.0%	44.1%	5.1%	1.7%	7.6%	2.3%	4.7%	11.1%

*Material type assumptions:

Actual productivity for: Conduit = 2" Rigid metal conduit, Pipe = 2" High purity stainless steel, Wireway = 4" x 4" screw cover NEMA Type 1

Baseline productivity values for: Conduit = 2" EMT (NECA), Pipe = 2" Carbon steel welded (MCA), Wireway = 4" x 4" screw cover NEMA Type 1 (NECA)

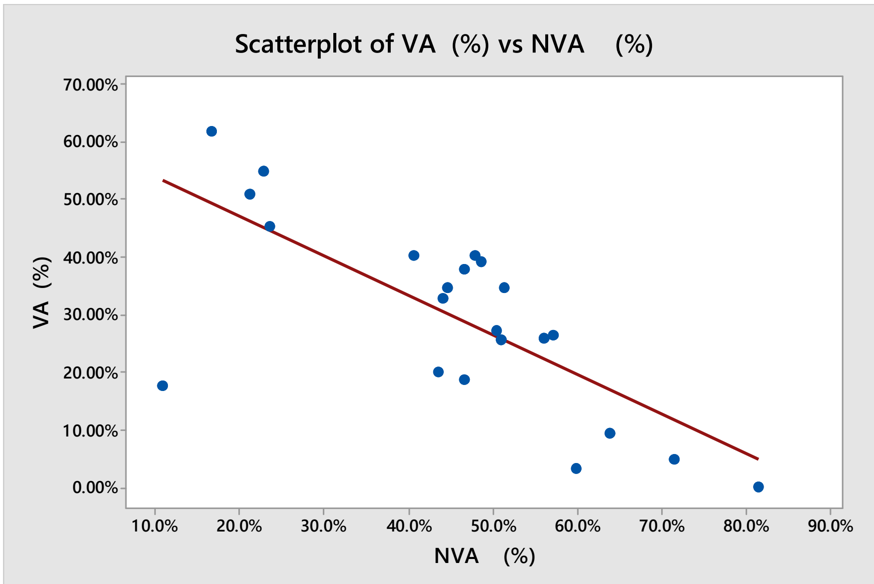
Productivity and Labor Time Utilization. This study measures productivity as a unit rate i.e. input/output or labor-hour/feet. The *actual productivity* rate is the data collected by the author as direct observations. The *planned or estimated productivity* are the values used in the contract. *Baseline* represents the labor unit suggested by MCA or NECA as indicated *Performance ratio or factor* is the estimated unit rate divided by the actual unit rate and represents the earned value to the project (Thomas, 1991).

According to Thomas (1991), it is irrational to expect the two measures (productivity and labor time utilization or work sampling) to behave in the same way because the number and combinations of variables affecting these measures are different. Labor time utilization is a measure of an *input* (hours) variable only and is affected by work-sample procedural factors such as activity definition, craft type, study windows, observer bias etc. while productivity is a measure of an *output* (real value add) and an *input* (hours) variable and is affected by project attributes, mangament control, external factors such as weather and behavioral factors affecting the installers. Due to a lack of a formal method of task level productivity measurement, it was natural for the stakeholders of the project in this case study to measure labor time utilization factors as a measurement of productivity based on the hypothesis that the VAT and NVAT percentages in a labor work-day can predict labor productivity. This hypothesis is based on the following assumptions:

1. Reducing the NVAT improves VAT
2. As VAT increases, then the productivity improves

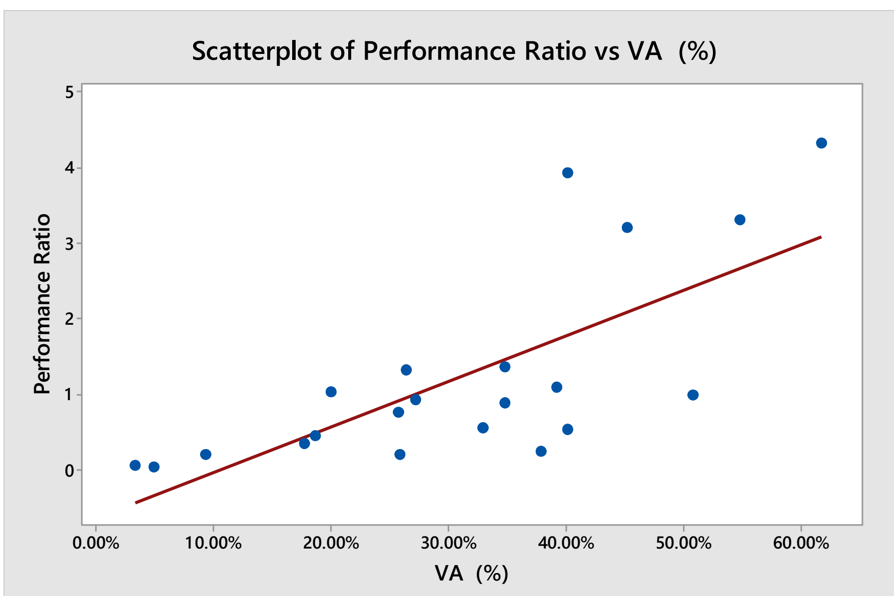
In analyzing the scatterplot and correlation coefficient value, we can see that as NVAT increases VAT decreases. The correlation coefficient value of - 0.728 shows us that there is a moderate negative correlation between NVAT and VAT (*Figure 42*).

Performance Ratio vs. VAT. The correlation coefficient value of +0.724 shows that there is moderate positive correlation between Performance Ratio and VAT *i.e.* as VAT increases the performance ratio increases as well. This means that a high VAT improves the probability for a better productivity per task (*Figure 43*).



Pearson Correlation = - 0.728, p-value = 0.000, N=22

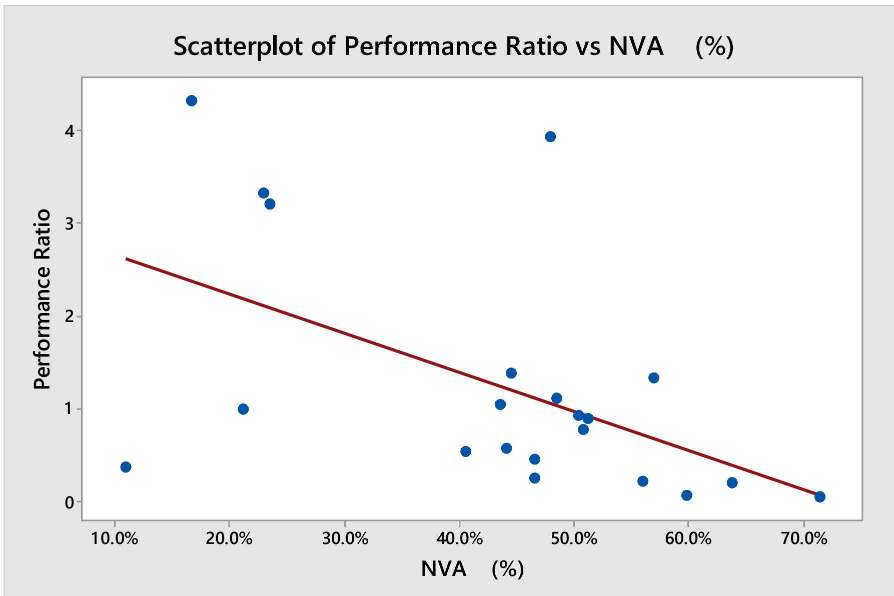
Figure 42. VAT vs. NVAT Scatter Plot



Pearson Correlation = + 0.724, p-value = 0.000, N=22

Figure 43. Performance Ratio vs. VAT Scatter Plot

Performance Ratio vs. NVAT. In analyzing the scatterplot between Performance ratio and NVAT, we find a violation of linearity assumptions. Thus, the Pearson's correlation coefficient value of - 0.520 shows us that there is a weak negative correlation between Performance ratio and NVAT (*Figure 44*).



Pearson Correlation = - 0.520, p-value = 0.016, N=22

Figure 44. Performance Ratio vs. NVAT Scatter Plot

The analysis above shows that there is high variation in daily work activities, which we classify as VAT, NNVAT and NVAT. The subcategory of "rework" shows a low to moderate positive correlation with NVAT (r = 0.463, p-value = 0.001) and low to moderate negative correlation with VAT (r = -0.469, p-value = 0.001), providing enough evidence to not to dismiss the correlation between these factors. A further investigation reveals that VAT and NVAT have a moderate positive correlation (assumption 1); performance ratio i.e. estimated productivity / actual productivity (measured as labor-hour/feet) and VAT also have a moderate positive correlation (assumption 2), but performance ratio and NVAT have a weak negative correlation. This means that we cannot suggest that labor-time utilization and productivity have a correlation. A higher VAT improves the probability of a better productivity, but a higher VAT does not cause better productivity. The next section discusses the disruptions in the worker activity or labor workflow attributed to BIM by the installers, as observed during the daily observations.

4.2.3. Workflow Disruptions

According to Thomas et al. (1990), the work-study technique relies on collecting large amounts of data to establish average values, however, few attempts determine the causes of variations. Thus, the second set of observations measures the frequency of interruptions occurring during the on-site installation activity during a workday that contributed to a high NVAT. Disruptions in workflow lead to deviations from the original sequence of work, which in turn leads to productivity loss. A retrofit project will have certain adjustment factors, such as congestion, joint occupancy, concurrent operations, and trade stacking, which can potentially affect labor productivity more than a new construction project. A popular method of measuring disruptions is the “measured mile” approach (Gulezian & Samelian, 2003) in which the productivity in a disrupted section is compared with the productivity in a non-disrupted section. A limitation of this approach is in highly complex projects where there are no non-disrupted hours. In which case, a better method is the statistical analysis of change and the productivity loss due to a disruption represented as a Leonard curve or the Ibbs curve (Baldwin & Bordoli, 2014). The author spent several days on the site conducting preliminary observations of the work method and capturing comments and complaints by installers (see Table 22 for examples) relating to either BIM or prefabrication. After coding the qualitative data, the author identified six major themes or types of disruptions in the workflow. Identification of these disruption categories are based on empirical research. This is not to say that these are the only issues, there could be more. However, for the purpose of this study, we begin with these six categories:

1. Deviation in representation of information (descriptive and geometric) in the 3D model or 2D drawing package (generated from BIM) *versus* actual conditions on site which leads to non-value added activities such as;
    - *Discussion* with Superintendent and/or BIM Modeler/Manager for verification & validations,
    - *Waiting* for clarifications,
    - Inaccurately constructed prefabricated assembly which does not fit as per design
2. Rework on prefabricated assembly: Workers at the fabrication shop create prefabricated assemblies (100% prefab and "kit of parts") based on drawings generated from a clash-free model. Hence, any adjustments made to the prefabricated assembly are a deviation from the model. The cause of this issue can be traced to an error in the model, an error made during the prefabrication process or an incorrectly installed assembly (explained in Section 4.3). This issue leads to conditions such as:
    - *Moving* to the utility level or outside the clean fab level to use the cutting tools
    - Unnecessary *measurement*
    - *Waste* of material, time and money
3. Risk of encountering installation issues on site after coordination in BIM (clash on site): The Issue for Fabrication milestone is reached only after the Model Coordinator has checked and resolved any potential clashes in BIM. If issues are encountered on site, this can lead to temporary work stoppage, rework and waste.
4. The absence of real-time two-way communication between an installer and modeler for BIM related clarifications causes the installer to *wait* on communication leading to a time lag between the request and receipt of information.
5. Lack of use of technologies such as robotic total stations, RFID, laser scanning and augmented reality with BIM leads to NVAT spent on labor-intensive manual work such as measuring, layouts, material tracking, and consulting drawings.

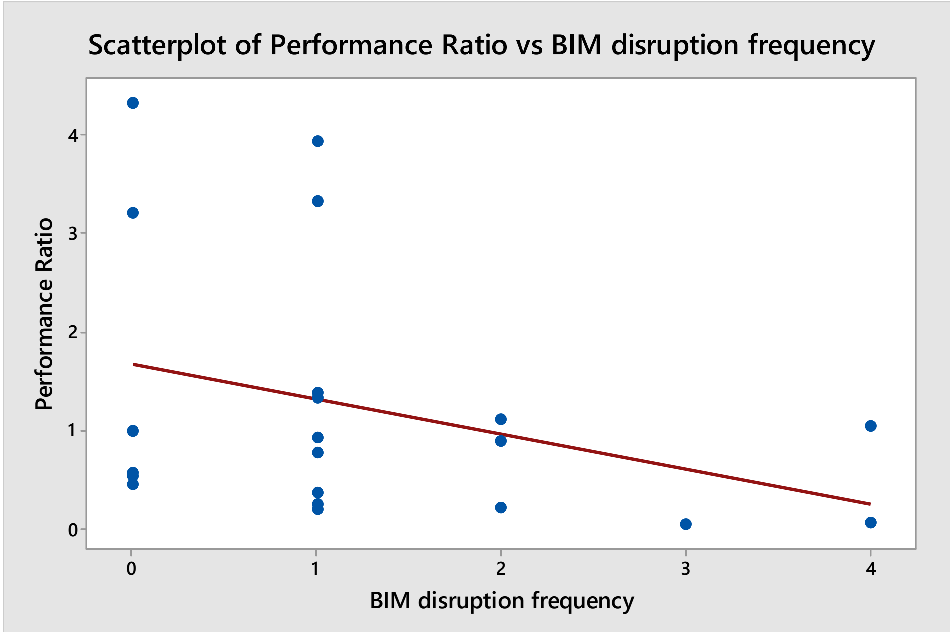
6. Lack of control and supervision on site causes out-of-sequence work. Most times, the change is not updated on time to the federated model leading to a cascading issue of errors such as schedule delay, workflow interruption (*e.g.* waiting, discussion, review) for the installer and waste (material and time).

We recorded the number of occurrences per day for each of the above disruptions. Past research (Liu et al., 2011; Thomas et al., 2003) has established a positive correlation between the number of interruptions or disruptions in the workflow and the loss in productivity (Hester & Kuprenas, 1987; Ibbs, 2005; Thomas & Napolitan, 1995). In a retrofit construction project, there are several external factors such as congestions, trade stacking and concurrent operations, which can exaggerate the productivity loss when compared with a new construction. In our dataset, we ignore the disruptions caused by all other factors and consider only those caused by a factor related with BIM and/or prefabrication. Thus, our dataset is limited in providing accurate results. To test the relationship between the number of disruptions attributed to a BIM related cause and productivity, we statistically test the correlation between the following:

Workflow disruptions (BIM) vs. Performance ratio: In analyzing the scatterplot, we see weak correlation between BIM disruptions and Performance ratio (r = - 0.335) at a p-value of 0.138 (see *Figure 45*)

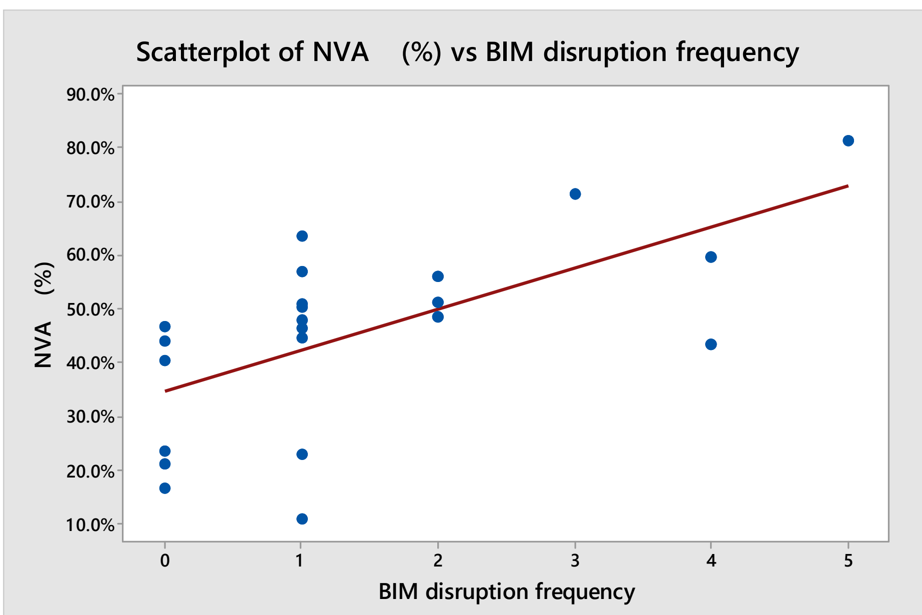
Workflow disruptions (BIM) vs. NVAT: In analyzing the scatterplot, we see moderate positive correlation between BIM disruptions and NVAT. Correlation coefficient value of 0.628 indicates moderate positive correlation (*Figure 46*).

Workflow disruptions (BIM) vs. Rework: The scatter plot shows moderate positive correlation, and correlation coefficient of 0.729, indicating more disruptions cause leads to more rework (*Figure 47*).



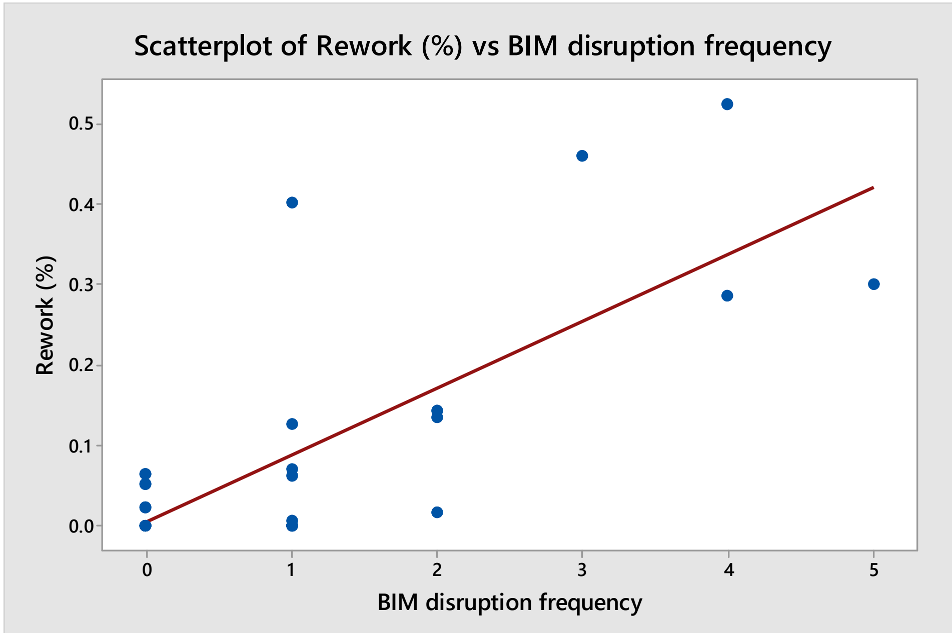
Pearson Correlation = - 0.335, p-value = 0.138, N=22

Figure 45. Workflow Disruption vs. Performance Ratio



Pearson Correlation = 0.628, p-value = 0.002, N=22

Figure 46. Workflow Disruption vs. NVAT



Pearson Correlation = 0.729, p-value = 0.000, N=22

Figure 47. Workflow Disruption vs. Rework

In the next section, we further evaluate the workflow disruptions through a *"root-cause analysis."*

4.3. Root Cause Analysis

To trace the decision-criteria leading up to the BIM disruptions in the labor workflow, we adopted a root-cause analysis approach based on the “5-why” methodology. The author considered each of the six disruptions described in the previous section as the starting point and evaluated them separately. This effort referred a series of interviews with project stakeholders and other internal document reviews. The owners’ BIM Manager provided guidance and validations for our findings. The author shared this data with the trade contractors, owner and model coordinator, as she developed it to receive feedback and gain validation. The author identified the “whys” up to the point until where she had visibility in the process. The author also referred to past literature studies to generalize the “root-causes” in order to protect any proprietary process or method of the owner and trade contractors in the case study.

After identifying the root-causes, the author analyzed whether she could classify the root causes as an aspect of BIM. For the purpose of this research, the author identifies BIM as a process or an activity (modeling) that encompasses three subject areas; geometric information, descriptive information and workflows. The definitions of each is as follows:

- *Geometric Information (G):* Defined as the three-dimensional parametric modeling of geometry representing physical and spatial building components, including factors such as local attributes, spatial attributes and dimensions,
- *Descriptive Information (D):* This includes all functional characteristics and semantic data about the objects, including information such as the type, function, material, cost etc. It constitutes the object, specifications, performance requirements and all the information required to build and maintain the building,
- *Workflows (W):* This aspect refers to the process of planning, implementing and using 3D CAD models with geometric and descriptive information; including, but not limited to acquiring, managing, modifying and updating information.

The first objective of this methodology is to trace the path of decision-making and identify the probable origin of the disruption. The second objective is to reason whether the probable origin is in fact a decision related with BIM or not. The goal is thus to establish how BIM-decisions impact task-level labor productivity. Figure 48 describes the steps followed in the analysis. Figure 49 and Figure 50 outline the root cause analysis.

The analysis shows that we can trace the root-cause of the disruptions attributed to BIM to a combination of factors such as, incomplete BIM use, lack of technology use with BIM (or VDC), lack of supervision, lack of communication/collaboration, improper scheduling and lack of project controls. These factors are aspects of certain decision-factors, which arise during the decision-phases of planning, implementation and management of BIM as identified in Chapter 3 (Table 20). Table 26 relates the disruptions with the BIM planning and management decision-factors.

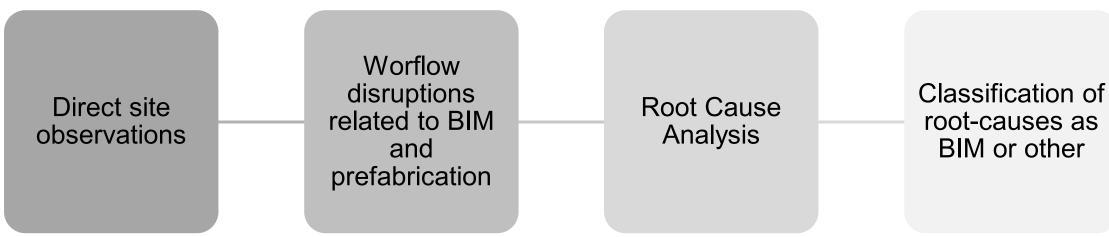


Figure 48. Steps for Analysis of BIM Related Labor Workflow Disruptions

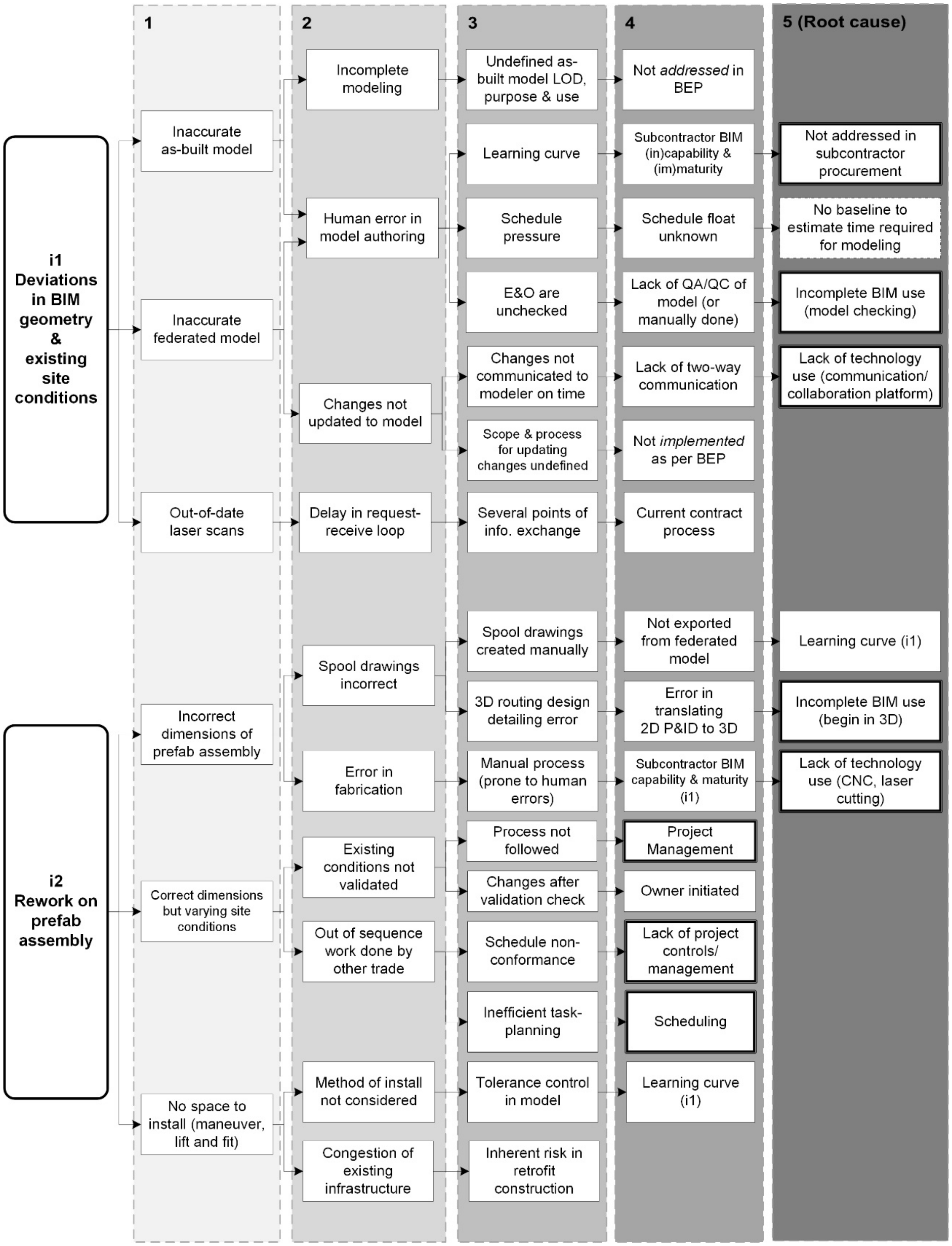


Figure 49. Root Cause Analysis for Disruptions i1 and i2

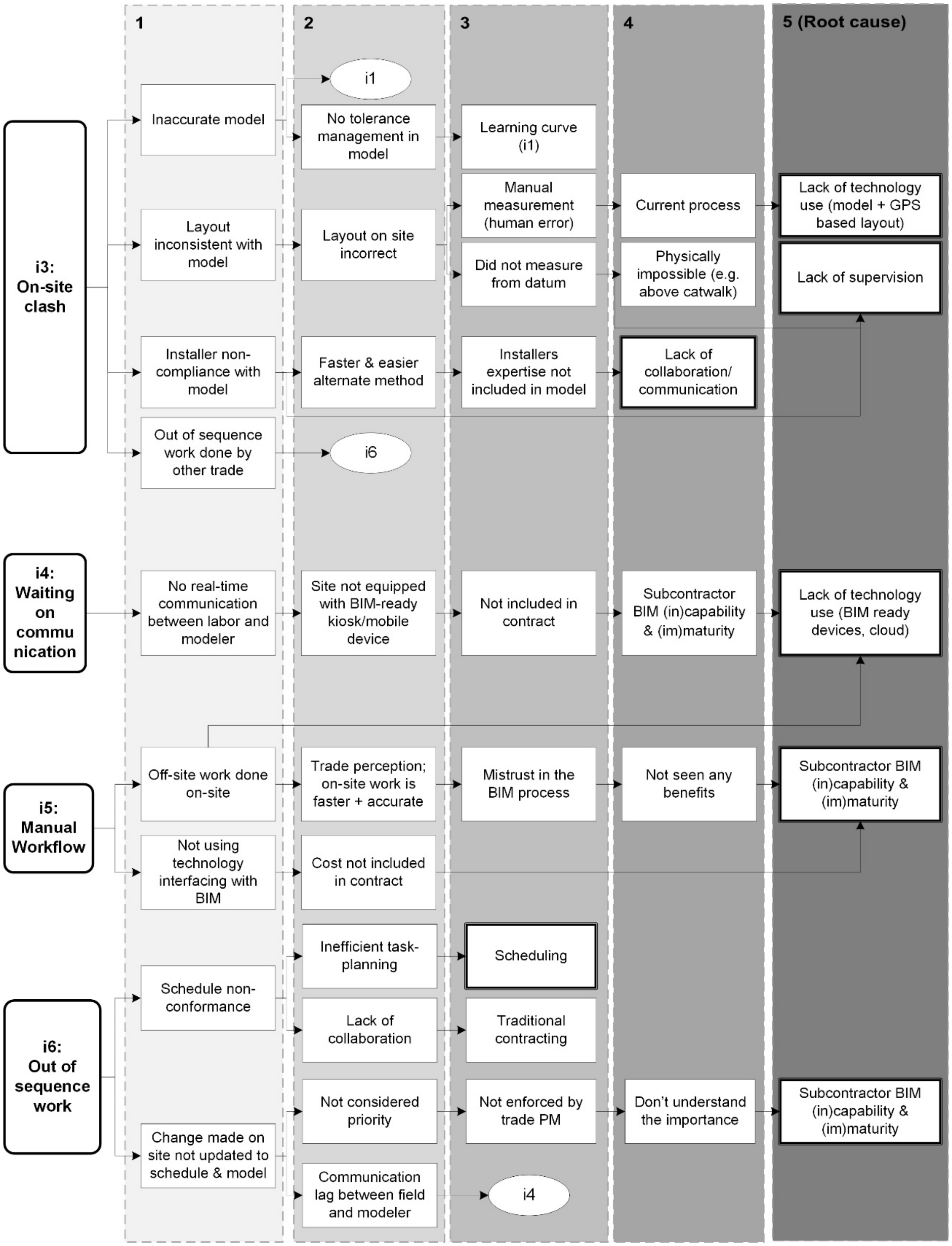


Figure 50. Root Cause Analysis for Disruptions i3, i4, i5 and i6

Table 26

Workflow Disruptions and BIM Planning & Management Decision-Factors

	Disruptions	Root-Cause	Decision-Factors (from chapter 3, Table 20)
i1	Differing BIM and existing site conditions	Not addressed in BIM Execution Plan (BEP)	(P4a)/(P4b) Standards & spec. dev. (Contracts & legal, Execution plan)
		Subcontractor BIM incapability & immaturity	(P3) Contractor selection, (M1) Workforce training & onboarding, (M2) Project team alignment
		No baseline to estimate time for modeling	(I5) BIM schedule
		No model checking	(P4c) Standards & spec. dev. (Quality management plan), (I6) Model authoring workflow
		No communication & collaboration platform	(P4b) Standards & spec. dev. (Execution plan), (M2) Project team alignment (M3) Multiparty communication/collaboration platform
		Not implemented as per BEP	*Project Management, Leadership
i2	Rework on prefabricated assembly	Learning curve	(M1) Workforce training & onboarding
		Lack of technology use	(I12) Field Technology use
		Did not begin in 3D	(P4b) Standards & spec. (BIM execution plan), (P3) Contractor selection, *Project delivery method
		Lack of project control	(I8) Project controls *Site supervision
		Scheduling	*Scheduling
		Project Management	*Project Management
i3	On-site clash	Lack of technology use	(P1) Investment in BIM, (I12) Technology use in field
		Lack of supervision	*Project Management, Leadership
		Lack of communication & collaboration	(P4b) Standards & spec. dev. (Execution plan), (M2) Project team alignment (M3) Multiparty communication/collaboration platform
i4	Waiting on communication	No communication & collaboration platform	(P4b) Standards & spec. dev. (Execution plan), (M2) Project team alignment (M3) Multiparty communication/collaboration platform
i5	Manual workflow	Subcontractor BIM incapability & immaturity	(P1) Investment in BIM & related strategies, (P3) Contractor selection, (I3) Legacy data migration, (I4) Workflow evolution
i6	Revision control	Scheduling Subcontractor BIM incapability & immaturity	* Scheduling (P1) Investment in BIM & related strategies, (111) Revision control/management process

Note.

P = Planning, M = Management, I = Implementation, * = Project decision factor (not BIM related)

Refer to Table 20, pg. 131 for legend for decision-factor

From Table 26, we infer that the root-cause of the workflow disruptions are factors related to decision-factors such as:

1. P1. Investment in BIM and related strategies
2. P2. Contractor selection (BIM capability & maturity)
3. P4. Standards and specifications development (Contract, Execution plan, Quality management)
4. M1. Workforce training & onboarding
5. M2. Project team alignment
6. M3. Multiparty communication/collaboration
7. M4. Technical requirements
8. I3. Legacy data migration
9. I4. Workflow evolution
10. I5. BIM schedule
11. I6. Project controls with BIM
12. I12. Revision control/change management process
13. I14. Technology use in field
14. Project management & leadership, site supervision
15. Scheduling
16. Project delivery method & contracting

A comparison with the decision factors identified in Chapter 3, we find that the workflow disruptions at the labor workface lead to at least three out of four planning factors, four out of five management factors and six out of fourteen implementation factors. In addition, project management factors such as leadership, scheduling and project delivery method and contracting are also identified. The above are decisions made by stakeholders during the front-end planning for BIM as well during the management and implementation of BIM. Most often, the trade contractors are not involved in planning, but are expected to implement and manage the process. The labor workforce, who are the end-user of BIM for design and construction are even further separated from such decision-making.

4.4. Findings

From the case study, we can infer that a retrofit project will have certain inherent complexities including technical, organizational, cultural and functional; creating additional process steps in BIM implementation. We also find that the existing conditions would pose a greater challenge for task-level labor productivity. In order to analyze how BIM use (clash detection, prefabrication) affects labor productivity, the author conducted three types of observations on site; (1) labor-time utilization using a stopwatch method, (2) identification of workflow interruptions attributed to BIM and (3) total value-added output per day. Analysis of 22 data points presents the following correlations (see Table 27):

Table 27

Correlation Statistics (n=22)

X (independent)	Y (response)	r	p-value	Strength
NVAT	VAT	- 0.728	0.000	Strong
Rework	VAT	- 0.745	0.000	Strong
Rework	NVAT	+ 0.650	0.001	Moderate
VAT	Performance Ratio	+ 0.724	0.000	Strong
NVAT	Performance Ratio	- 0.520	0.016	Moderate
Rework	Performance Ratio	- 0.422	0.057	Very weak
BIM disruption	VAT	- 0.671	0.001	Moderate
BIM disruption	NVAT	+ 0.628	0.002	Moderate
BIM disruption	Rework	+ 0.729	0.000	Strong
BIM disruption	Performance Ratio	- 0.335	0.138	Very weak to No correlation

We observe the following from the data analysis:

- There is evidence that supports the owner's initial assumptions that as NVAT reduces, VAT increases and the Performance Ratio increases. Although there are moderate to strong correlations, this does not indicate that increasing VAT will *cause* a better productivity.
- The data shows that if Rework increases, VAT decreases. However, the same dataset shows a moderate positive correlation of Rework with NVAT and very weak to no negative correlation of Rework with Performance Ratio. This could mean that there are other factors contributing to NVAT and productivity such as measuring, moving, consulting drawings etc.
- The strong positive correlation between Rework and BIM disruption frequency indicates that the more the disruptions, the greater the amounts of Rework. However, the data shows weak or no correlation between workflow disruption and performance ratio. A high p-value suggests that there is a high chance that these variables (Disruption and Performance Ratio) are unrelated.
- The limited dataset presents inconclusive evidence. Although the strengths are weak, the directions of the correlations align with our assumptions. A further analysis through a root-cause analysis indicates that the disruptions attributed to BIM can be traced to decision-factors considered during planning, management and implementation of BIM.

4.5. Limitations

The analysis presented in this chapter has certain limitations. The author presents the limitations and suggests steps, which future researchers can take to develop stronger evidence to support their findings:

- The data analysis suffers due to a very small dataset. The inference based on correlation coefficients may not be representative of the actual process. Future research must look at collecting more data.

- The author found a high variation in daily activities, which is a characteristic of the semiconductor / complex / retrofit process. This decreases the chance for identifying predictability in the process. The high variation in daily activities is a fundamental difference between manufacturing and construction. Thus a future research question develops: What strategies can a project team adopt in order to reduce the variation between the construction methods in a semiconductor manufacturing facility and/or retrofit construction projects?
- The method of data collection for the productivity data (labor-time utilization and total daily output) was time-intensive and may not be the most productive use of a researcher's time. The same data could be collected from records maintained by the trade contractors. This is possible if there is closer involvement of the trade contractors and owner and willingness to share actual data.
- Measuring total value added output in a complex highly uncertain retrofit project through a work-study method is a wasteful process for an owner as well. The limitations include unreliable manually collected data and the hours and cost of a full time employee collecting this data. The project type also poses hurdles such as several small projects distributed over a large area and a high variation in daily activities. This leads to a question for future research: *How can we leverage BIM for measuring task-level labor productivity?* A few areas that future researchers can explore are:
    - Resource loading the 3D model with information such as schedule (4D) and cost (5D) to simulate the progress. Pre-conditions for these BIM uses are accurate and reliable geometrical & descriptive information in BIM and experienced personnel to manage the process. Metrics that can be measured from the model are material installed by schedule, earned value (cost) and schedule compliance. A system such as this will provide a quantifiable metric to benchmark performance of trade contractors.
    - Another use of BIM/VDC includes material tracking using barcodes. Although this would warrant an increased cost of investment in RFIDs or barcodes and the supporting systems, a real-time material tracking system will ensure a sound method

of ensuring transparency in the supply chain, reducing waste and thus improving labor productivity.

- The author did not find any past literature to establish a baseline for task-level labor productivity in retrofit construction for semiconductor tool install. The only available information was the MCA and NECA discount factors for productivity loss. The industry can truly realize the potential of BIM and off-site prefabrication if the productivity rates in retrofit projects with complex MEP systems are benchmarked.

4.6. Conclusions

The data presented in this research is not representative of the benefits or limitations of BIM; rather it is an effort to develop knowledge surrounding the practical implementation of the resource in a complex construction environment. This chapter explores the research question; *How does BIM use impact activity-level labor productivity in retrofit construction?* Towards this effort, the author adopts a research method of "work-study" through direct site observations, collects data such as labor-time utilization, value-added output per day, and observes causes for workflow disruptions. The data is analyzed quantitatively through a statistical correlation and qualitatively via a root cause analysis. In conclusion, the author finds that workflow disruptions, which the labor workface attributes to BIM, correlate with rework and reduced value-added time. However, there is not enough evidence to say that these disruptions affect productivity adversely. Also, we find that the said workflow disruptions find their origins in decision-factors considered in the planning, management and implementation of BIM such as; investment in BIM, contractor selection, project team alignment, workflow evolution, data migration, version control and technology use in the field.

From the BIM analysis presented in Chapter 3, the author establishes that project stakeholders involved in decision making related to BIM planning, management and implementation, have different set of expectations or utility from BIM and hence, identify BIM-value differently. In addition, in an organization that is beginning to adopt BIM, not all factors of implementation are considered during planning. An incomplete understanding and consideration of these factors lead to disruptions in the construction workflow at the labor workface. The author thus hypothesizes that:

“A differing value-system for BIM ultimately manifests in the form of unreliable and inaccurate information causing variability in the workflow at the labor workface.”

The next chapter discusses the design and validation of a BIM-value framework, relating stakeholders with their relative value for BIM, the decision-factors for the planning, management and implementation of BIM and the potential impact of those decisions on labor productivity.

CHAPTER 5

THEORY DEVELOPMENT: A BIM-VALUE FRAMEWORK

The previous chapters presented an extensive literature review and an in-depth case study of BIM implementation by the construction supply chain of a semiconductor manufacturing facility and the immediate impact of the BIM use on task-level labor productivity. This chapter serves as the summary of the findings (Sections 5.1 and 5.2) and develops a framework to answer the research question (see Figure 51):

R2: **How** can an owner facilitate the planning, management and implementation of BIM, such that task-level labor productivity is positively impacted?

Towards this effort, the author presents a BIM-value framework in Section 5.3, to formalize the theory developed from the research i.e. a differing value-system for BIM ultimately manifests in the form of unreliable and inaccurate information causing variability in the workflow at the labor workface. The theory can be generalized into the two hypotheses; H1: *the stakeholders of a construction project value the BIM-aspects (i.e. geometrical information, descriptive information and workflows) differently and,* H2: *the accuracy & reliability of geometrical information is critical for effective labor productivity when using BIM and prefabrication in retrofit construction.* The BIM-value framework was adapted in the form of a survey to gauge the response of industry members.

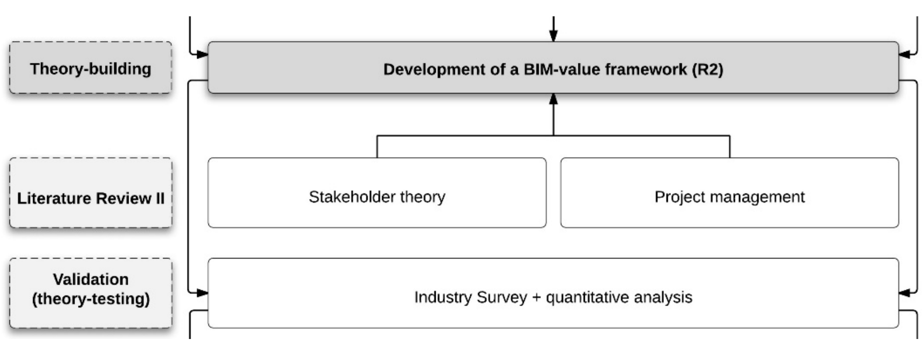


Figure 51. Research Method for BIM-Value Framework Development

5.1. Findings from BIM Analysis

This section summarizes the findings from the literature review and the BIM case study. Section 5.1.1 identifies the stakeholders of the BIM process, their value for BIM and the decision-factors in BIM planning, management and implementation, for which they are typically responsible. Section 5.1.2 further elaborates on the decision-factors and identifies the *criteria,* which guide or support these decision-factors, as found through past research and the case study. These criteria are then classified as a BIM-aspect to emphasize the decision foci as regards to the definition of BIM.

5.1.1. Stakeholders of BIM

In the case of construction, the project is a temporary organization and the stakeholders include the prime beneficiary of the project (owner), project participants (architect, engineer, construction manager, contractors, subcontractors and vendors) and the greater community and environment affected by the project. This research defines **stakeholders of the BIM process** as *any group or individual, directly or indirectly involved in supplying, creating, managing and using information in any form or format that is included in project documentation for the ultimate purpose of meeting the objectives of BIM use as defined by the owner.* We find that the utility of BIM use or the **BIM-value** defined by the stakeholders vary based on their immediate scope of work and the desired outcome.

This research classifies the phases of BIM as *planning, management and implementation* (including use). A fourth criterion of *maintenance* of information must also be considered, but the scope is outside the boundaries of this research. From a thorough analysis of past literature and case study, the author identifies the **decision-factors driving the adoption of BIM** in each of the above-mentioned phases. The case study reveals that in this particular case study, the emphasis was on *process* integration and less on the integration of people and technology. This finding corresponds with past research that have found organizational divisions in BIM processes (Dossick & Neff, 2010) and have further emphasized on the cultural adaptation as a critical factor for BIM adoption (Dossick & Neff, 2010; Gu et al., 2010; Won et al., 2013). Table 28 identifies the relation between the stakeholder, their BIM-value and their decision-factors for planning, management and implementation of BIM.

In enabling the use of BIM, the knowledge and skill of each party is required for the overall success of the project. Hence, each party naturally becomes a stakeholder in the BIM process. We hypothesize that in a BIM process, “each process is a customer to the previous process.” The information development can be additive or concurrent depending on the delivery method, timing of engagement and the ability of the disparate tools to play together. The success of BIM use is determined by the meeting of the objectives for which it is being used. From Table 28, we can infer that the expected value from BIM for the five stakeholder groups depends on the value BIM adds to their business process and their scope of work in the project. We also find that there are overlapping decision-factors for which they are responsible. Decision-making is thus collaborative and must consider the needs of the stakeholders who are using BIM.

Table 28

Stakeholder BIM-Value and Decision-Factors

Stakeholder (from Ch. 3, Table 16, 21)	**BIM-Value** (from Ch. 3, Table 16, 21)	**Primary Decision-Factors** (from Ch. 3, Table 20)
Owner: "The owner, whether public or private, is the instigating party that gets the project financed, designed and built" (Sears, Sears, & Clough, 2010)	• Financial gain (cost, schedule, performance, quality)	• P1. Investment in BIM • P2. BIM strategy • P3. Contractor selection • P4. Standards & spec. dev. *Risk transfer to project team* • I1. Existing conditions data capture
Architect-Engineer: "The architect-engineer is the party or firm that designs the project" (Sears et al., 2010) by applying design and engineering principles to convert resources to meet a stated objective.	• Quality of design • Analysis of design • Improved design schedule • Improved communication • Documentation	• P4. Standards & spec. dev. • M1. Workforce training • M4. Technical upgrades • M5. Risk management • I2. Verification & validation of data • I3. Legacy data migration • I4. Workflow evolution
Construction Project Management "Construction Management is a professional management practice applied to construction projects from project inception to completion for the purpose of controlling time, cost, scope and quality" (CMAA, 2011). The participants include the construction manager, the program manager and the contractors.	• Improved const. schedule • Multiparty communication • Predictability (cost, time, performance, risk) of decisions • Spatial coordination • Efficient management process	• P4. Standards & spec. dev. • M1. Workforce training • M2. Project team alignment • M3. Multiparty communication • M4. Technical upgrades • M5. Risk management • I2. Verification & validation of data • I3. Legacy data & workflow migration • I4. Workflow evolution • I5. BIM schedule development • I7. Resource forecasting • I8. Project controls
BIM Modeler *: Resource responsible for model authoring, content development, model management, collaboration and coordination with multiple disciplines *(* employed by the A/E, CM or trade. Considered separately to highlight significance of role)*	• Efficient modeling process • Accurate, reliable and timely availability of information	*N/A* *N/A* • I2. Verification & validation of data • I3. Legacy data migration • I4. Workflow evolution • I6. Model authoring workflow • I9. Coordination • I10. Fabrication drawing creation • I11. Revision control
Construction (trade) installers Performs tasks involving physical labor at job sites, specifically cutting and joining of materials, measuring, layout and installation of mechanical, electrical and process piping	• Accurate, reliable, timely and complete information • Error free installation drawings • Reduced rework	*N/A* *N/A* • I11. Revision control • I12. Field Technology use • I13. Field Quality Management

5.1.2. Decision-Factors and Criteria

Good decision-making in AEC requires informative formulation *i.e.* extensive and balanced inputs of decision contents (alternatives, predictions and criteria), clear and flexible evaluation *i.e.* understanding the predicted performance of an alternative against a decision criteria, and quick re-formulation *i.e.* quicker alternative generation to obtain better value from the decision-making process (Kam & Fischer, 2004). Kunz & Fischer (2012) introduce the concept of product, organization and process (POP) modeling as an approach for decision-making. The POP model emphasizes aspects that can be designed and managed by the stakeholders *i.e.* "the *product*, the *organization* that will define, design, construct and operate it, and the *process* that the organization teams will follow" (Kunz & Fischer, 2012). Succar (2009) proposes a tri-axial knowledge model for BIM implementation comprising of "BIM fields" identifying stakeholders and deliverables in sub-groups of technology, policy and process; "BIM stages" outlining implementation maturity levels; and "BIM lenses" identifying the depth and breadth of inquiry. Jung & Joo (2011) propose a similar BIM framework for practical implementation, which incorporates "BIM technologies in terms of property, relation, standards, and utilization across different construction business functions throughout project, organization, and industry perspectives." Gu et al. (2010) propose a "collaborative BIM decision framework" to facilitate BIM adoption by addressing four key aspects; defining scope, purpose, roles, relationships and project phases, developing work-process roadmaps, identifying technical requirements for BIM and, customization of the framework based on skills, knowledge and capabilities. While all the above-mentioned frameworks outline decision-factors for successful BIM adoption, Won et al. (2013) argue that "too many considerations have been proposed by previous studies", without prioritizing the factors for early adoption. Through an industry survey, they found that, "nontechnical organizational readiness was considered relatively more urgent than technological readiness" especially in the early stages of BIM adoption.

This dissertation identified 22 factors for BIM adoption from an extensive literature review of past implementation frameworks and strategies as well as the case study as shown in Table

20. In Table 29, Table 30 and Table 31, we identify the *criteria* for decision-making. It is generally acceptable to assume that the *criteria* common to each of these factors are cost-benefit, resource (time, material, personnel) requirement and risk impact for each of these decisions factors. The following tables are a non-exhaustive list of additional *criteria* that drive the decision-making process. Further, we identify the BIM-aspect *i.e.* geometric information (G), descriptive information (D), and workflows (W), which are considered during the phase of decision-making. From the analysis, we find that while all BIM-phases address all three BIM-aspects, the emphasis on the workflows is more critical than geometrical and descriptive information.

Table 29

Decision Criteria for BIM planning

Decision-Factors	**Decision-Criteria** *(from Chapter 2 and Chapter 3)*		**BIM-Aspects**
	Literature Review	*Case Study*	
P1. Investment in BIM	Hardware/software/IT infrastructure requirements, other technology, ROI (Barlish & Sullivan, 2012; Giel & Issa, 2013)	Infrastructure, cost-benefit	N/A
P2. BIM strategy	Project type, purpose, goals, uses, expected outcome, limitations (CIC, 2010; Gu et al., 2010)	Retrofit tool install, off-site prefabrication	N/A
P3. Contractor selection	Capability & maturity, experience (Kam et al., 2013; NIBS, 2012; Succar et al., 2012), Project delivery method & contracting	*Not defined*	D, W
P4. Standards & spec. development a. Contract documents	Scope of work, roles & responsibilities, performance metrics, deliverables, legal, BIM/CAD standards (CIC, 2010, 2013a; NIBS, 2012)	*See Chapter 3, section 3.2.1*	G, D, W
b. Execution plan	Information exchange, Level of Development/Detail of model, software compatibility, collaboration & communication, existing conditions data capture & processing, legacy data management & integration, cultural acceptance/change (CIC, 2010, 2013; Gu et al., 2010; NIBS, 2012; Volk et al., 2014)	*See Chapter 3, section 3.2.1*	G, D, W
c. Quality management		Model vs. physical tolerances	G, W

G = Geometric Information, D = Descriptive Information, W = Workflows

Table 30

Decision Criteria for BIM Management

Decision-Factors	**Decision-Criteria** *(from Chapter 2 and Chapter 3)*		BIM-Aspects
	Literature Review	*Case Study*	
M1. Workforce training	New software, technology & workflows (Khosrowshahi & Arayici, 2012), Learning curve, existing knowledge (McGraw-Hill Construction, 2012a)	*Not defined*	G, D, W
M2. Project team alignment	Delivery method, time of engagement, scope of work, project management	*Not defined*	W
M3. Multiparty communication	Communication platform, collaboration platform, BIM-server technical requirements (Lu et al., 2011)	*Not defined*	W
M4. Technical upgrades & maintenance	Cost of investment, purpose & use, software types & file size	*Not defined*	N/A
M5. Risk management	Scope of work, impact analysis	*Not defined*	N/A

G = Geometric information, D = Descriptive information, W = Workflows

Table 31

Decision Criteria for BIM Implementation & Use

Decision-Factors	**Decision-Criteria** *(from Chapter 2 and Chapter 3)*		BIM-Aspects
	Literature Review	*Case Study*	
I1. Existing conditions data capture	Manual process: Data capture, data processing, semantic labeling & BIM modeling (Volk et al., 2014), Automated process: Geometric modeling, object recognition and object relationship modeling (Tang et al., 2010)	Resolution, equipment cost, processing time	G, D, W
I2. Verification & validation of data	Technology use (laser scanning, photogrammetry): accuracy, resolution, equipment cost, required skill, portability, spatial-environmental challenges (Klein, Li, & Becerik-Gerber, 2012)	Trust in information, frequency of change	G, D, W
I3. Legacy data migration	Project scoping, data security, data quality, flexibility, methodology (extraction, migration, integration), business engagement, legacy decommissioning (Morris, 2012)	*Not defined*	G, D, W

Decision-Factors	Decision-Criteria *(from Chapter 2 and Chapter 3)* Literature Review	*Case Study*	BIM-Aspects
I4. Workflow evolution	Adaptability, process-improvement (effectiveness, efficiency, quality, communication etc.) (Tsai et al., 2014), risk and impact assessment, learning curve, acceptance	*Not defined*	W
I5. BIM schedule development	Time to model (Leite et al., 2011), Integration with Last Planner System	*Not defined*	W
I6. Model authoring workflow	BIM use, data input, data output, data reuse, creation of "families", model library, parametric modeling, rules-based modeling, layer creation, object ID creation, semantic labeling, level of development/detail (Eastman et al., 2011; Monteiro & Poças Martins, 2013), collaborative design & modeling (Kassem, 2014)	Measure & model, information reuse, creation of families, application of rules	G, D, W
I7. Resource forecasting		Use, data input, data output	G, D, W
I8. Project controls	Cost/benefit, interoperability, information exchange, relational dependencies, real-time access, use of complementary technologies	*Not defined*	W
I9. Coordination	BIM level of detail and development, retrieved clashes vs. relevant clashes (Leite et al., 2011) Goal setting, team organization, metrics to track progress, technical logistics to setup coordination, schedule for coordination, tracking performance (Khanzode et al., 2007) Knowledge of team in locating clashes & perform analysis on context, cause & severity of clash (Wang & Leite, 2014)	Clash prioritization	G, D, W
I10. Fabrication drawing creation (BIM to prefab)	Level of detail/development, Level of accuracy, fabrication schedule, software compatibility, material tracking	Fabrication method (manual or automated), Percentage of prefab	G, D, W
I11. Revision control	Conformance to model, supervision, time lag in change update, impact assessment	*Not defined*	W
I12. Field Technology use (BIM to VDC)	Model-based layout: addition of control points in 3D model, line of sight		G, D, W
I13. Field Quality management	Accuracy specifications, tolerance Automated: Deviation analysis using laser scans (technology not completely developed) (Anil, Tang, Akinci, & Huber, 2013)	Tolerance definition, Risk-impact	G, D

G = Geometric Information, D = Descriptive Information, W = Workflows

The author identified the BIM-aspects mentioned in Table 29, 30 and 31 based on the definition of the criteria for each decision-factor and experience. Adding these values, we find that importance of geometric information, descriptive information and workflows balance as 3:3:4 for BIM-planning, 1:1:3 for BIM-management, and as 3:3:4 for BIM-implementation.

5.2. Findings from Productivity Analysis

5.2.1. BIM-disruptions, Decision-Factors and Productivity

During the case study, we found the occurrence of workflow disruptions at the labor workface, which the labor workface attributed to the BIM process. We classified them into six types based on their immediate cause; (1) differing BIM and site condition, (2) rework, (3) on-site clash, (4) waiting on communication, (5) manual workflow and (6) version control. A root cause analysis traced these disruptions to decision-factors during the planning, management and implementation of BIM as well as project decision factors such as project management & leadership, scheduling and the project delivery method (chapter 4, Table 26). The factors are identified below:

1. P1. Investment in BIM and related strategies
2. P3. Contractor selection (BIM capability & maturity)
3. P4. Standards and specifications development (Contract, Execution plan, Quality management)
4. M1. Workforce training & onboarding
5. M2. Project team alignment
6. M3. Multiparty communication/collaboration
7. M4. Technical requirements
8. I3. Legacy data migration
9. I4. Workflow evolution
10. I5. BIM schedule
11. I6. Project controls with BIM

12. I11. Revision control/change management process
13. I12. Field Technology use
14. Project management & leadership, site supervision
15. Scheduling
16. Project delivery method & contracting

From this analysis we can conclude that addressing and managing the above 16 factors during the planning, management and implementation of BIM, has the potential of ensuring reduced workflow disruptions at the labor workface. Further, controlling the variability at the labor workface can improve labor productivity by reducing rework and improving predictability.

5.2.2. BIM-aspects and Retrofit Construction

Three out of the six workflow disruptions i.e. deviations in BIM and site condition, rework on prefabricated assembly, and clash on site are related to the accuracy of the geometrical information in the 3D model. The primary cause for these issues is inaccurate dimensions of the model because of human errors, inaccurate information or inaccuracies in the capture of existing conditions (Figure 49 and Figure 50). We can infer from these indicators that geometrical accuracy is critical for retrofit construction, especially when prefabrication is being used as a production method. However, more evidence is required to draw a conclusive connection. Future research must look at whether the level of geometrical accuracies in the 3D model has a correlation with labor productivity.

5.3. The BIM-value Framework

In previous chapters, we discuss the concept of *"stakeholder value of BIM,"* which states that the quality (reliability, accuracy, and timeliness) of information received, created and shared by the stakeholders will determine the overall success of using BIM on a project. Compiling the

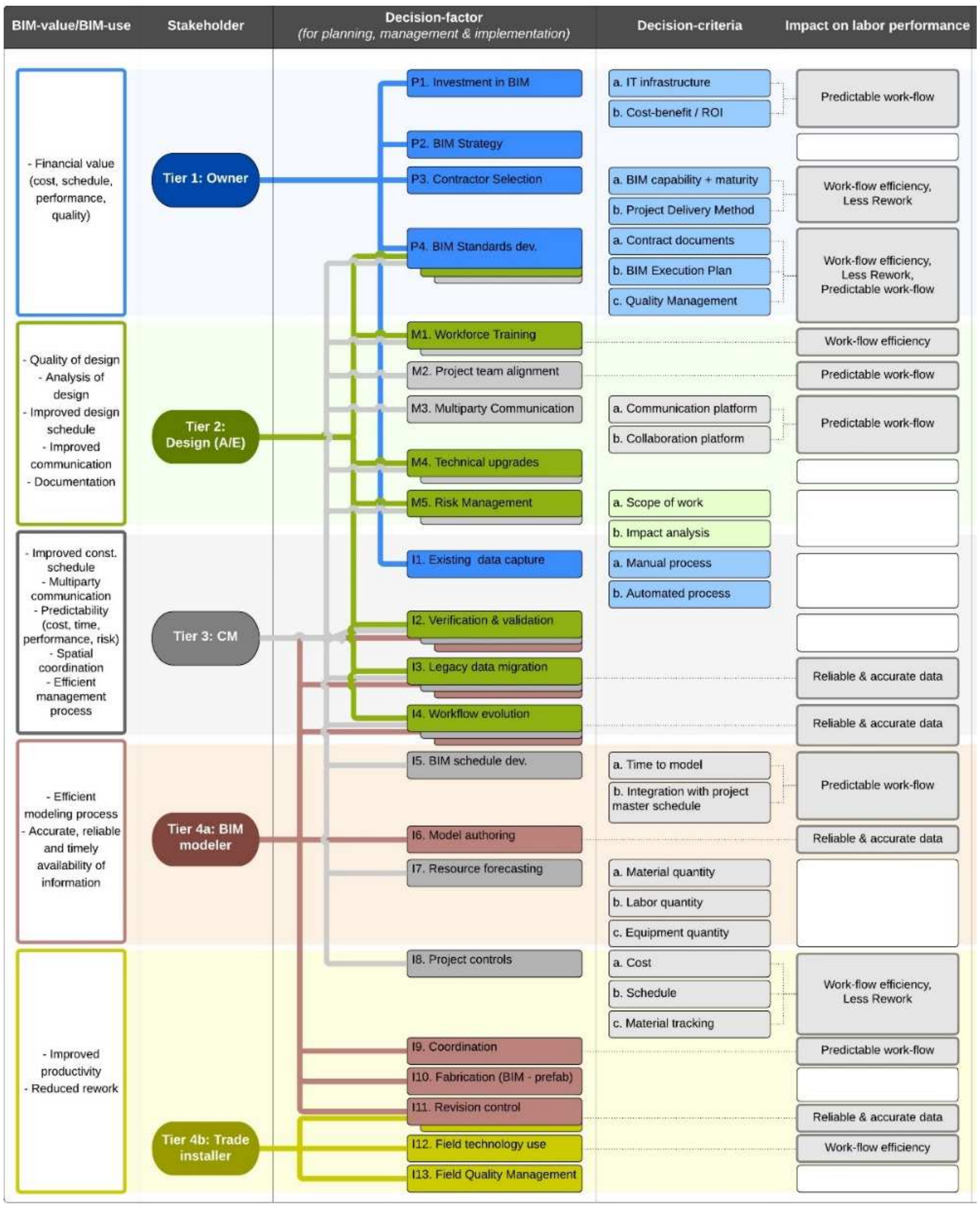


Figure 52. BIM-value framework (see Appendix F for larger version)

data presented in Tables 28, 29, 30 and 31, this research presents a “BIM-value Framework” which relates the BIM stakeholders with their relative value for BIM, the decision-factors for the planning, management and implementation of BIM and the potential impact of those decisions on labor productivity. Figure 52 is the BIM-value framework.

5.3.1. Validating the BIM-value Framework

The author presents a BIM-value framework to formalize the theory developed from the research, which states:

H1: *The stakeholders of a construction project value the BIM-aspects (i.e. geometrical information, descriptive information and workflows) differently,*

H2: *The accuracy & reliability of geometrical information is critical for effective labor productivity when using BIM and prefabrication in retrofit construction.*

In order to test these hypotheses, the author conducted an industry survey based on the BIM-value framework. The author designed and hosted the survey on a commercial website called www.qualtrics.com. The author distributed a link to the survey via email to 65 individuals from architecture, engineering, construction and owner organizations. The survey was open from October 15, 2014 to December 31, 2014. During this time, the survey was accessed by 45 individuals and the completed by 40 individuals, thus the effective response rate is 61.54% and the margin of error is 9.68% at a 95% confidence interval. Table 32 provides a summary of the type and number of responses by category. Responses were recorded anonymously (Qualtrics.com recorded the responses by capturing the IP addresses of the respondents). The survey was based on a Likert-type scale from 1 to 7, with 1 being least important and 7 being the most important. The option for not selecting a response was also provided. In addition, the respondents had the choice of providing additional feedback about their BIM use by entering text. The survey was designed to take approximately 15 minutes of an individual’s time. The survey along with the IRB compliance letter is included in Appendix G.

Table 32

Survey Response Data

	Respondent Category	Number of Responses	%age of Total
1	Decision makers in planning, procurement, contracting, strategic development and financing (Tier 1: Owner)	10	25%
2	Decision makers responsible for design and engineering information input (Tier 2: Design (A/E))	3	8%
3	Decision makers involved in the day to day management, implementation and coordination (Tier 3: CM)	21	53%
4	Personnel involved in drafting and modeling of 2D and 3D, fabrication, construction & installation drawings (Tier 4: Modeler)	6	15%
	Total	40	100%

5.3.2. Likert-scale Data Analysis

The survey was designed to direct the respondents to specific questions based on their role type. The same set of questions were asked three times emphasizing the importance of geometrical information, descriptive information or workflow for the particular decision factor identified in the question on a scale from 1 (not important at all) to 7 (extremely important). Table 33 highlights a few sample questions (Complete list is included in Appendix G).

In order to test hypothesis **H1**, the author conducted an analysis to find the variance in the medians of the responses *within* the stakeholder groups and *between* the stakeholder groups. The author uses a statistical test known as the Friedman Test for non-parametric data types to test the variance within the stakeholder groups. The Friedman test is a non-parametric test used to determine whether there are any statistically significant differences between the distributions of three or more related groups. The groups contain the same cases (*e.g.,* stakeholders) in each group and each group represents a repeated measurement (*e.g.,* descriptive information, geometric information & workflow) on the same dependent variable (*e.g.,* contractor selection, workforce training). The null hypothesis (H_0) is that the level of importance assigned to the BIM-aspects (*geometrical information, descriptive information and workflows),* by the respondents are the same. If the p-value is small, we can reject the idea that all of the differences are due to random sampling, and conclude instead that at least one of the treatments or BIM-aspects (G, D, W) differs from the rest. If the p-value is large, the data does not give us any reason to conclude that the overall medians differ. This is not the same as saying that the medians are the same. We have no compelling evidence that they differ.

We find that for all but two decision-factors the p-value is greater than 0.05, thus indicating that the respondents *within* the stakeholder groups have provided similar weights to the importance of the three BIM-aspects for the decision-factors, i.e. they value the three BIM-aspects similarly during decision-making. The p-value is less than 0.05 for two decision factors, (P1) BIM Investment for Owner and (P8) Project Controls (schedule) for CM. The author suggests future research to further evaluate the decision-making method for these particular factors.

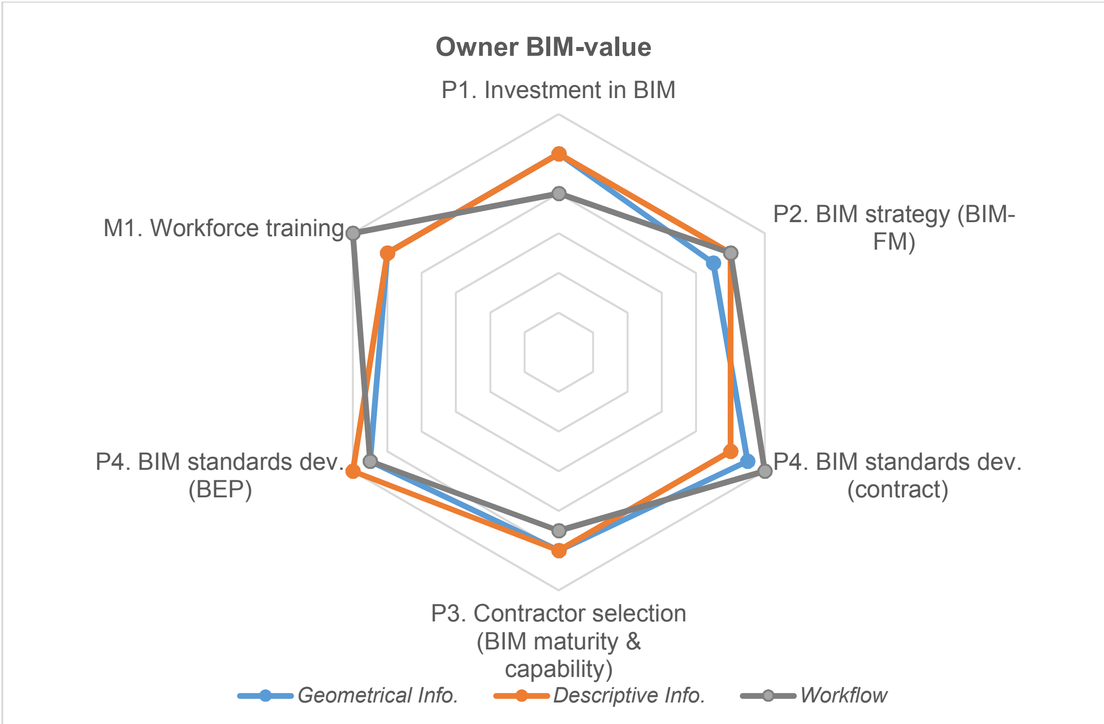
To evaluate the responses between the *stakeholder* groups, the author plotted the median values from the responses on a radar graph as shown in Figure 53 & Figure 54. We observe that Owners and Construction Managers consistently put more emphasis on the importance of descriptive information (orange color line in graph) and the management of that information as well as the work-processes (grey color line in graph) for BIM planning and development. In some cases such as Workforce Training, Resource Forecasting and Project Controls, the relative value of BIM workflows and processes is more. While on the other hand, for BIM Modelers, the relative value of geometrical information (blue color line in graph) seems more, especially for decision factors such as Model Authoring, BIM to Prefabrication, Existing data capture and Revision Control. Although this is a visual analysis, it provides us with the motivation to investigate the relative value of the BIM-aspects as defined by the stakeholder groups. Future research must consider statistically validating this hypothesis.

Thus, from this analysis, the author concludes that the BIM-aspects (i.e. geometrical information, descriptive information and workflows) are valued *similarly* by stakeholders *within* their groups (i.e. Owner, A/E, CM and Modeler), but may *differ* when they are considered *between* the groups (i.e. Owner vs. Modeler, CM vs. A/E, CM vs. Modeler).

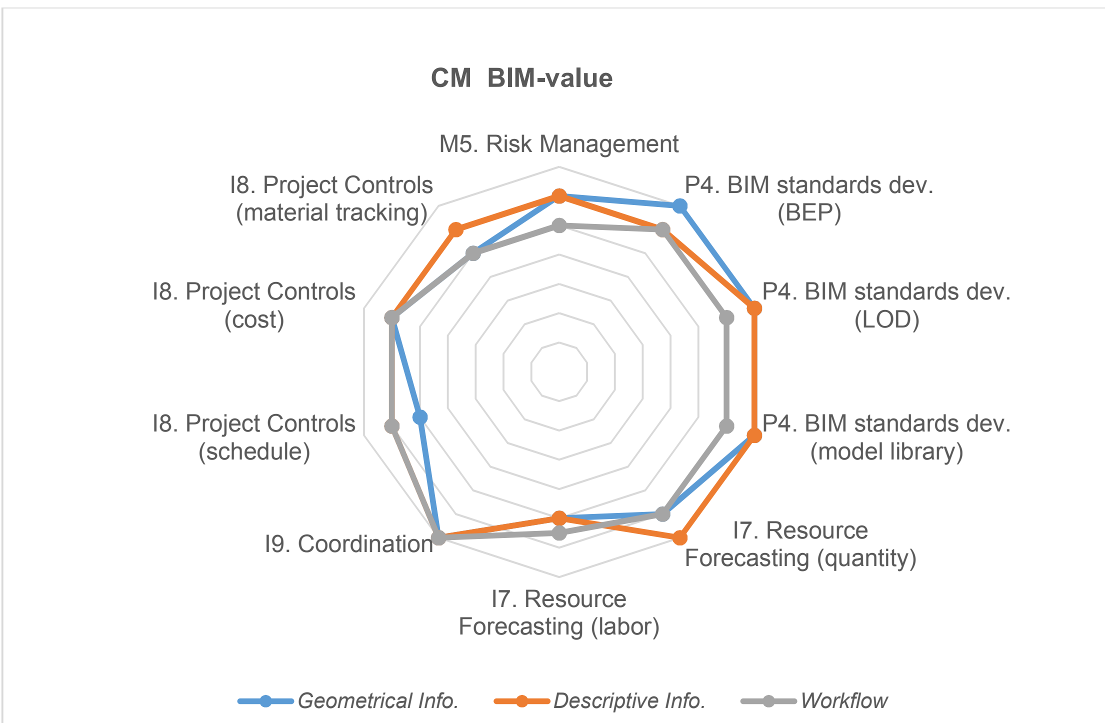
Table 33

Sample of Responses

Questions/Decision-Factors	Geometrical Information	Descriptive Information	Workflows	p-value
	Median	Median	Median	
P1. Investment: *Is geometrical accuracy/information management/ workflows, important criteria when planning for investment in BIM software/hardware? (n=9)*	6.00	6.33	5.66	*0.029*
P3. Contractor Selection: *How important is the criterion for measuring the contractors plan for managing geometry/ information/ workflows in BIM during procurement of contractors? (n=10)*	6.08	6.25	5.91	0.368
P4. BIM standards dev. (Contract): *Is the contractors plan for managing information in BIM/ geometrical accuracy of the 3D model/ 3D model workflow, an important criterion in the contract? (n=10)*	6.50	6.33	6.66	0.156
M1. Workforce Training: *What is the level of importance of an education in accurate 2D/3D modeling/information management/ BIM work processes? (n=10)*	6.50	6.50	6.50	0.401
I6. Model Authoring: *How important is a standard BIM workflow/ geometry & dimensions/ reliable project information when creating detail drawings?*	6.00	6.00	6.00	0.135
I7. Resource forecasting (labor): *What is the level of importance of model geometry/ BIM workflow/descriptive information in BIM for forecasting labor headcount requirements? (n=13)*	5.66	5.33	5.00	0.313
I8. Project Controls (schedule): *How important is reliable information in BIM/standard BIM workflow/accurate model geometry for schedule control? (n=13)*	6.00	6.00	5..00	*0.011*
I9: Coordination: *How important are reliable information in BIM/ accurate model geometry/ standardized workflows when performing clash detection? (n=13)*	7.00	7.00	7.00	0.646
I10. BIM to prefab: *How important is the reliability of information/ accuracy of geometry/ BIM workflow when automating spool drawings or fabrication drawings from BIM for prefabricating at an offsite location?*	6.00	6.00	6.00	0.156
I11. Revision Control: *How important is geometrical tolerance/ information management/ workflow when managing changes in the model? (n=5)*	5.00	5.00	5.00	0.867

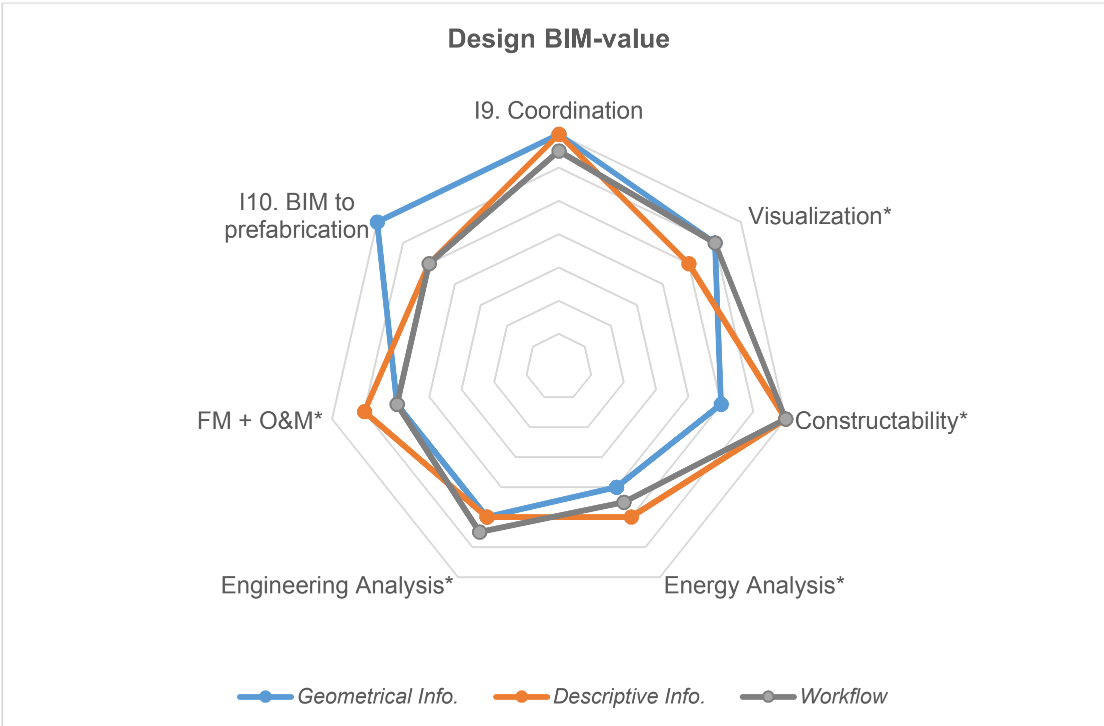


n = 10

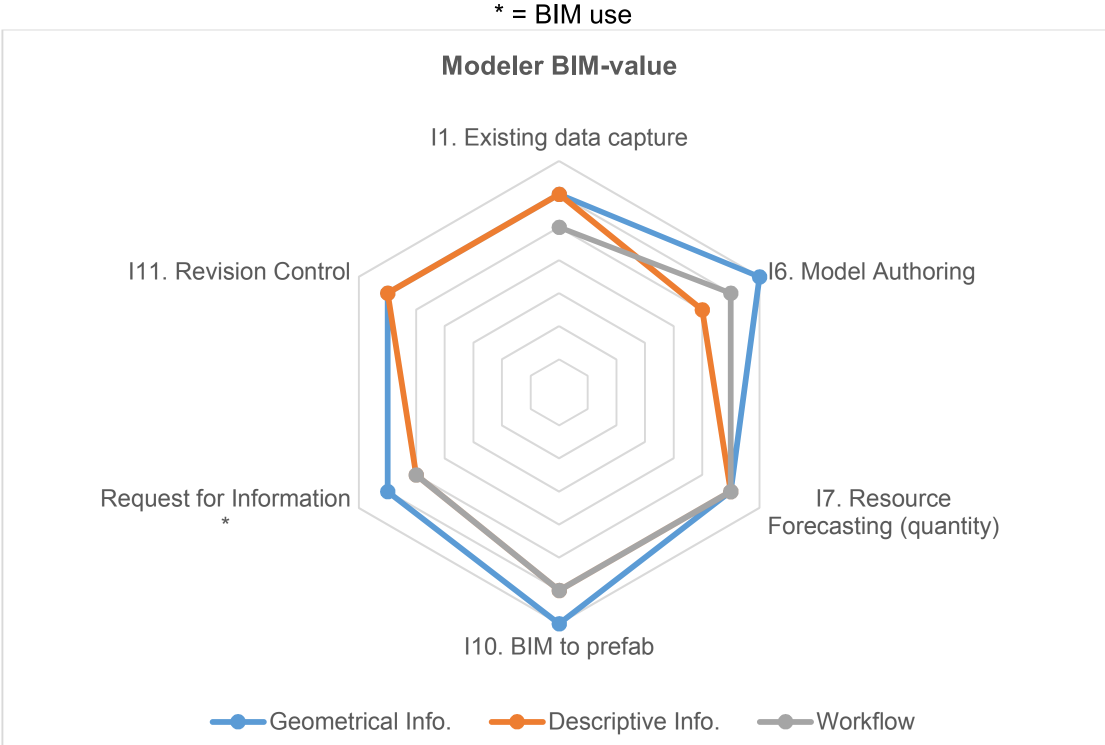


n = 21

Figure 53. Median Values from Likert-Scale Data (Owner & CM)



n = 3
* = BIM use



n = 6
* = BIM use

Figure 54. Median Values from Likert-Scale Data (Designer/AE & Modeler)

5.3.3. Qualitative Data Analysis

As part of the same survey, the respondents were encouraged to provide subjective feedback by defining the value of BIM in their own words. Responses were received from 7 owners, 3 architect/engineers, 14 construction management personnel and 5 BIM modelers. The author follows a qualitative research method approach of focused coding and thematic coding to analyze the responses. Three themes were found in the responses, which were the answers to the questions:

1. What is BIM?
2. The respondents expected value from BIM
3. The requirements for BIM implementation from the perspective of the respondent

Table 34 presents the summary of the analyses. We find that the findings are consistent with the findings from literature and case study as outlined in the BIM-value framework. The detailed analysis is presented in Appendix G.

Table 34

Qualitative Analysis of BIM-Value Survey Responses

Stakeholder	What is BIM?	BIM-value	Requirements

Tier 1: Owner	Program
	Tool
	Process
		- Better project outcome
		  - Reduce cost
		  - Reduce schedule
		  - Improve quality
		- Informed decision-making
		- Improve productivity
		  - Better coordination
		  - Accurate installation
		  - Better sequencing
			- Investment (P1)
			- Standards (P4)

Tier 2: Design	Tool	- Database - Intelligent modeling	- Owner involvement

Tier 3: CM	Tool/Technology
	Process
	Program
		- Design
		  - Early detection
		  - Analysis
		  - Revision
		  - Detection of errors
		- Management
		  - Project Controls
		  - Coordination
		- On-site/Install
		  - Visualization
		  - Less waste
		  - Less rework
		  - Safe install
		  - Reduced install time
		  - Reduced headcount
		  - Prefabrication
			- Front-end planning
			- Technology upgrades
			- Initial investment (P1)
			- Interoperability (P4)
			- Standards (P4)
			- Communication (M3)
			- Strategy (P2)
			- Accurate information

Tier 4a: Modeler	Process	- Reduced time - Reduced cost - Reduced headcount - Coordination - Means & methods	- Stakeholder buy-in - Reliable information - Standard workflow - Information sharing - Complete adoption

5.4. Conclusion

This chapter presents a BIM-value framework, which was developed based on the findings from an extensive literature review and case study. The BIM-value framework relates the BIM stakeholders with their relative value for BIM, the decision-factors for the planning, management and implementation of BIM and the potential impact of those decisions on labor productivity. This chapter also identifies specific decision-criteria for each of the decision-factors for the planning, management and implementation of BIM. As a part of future research, the author proposes developing the BIM-value framework further as a risk identification tool for BIM adoption and implementation.

The BIM-value framework served as the basis of an industry-wide survey to validate the theory developed from the research, which the author hypothesizes as:

> ***H1:*** *The stakeholders of a construction project value the BIM-aspects (i.e. geometrical information, descriptive information and workflows) differently,*
>
> ***H2:*** *The accuracy & reliability of geometrical information is critical for effective labor productivity when using BIM and prefabrication in retrofit construction.*

The Likert-scale based survey revealed that stakeholders value the three aspects of BIM almost equally within the stakeholder groups. However, there is a slight difference in how the BIM-aspects are valued between the stakeholder groups (H1). The research also identified the primary cause for the workflow disruptions as inaccurate dimensions of the model because of human errors, inaccurate information or inaccuracies in the capture of existing conditions. We can infer from these indicators that geometrical accuracy is critical for retrofit construction, especially when prefabrication is being used as a production method, which is the second hypothesis (H2). However, there is not enough data or evidence to validate hypothesis H2 and future research must explore this question.

CHAPTER 6

CONCLUSION & FUTURE RESEARCH

This research provides a case study analysis of BIM use for retrofit tool installation at a semiconductor manufacturing facility and an analysis of BIM impact on task-level labor productivity. The productivity study analyzes the correlations between labor time utilization (VA and NVA time), performance ratio (estimated/actual productivity) and the frequency of workflow disruptions attributed to BIM. A root-cause analysis relates the workflow disruptions to critical decision-factors during the planning, management and implementation of BIM. Grounding the analysis in a comprehensive literature review, observations from the case study and labor productivity studies, the author hypothesizes that the *varying stakeholder value for BIM and BIM-aspects manifests in the form of workflow disruptions at the labor workface.* This theory develops into a BIM-value framework, which can be used by decision-makers involved in the planning, management and implementation of BIM as a risk identification tool and/or as a way of analyzing the impact of their decisions on BIM use and productivity. An industry survey gathers input on the BIM-value framework to assess the stakeholder-value for the three BIM aspects (geometrical information, descriptive information and workflows) at the time of decision-making. The research arrives at the following conclusions:

- The expected value from BIM for the five stakeholder groups depends on the value BIM adds to their business process and their scope of work in the project. There are overlapping decision-factors for which the stakeholder groups are responsible. Decision-making is thus collaborative and must consider the needs of the stakeholders who are using BIM.
- The BIM-aspects (i.e. geometrical information, descriptive information and workflows) are valued *similarly* by stakeholders *within* their groups (i.e. Owner, A/E, CM and Modeler), but may *differ* when they are considered *between* the groups (i.e. Owner vs. Modeler, CM vs. A/E, CM vs. Modeler).
- Addressing and managing the decision-factors for the planning, management and implementation of BIM, has the potential of ensuring reduced workflow disruptions at the

labor workface. Geometrical accuracy is critical for retrofit construction, especially when prefabrication is being used as a production method. However, more evidence is required to draw a conclusive connection.

The results of this dissertation has led to distinct contributions to the body of knowledge. The following sections will provide a summary of these contributions along with a brief discussion on the applications of the findings from the research towards streamlining BIM at the case study facility, a discussion of the limitations of the research study and finally recommendations for future research.

6.1. Summary of Results and Contributions

The primary objective of this research was to explore the impact of BIM on labor productivity (metric) in retrofits (context). To guide the effort, the author developed the following research questions:

R1: **How** can we evaluate the impact of decisions made during the planning, management and implementation of BIM on task-level labor productivity in retrofit construction?

R1a: **Who** are the decision-makers involved with the planning, management and implementation of BIM and **what** is their expected value from BIM?

R1b: **What** are the decision-criteria (*i.e.* factors considered during decision making) identified during the planning, management and implementation of BIM?

R1c: **How** does BIM use impact task-level labor productivity in retrofit construction?

R2: **How** can an owner facilitate the planning, management and implementation of BIM, such that task-level labor productivity is positively impacted?

Through a concurrent mixed-methods research with qualitative and quantitative analysis, the author developed a framework to answer the above questions and provided the following contributions to the AEC industry:

1. *BIM-use in retrofit construction*: The case study highlighted the work-processes of BIM planning, management and modeling at a semiconductor manufacturing facility. Several redundant steps were identified which were the direct consequence of an immature and incomplete use of BIM, the lack of technology use (VDC) and lack of experience and understanding of BIM by the construction supply chain. This study also highlighted the unique conditions for design and construction decision-making in a complex manufacturing environment and the apparent differences in the construction and manufacturing industries.
2. *Workflow disruptions attributed to an incomplete development of BIM:* Through direct observations on site, the author identified six common types of disruptions at the labor workface, which are attributed to an incomplete and immature use of BIM. The identification of these workflow disruptions is the first step towards resolving the inconsistencies in BIM and ensuring that the implementation of BIM is streamlined. Longitudinal studies are required to study the impact of these disruptions on labor productivity with an improvement in BIM maturity.
3. *BIM-value framework*: The findings from the literature and case study were compiled in the form of a BIM-value framework, which relates the stakeholders of the BIM process (owner, designer, construction management, modeler and installer) with their relative value for BIM, the decision-factors for planning, management and implementation of BIM and the potential impact on labor productivity. The author proposes developing this framework into a risk identification tool for the industry.

This dissertation has answered research questions R1a, R1b, and R1c, thus effectively answering research question R1. In order to answer research question R2, the author spearheaded a BIM-pull planning and streamlining effort at the case study as described in the next section.

6.1.1. Practical Implementation

This research provided the author the opportunity to intimately study the BIM implementation at the semiconductor manufacturing facility. During the course of the research, the author was able to identify the process gaps and recommend areas for improvement. The author and the BIM Manager of the facility pioneered a "BIM Pull-Planning" effort to outline the needs of the customers of the BIM process and align the stakeholders regarding their expectations from BIM. This also helped in clearly articulating the inputs and the outputs in each BIM phase, identify the areas that were lacking and locate areas where more investment was required. This effort was started around September 2015 and is continuing as a current project. The following method guides this project:

- **Goal:** To make BIM lean and reliable to improve construction performance
- **Objectives:**
    1. Identify the problems in the current process
    2. Define the expected performance goal
    3. Recommend process improvements to achieve the performance goal
- **Method:**
    1. First, identify the BIM phases, the objective of each phase, the owner (primary stakeholder), customer and the deliverable (in the current process) from each phase.
    2. Second, identify the expectations of the customers of the process or product from each phase i.e. requirements in BIM for being successful in their current job.
    3. Third, discuss and validate the BIM matrix with the owners and customers of each BIM phase
    4. Fourth, suggest process changes as an organization, articulate any pre-conditions (investment, legacy updates, workflow changes etc.) and the impacts of the changes on the overall project.

The impact of this streamlining effort is currently not known since the project is still ongoing. However, considering the research presented in this dissertation, we can say that identifying and closing some of the gaps in the BIM planning, management and implementation should reduce the disruptions in the workflow at the labor workface.

6.2. Research Limitations

This research has a few limitations, which future projects undertaking a similar study must consider.

- The semiconductor industry is a complex environment for any research study. Due to its uniqueness, the author was unable to find studies or examples with similar cases and/or situations. This research thus suffers from the lack of multiple case studies to generalize the findings for other construction sectors.
- This study is primarily qualitative. Although the author utilized a mixed-methods approach, the lack of established metrics at the case study facility made it difficult to comparatively analyze performance. In addition, the limited data points made it difficult to arrive at statistically sound conclusions. However, the results can provide a foundation for future research.
- The wide scope of the research has its limitations and benefits. The limitation was in the time available for research during the course of the PhD program. However, the benefit is in the development of a framework for research and the identification of several areas for future research.

6.3. Future Research

This dissertation covers three knowledge areas in construction management; Building Information Modeling (BIM), labor productivity and retrofit construction in a semiconductor manufacturing facility. The author recommends the following areas for future research based on the observations and experience of the current research study:

1. *Construction Management for Manufacturing Facilities:* This dissertation highlights the unique characteristics of the construction and manufacturing industries and explores a construction project in a manufacturing setting. We also find certain struggles, which manufacturing facility owners face, especially in justifying the increasing capital expenditure for construction services. Research groups such as the Construction Industry Institute (CII) and academic studies on lean construction have addressed subject matters in CM for manufacturing. However, future studies must explore specific studies in BIM use in manufacturing settings.
2. *Retrofit construction projects:* This dissertation offers a window into the area of retrofit tool installation in semiconductor manufacturing environments. Future studies must address and resolve practical implementation issues in retrofit construction such as;
    a. Developing a productivity metric for retrofit projects and the process for measuring productivity in a BIM/VDC environment
    b. Determining whether the level of geometrical accuracies in the 3D model has a correlation with labor productivity. This stems from the hypothesis developed from the research; *the accuracy & reliability of geometrical information is critical for effective labor productivity when using BIM and prefabrication in retrofit construction.*
3. *Building Information Modeling & Labor Productivity*: This research explored the BIM impacts on task-level construction labor productivity, i.e. the direct impacts of BIM on the field. A few questions are asked throughout this dissertation, which require further studies and explorations;
    a. What is a BIM schedule and how does it relate with the projects schedule? How much time does it take to model and manage information?
    b. How does labor productivity improve with increasing BIM maturity?

The author recommends that BIM-stakeholders conduct longitudinal surveys to document the six workflow disruptions identified by the author during the productivity studies to validate the true impacts of increasing BIM maturity on labor productivity.

The author recommends extending the research presented in this dissertation by developing the BIM-Value framework into a risk-analysis tool by assigning quantitative impact factors to each decision-factor. This tool can then serve the stakeholders of the construction project to make informed decisions regarding BIM. The second project which the author recommends is re-thinking the way 3D modeling is performed and instead exploring the area of algorithmically developing design, construction and prefabrication models to eliminate the issues with geometrical and information discrepancies as found in this case study.

6.4. Final Remarks

BIM is still an emerging process and although the technology is present, to realize the benefits from its implementation, the processes need developing and refining. Academic research can contribute to this field of study by encouraging construction management research in BIM based processes. Leveraging a methodology based on a mixed-methods form of inquiry, this dissertation has successfully bridged the gap between academia and industry by exploring a problem in a practical setting, explaining the theory based on research and applying the findings towards streamlining the BIM process at a large semiconductor manufacturing facility in the southwestern United States.

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APPENDIX A

RESEARCH SCHEDULE

Meeting schedule for research meetings, data collection and implementation efforts at case study facility. Schedule does not include Informal discussions and meetings with advisor.

		Purpose	Date
1	***Research update meetings***		
	Project kick-off	proposal presentation	11-Oct
	Project close-out	final results presentation	27-Oct
	Research funding committee		
	Meeting 1	update	12-Dec
	Meeting 2	update	13-Feb
	Meeting 3	productivity data	9-May
	Meeting 4	year 2 funding	7-Aug
	Steering committee (updates)		
	Meeting 1	update	17-Oct
	Meeting 2	problem statement dev.	8-Nov
	Meeting 3	literature review/findings	31-Jan
	Meeting 4	research questions	6-Feb
	Meeting 5	research method	7-Mar
	Meeting 6	update	28-Mar
	Meeting 7	update	4-Apr
	Owner (VP Construction)	research results	16-May
	Steering committee (1:1 discussions)		
	Meeting 1	clarifications	1-Nov
	Meeting 2	clarifications	21-Feb
	Meeting 3	clarifications	18-Apr
	Meeting 4	update	20-Jun
	Meeting 5	update	18-Aug
	Meeting 6	update	26-Sep
2	***Interviews (R1a, R1b: Chapter 3)***		
	BIM coordinator	structured interview	8-Nov
	Trade BIM manager (pipe 1)	structured interview	13-Nov
	Trade BIM manager (pipe 2)	structured interview	20-Jan
	Owner BIM manager	structured interview	13-Nov
	Trade BIM manager (electrical 1	fabrication facility visit	28-Jan
	Trade BIM manager (electrical 2	structured interview	20-Feb
	Trade BIM manager (architectur	structured interview	23-Apr
	A/E BIM Manager	conversational interview	19-Dec
3	***Process Mapping (R1a, R1b: Ch***	2-day event	9-Sep
4	***Job shadow (R1a, R1b, R1c: Chapter 3,4)***		
	Piping trade	modeling workflow	16-Sep
	Electrical trade	modeling workflow	17-Sep
	Mechanical trade	modeling workflow	18-Sep
5	***Productivity studies (R1c: Chapter 4)***		
	Direct Observations (trial)	3 weeks	25-Feb
	Direct Observations (final)	6 weeks	24-Mar
6	***Validation survey (Chapter 5)***	8 weeks (open)	10-Nov
7	***Implementation (Chapter 6)***	mtgs. w/ BIM mgr. owner	
	5-Sep, 8-Sep, 8-Oct, 16-Oct, 17-Oct, 12-Nov		

Problem framing
Analysis + Solution dev.
Data Collection
Implementation
Literature Review
Validation

Figure A1. *Research Schedule*

APPENDIX B

PDRI ANALYSIS VERSION 3

PDRI 3 - Summary Results

PDRI Industrial | CII

Project:	Case study
Project Manager:	
Facilitator:	
Status of Project:	
Date:	

Section	Description	PDRI 3 Score	Min Score	Max Score	Def[1] (%)
I	BASIS OF PROJECT DECISION	220	28	487	58%
II	BASIS OF DESIGN	100	27	313	74%
III	EXECUTION APPROACH	23	5	78	75%
	Total	**343**	**60**	**878**	**65%**
	PDRI TOTAL MAXIMUM SCORE = 1000 **Normalized Score:**				**391**

Category	Description	PDRI 3 Score	Min Score	Max Score	Def[1] (%)
A	MANUFACTURING OBJECTIVES CRITERIA	8	3	45	88%
B	BUSINESS OBJECTIVES	53	10	201	77%
C	BASIC DATA RESEARCH & DEVELOPMENT	67	4	94	30%
D	PROJECT SCOPE	73	11	120	43%
E	VALUE ENGINEERING	19	-	27	30%
F	SITE INFORMATION	3	3	38	100%
G	PROCESS/MECHANICAL	78	14	179	61%
H	EQUIPMENT SCOPE	12	3	33	70%
I	CIVIL, STRUCTURAL, & ARCHITECTURAL	1	1	7	100%
J	INFRASTRUCTURE	1	1	10	100%
K	INSTRUMENT & ELECTRICAL	5	5	46	100%
L	PROCUREMENT STRATEGY	2	1	16	93%
M	DELIVERABLES	5	-	9	44%
N	PROJECT CONTROL	7	1	17	63%
P	PROJECT EXECUTION PLAN	9	3	36	82%
Total		**343**	**60**	**878**	**65%**

Top 10 Elements	Description	PDRI 3 Score	Min Score	Max Score	Def[1] (%)
B.1	Products	1	1	56	100%
B.5	Capacities	2	2	55	100%
C.1	Technology	39	2	54	29%
C.2	Processes	28	2	40	32%
G.1	Process Flow Sheets	2	2	36	100%
F.1	Site Location	NA	NA	NA	NA
G.3	Piping and Instrumentation Diagrams (P&IDs)	23	2	31	28%
D.3	Site Characteristics Available vs. Required	22	2	29	26%
B.2	Market Strategy	5	2	26	88%
D.1	Project Objectives Statement	14	2	25	48%
Total		**136**	**17**	**352**	**64%**

Notes:
1 - Definition percentage indicates the level of completeness of specific Section, Category and Element.

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Tab: PDRI 3 - Summary Page 1 of 2 Date: 3/12/2015

Figure B1. *PDRI v3 Summary Results*

PDRI Industrial

PDRI 3 Low Definition Summary

Project:	Level	Count	Date:
Case study	>3	20	Enter on Summary Page

PDRI 3 - Low Definition Items

Section	Element	Element Description	Level	Score	Comments	Additional Comments	Assigned to:	Target Date
		Low Definition Items:	20	241		38	-	-
I	B.3	Project Strategy	Level 4	14	Project strategy is defined but is affected by market fluctuations			
I	B.6	Future Expansion Considerations	Level 5	17	Not defined. Future expansion criterias are not predictable becuase there are no known guidelines to predict the design changes brought upon by the technology upgrades.			
I	B.7	Expected Project Life Cycle	Level 5	8	The lifecycle is typically 2 years on most tools installed. However, it also depends on the market demand if certain previous generation tools would be kept current or not. Hence, all tools within the facility may have different lifecycles.			
I	C.1	Technology	Level 4	39	The implementation of BIM and prefabrication for this project is not clearly defined			
I	C.2	Processes	Level 4	28	The new process is the off-site prefabrication. However, the process steps are not identified.			
I	D.3	Site Characteristics Available vs. Required	Level 4	22	The As-built was not reliable on this project. Most decisions regarding available vs. required are dependent on the design decisions which contnue after phase gate 3. Hence, reliable information is not available up front.			
I	D.4	Dismantling and Demolition Requirements	Level 5	15	The layout identified by the Industrial Engineers even though similar have to be adapted to the the local conditions of the fab. Because there is a large number of existing infrastructure, there is a considerable amount of modification/adjustments which are required. This often occurs simultaneously with construction. The timing of demolitions			
I	E.1	Process Simplification	Level 4	6	A detailed process mapping is done for the manufacturing process but not for construction. Optimization in construction is done in isolation by the trade contractors. These are captured at the end of the project as 'Best Practices', but this is not a structured value analysis process.			
I	E.2	Design & Material Alternatives Considered/Rejected	Level 4	5	The material specifications are specified by the owner. The contractors can recommend alternatives for materials and methods but most often it is not defined before phase gate 3.			
I	E.3	Design for Constructability Analysis	Level 4	8	BIM is used for constructability analyses but this is done after 100% design			
II	G.3	Piping and Instrumentation Diagrams (P&IDs)	Level 4	23	The initial layout is provided by the IE which are then converted into P&IDs based on the local information of the facility. (This is because of the companies 'copy-exact' philosophy, through which they are trying to acheive modularity in their designs. However, each site has special local conditions that need to be considered and field verified). The P&IDs are usually at 30% design at this stage. However, for this project, the contractors were providing the routing design and they would often request new POC's which would be more feasible from a field standpoint.			
II	G.5	Utility Flow Diagrams	Level 5	12	Does not exist at this stage. Provided by the trade constractors.			
II	G.9	Mechanical Equipment List	Level 4	13	A preliminary list exists at this point. Equipments are added as the design and construction proceeds.			
II	G.10	Line List	Level 5	8	Line list for existing utilities exists but not for new.			
II	G.11	Tie-in List	Level 4	4	Tie in list for existing utilities exists but not field verified			
II	G.12	Piping Specialty Items List	Level 5	4	NA			
II	G.13	Instrument Index	Level 4	5	NA			
II	H.2	Equipment Location Drawings	Level 4	7	Exists but subject to frequent change and hence requires re-validation and adjustment with the surrounding conditions. Several times the elevation of the equipment is incorrect.			
III	M.1	CADD/Model Requirements	Level 4	2	Defined but missing some information about implementation requirements.			
III	M.3	Distribution Matrix	Level 5	1	Does not exist			
Total			20	241		38	-	-

Figure B2. *PDRI v3 Low-definition Items*

APPENDIX C

STRUCTURED INTERVIEW WITH BIM-STAKEHOLDERS

PART A: General, stakeholder relationships*

1. What is your role in the current project?
2. Is this your first project with the owner?
3. What is the scope of work for your role?
4. What is the scope of work for your company?
5. Has the scope of work changed as the project has progressed? If yes, then what was added/subtracted from the original scope?
6. During which phase of the project was your company engaged?
7. How many personnel from your company are on site at present and what are their roles? Does this number vary as the project progresses?
8. What are the greatest challenges your company has faced on this project (up till now)?
9. What are your suggestions/recommendations for overcoming the said challenges?

PART B: BIM Use*

10. What aspects of BIM does your company use?
11. What is the justification (to your company) for using BIM?
12. What are the benefits received by using BIM?
13. What are some of the challenges in using BIM?
14. Did you create a BIM execution plan at the beginning of the project (other than the one issued by the owner with the BIM contract document?
15. How can certain functions of BIM be beneficial for:
    a. The daily process of chip manufacturing?
    b. Respond to changes in chip technology manufacturing?

PART C: Editing and validation of BIM process map

*** Questions are open-ended. Follow up questions encouraged**

APPENDIX D

BIM PROCESS MAPPING EVENT AT CASE STUDY FACILITY

Event details: The venue for this event was a “big-room” space on site. The room was approximately 50 feet long by 25 feet wide with blank walls. A conference table occupied the central area. The team used Post-it® notes and markers for the exercise.

Attendees: The following stakeholders/personnel attended this event:

Table D1

Event attendees

Name	Stakeholder role	Event role
Arundhati Ghosh	Graduate student/author	Moderator
John Cribbs	Graduate student	Transcriber
BIM Manager	Owner	Moderator
Lean operations Manager	Owner	Event facilitator
Project Manager	Owner	Participant
BIM Manager (P1 pipe)	Trade contractor	Participant
BIM Manager (P2 pipe)	Trade contractor	Participant
Modeler (P2 pipe)	Trade contractor	Participant
Site Manager (M1 mechanical)	Trade contractor	Participant
BIM Manager (E1 electrical)	Trade contractor	Participant
Modeler (E1 electrical)	Trade contractor	Participant
Modeler (M1 mechanical)	Trade contractor	Participant
BIM Coordinator (model manager)	BIM coordinator	Participant

Agenda: The agenda for the two days included the following:

<u>Day 1: SIPOC and Task creation</u>

a. Identification of Supplier, Inputs, Requirements, Process, Outputs and Customer

- *Supplier:* Stakeholders in the BIM process
- *Inputs:* Including all the inputs to the process; scope of work, schedule, cost approval, reference package (RP), location specific package (LSP), laser scans of existing facility, layouts, details, design model, construction model, federated model.

- *Requirements:* This includes all the requirements for the BIM process to work without major hindrances. This includes aspects such as accuracy, reliability, completeness and timeliness of information.
- *Process:* Five primary phases were identified; receive information, review documentation, model authoring, spool drawing and installation package creation (2D package).
- *Outputs:* The expected outputs or deliverable from the process includes; accurate and updated 2D package, updated federated model, bill of materials, installation drawings, prefabrication, appropriate headcount assignments and As-Built model for future use.
- *Customer:* The customers of the BIM management & implementation process were identified as; the modelers, BIM coordinator, owners project manager, prefabrication trades, installer, 3rd party quality control check and finally the owner.

b. Identification of process tasks and subtasks

1. For each of the five phases, tasks were identified and further for each task, at least five more sub-tasks were identified.

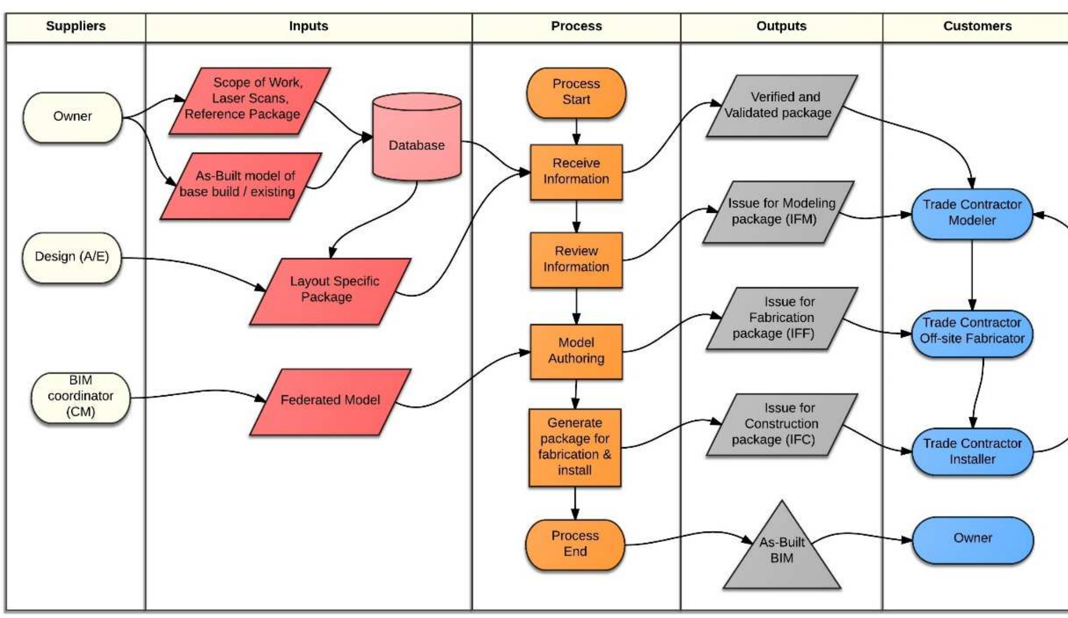


Figure D1. SIPOC Diagram

Day 2: Process Mapping and Value Stream Analysis

The second day was an intense session of a process mapping effort to link the tasks identified in Day 1 as a sequence of events. Each participant was assigned a dedicated swim lane in which they were asked to identify their processes. The trades were asked to identify their current process versus the best practice. This exercise was initially met with some resistance as the contractors of the similar trade (e.g. process piping) assumed that mapping their process would reveal their competitive advantage. After some persuading by the moderators, the trade contractors came to realize the value in this effort and agreed to participate. Due to the proprietary nature of the final process map, this dissertation does not present it in its original form.

2. Four primary phases in the BIM implementation process were identified as;
    1. Receive Information,
    2. Review Information,
    3. Model Authoring and,
    4. Generate package for fabrication & install.
3. The major milestones in the process were identified as;
    1. Design review package issued by A/E
    2. Issue for modeling (IFM) issued by BIM coordinator
    3. Issue for fabrication (IFF) issued by BIM coordinator
    4. Issue for construction (IFC) issued by owner

- Total activities = 169, value adding activities = 9 (5% of total)
    1. Verification and validation of POCs before modeling & construction
    2. Verification and validation of field walk package before modeling & construction
    3. Selection of new Popouts if they are obstructed
    4. Demolition and relocation of tools
    5. Issue for modeling (IFM) after release of design review package
    6. Modeling as per the schedule

7. Bill of Material (BOM) creation
8. Spool drawing creation
9. Final issue for fabrication (IFF)

Figure D2. Process Mapping Event

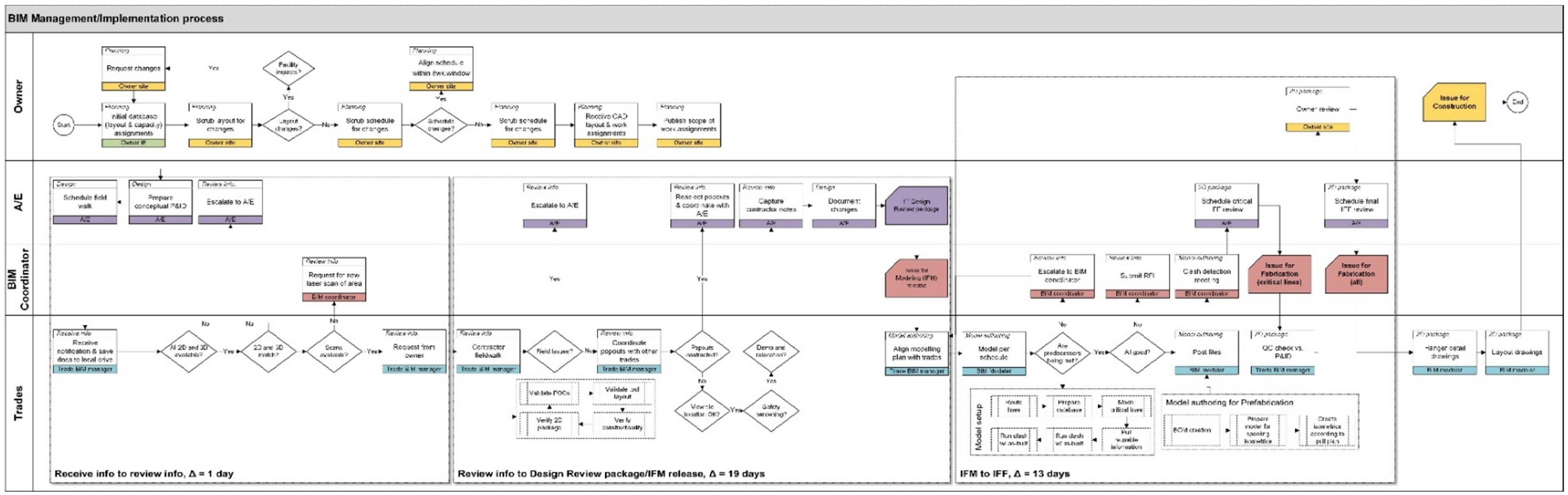


Figure D3. *BIM Management/Implementation Process Map*

APPENDIX E

BIM MODELER JOB SHADOW

Table E1.

Meeting Schedule with BIM Modelers

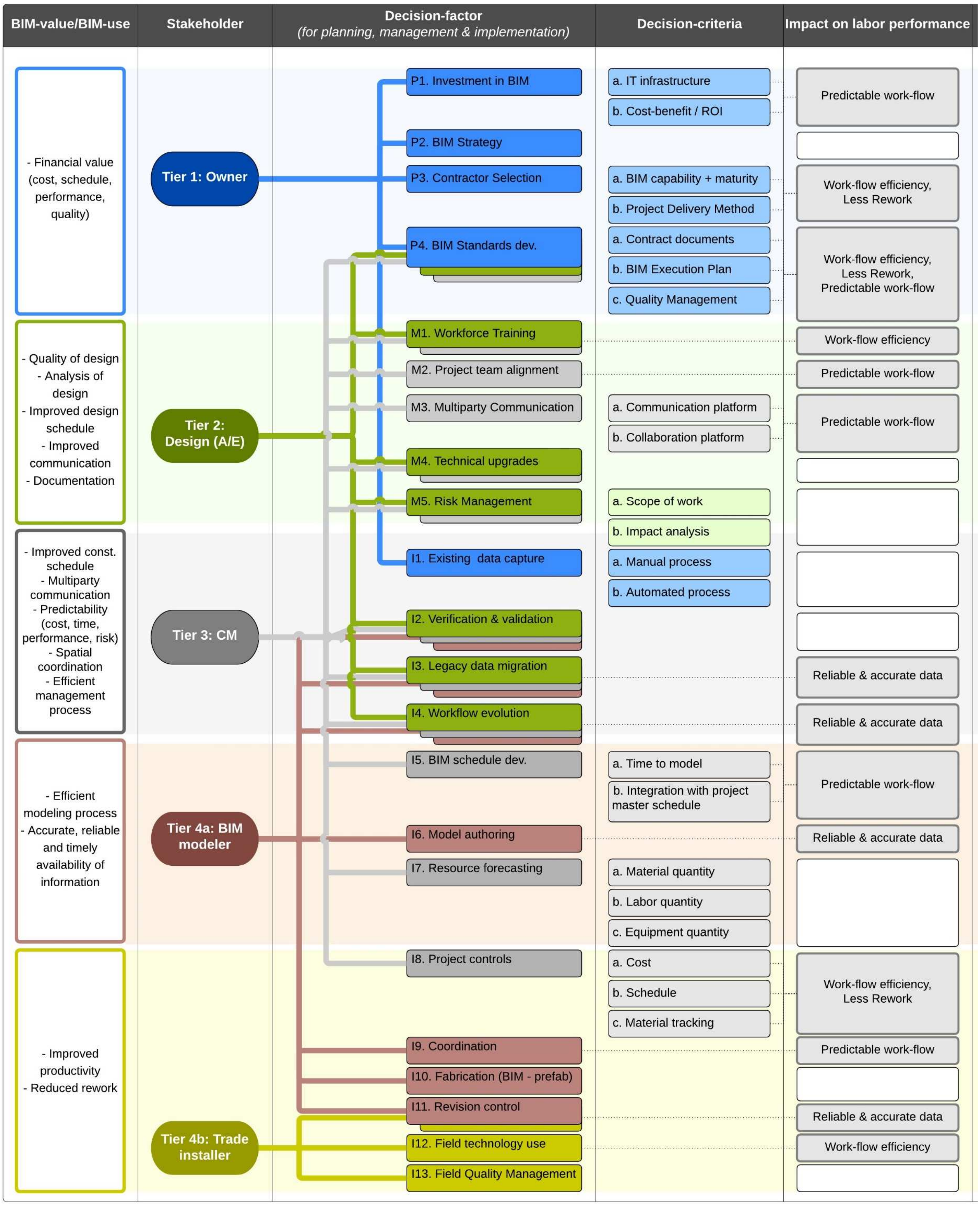
Trade/Company	**Time (hours)**	**Location**	**Job being performed on day**
P2 pipe	8.30 am – 2.00 pm (5.5 hours)	Job trailer + Subfab	Routing of new tool, validation and field walk
E1 electrical	1.30 pm – 4.30 pm (3 hours)	Job trailer	Preparing for clash detection meeting for next day
M1 mechanical	7.30 am – 1.00 pm (6.5 hours)	Subfab	Modeling pipe routing

The author used the following interview questions for capturing information from the BIM modelers. Apart from these, the author also captured general notes and quotes from the personnel. The notes were then developed in to process maps.

1. Provide a brief introduction of your background (educational, professional and software experience. Experience with current company)
2. What BIM software does your company use for model authoring? What is your experience using this particular software.
3. What are you working on today?
4. What are some of your responsibilities?
5. What benefits have you (in your current role) experienced from BIM?
6. What are the limitations of BIM (in the current project)?

APPENDIX F

BIM-VALUE FRAMEWORK


BIM-value/BIM-use
Stakeholder
Decision-factor
(for planning, management & implementation)
Decision-criteria
Impact on labor performance
- Financial value (cost, schedule, performance, quality)
- Quality of design
- Analysis of design
- Improved design schedule
- Improved communication
- Documentation
- Improved const. schedule
- Multiparty communication
- Predictability (cost, time, performance, risk)
- Spatial coordination
- Efficient management process
- Efficient modeling process
- Accurate, reliable and timely availability of information
- Improved productivity
- Reduced rework
Tier 1: Owner
Tier 2: Design (A/E)
Tier 3: CM
Tier 4a: BIM modeler
Tier 4b: Trade installer
P1. Investment in BIM
P2. BIM Strategy
P3. Contractor Selection
P4. BIM Standards dev.
M1. Workforce Training
M2. Project team alignment
M3. Multiparty Communication
M4. Technical upgrades
M5. Risk Management
I1. Existing data capture
I2. Verification & validation
I3. Legacy data migration
I4. Workflow evolution
I5. BIM schedule dev.
I6. Model authoring
I7. Resource forecasting
I8. Project controls
I9. Coordination
I10. Fabrication (BIM - prefab)
I11. Revision control
I12. Field technology use
I13. Field Quality Management
a. IT infrastructure
b. Cost-benefit / ROI
a. BIM capability + maturity
b. Project Delivery Method
a. Contract documents
b. BIM Execution Plan
c. Quality Management
a. Communication platform
b. Collaboration platform
a. Scope of work
b. Impact analysis
a. Manual process
b. Automated process
a. Time to model
b. Integration with project master schedule
a. Material quantity
b. Labor quantity
c. Equipment quantity
a. Cost
b. Schedule
c. Material tracking
Predictable work-flow
Work-flow efficiency, Less Rework
Work-flow efficiency, Less Rework, Predictable work-flow
Work-flow efficiency
Predictable work-flow
Predictable work-flow
Reliable & accurate data
Reliable & accurate data
Predictable work-flow
Reliable & accurate data
Work-flow efficiency, Less Rework
Predictable work-flow
Reliable & accurate data
Work-flow efficiency

APPENDIX G

BIM-VALUE SURVEY

EXEMPTION GRANTED

Allan Chasey
SEBE: Sustainable Engineering and the Built Environment, School of
480/965-7437
achasey@asu.edu

Dear Allan Chasey:

On 10/9/2014 the ASU IRB reviewed the following protocol:

Type of Review:	Initial Study
Title:	A BIM-value framework analyzing the impact of Building Information Modeling and Management on labor performance
Investigator:	Allan Chasey
IRB ID:	STUDY00001689
Funding:	Name: Semiconductor Research Corporation;
Grant Title:	
Grant ID:	
Documents Reviewed:	• IRB_aghosh_BIM, Category: IRB Protocol; • survey_flow_1, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • survey_flow_2, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • survey_flow_3, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • Survey questions_updated, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions);

The IRB determined that the protocol is considered exempt pursuant to Federal Regulations 45CFR46 (2) Tests, surveys, interviews, or observation on 10/9/2014.

The relative value of Building Information Modeling and Management for project stakeholders

Introduction

This study attempts to collect expert feedback from individuals representing Architecture/Engineering/Construction and Owner (AECO) organizations who are involved in the planning, execution, and implementation of Building Information Modeling (BIM) and Management. The intent is to analyze the value of BIM from the perspective of individuals involved in the BIM process.

Procedures

Based on your current role, you will be asked to answer a set of 3 questions with 6 to 10 options. The responses are based on a Likert type scale from "Not at all important" or "1" to "Extremely Important" or "7". There is also an option to select "NA" if you feel the question does not apply to your role type. The response is controlled by a slider, which you can hold and slide with your mouse. **The survey will take 15 minutes or less to complete.**

Risks/Discomforts

The risks are minimal to the participants for taking this survey.

Benefits

There are no individual direct benefits for participants. However, it is hoped that through your participation, the researchers will learn more about the state of BIM use in the industry and arrive at a conclusive analysis of BIM as the stakeholder groups value it.

Confidentiality

All data obtained from participants is **ANONYMOUS, will be kept confidential,** and will only be reported in an aggregate format (by reporting only combined results and never reporting individual ones). All questionnaires will be concealed, and no one other than the primary investigators (listed below) will have access to them. The data collected will be stored in the HIPPA-compliant, Qualtrics-secure database until the primary investigator has deleted it.

Participation

Participation in this research study is voluntary. You have the right to withdraw at any time or refuse to participate entirely.

Questions about the Research

If you have questions regarding this study, you may contact Arundhati Ghosh (PhD candidate, Construction Management, Del E. Webb School of Construction, Arizona State University) at aghosh9@asu.edu or Dr. Allan Chasey (Associate Professor and Program Chair, Del E. Webb School of Construction, Arizona State University) at achasey@asu.edu.

For any general questions you can contact the Institutional Review Board at Arizona State University at (480) 965-6788. Please attempt the survey based on your current role in BIM related decision making. We would like to capture the current state of the industry as accurately as possible.

Note: You may exit the survey at any time by closing out of the window.

I have read and understood the above and desire of my own free will to participate in this study.

Yes, please proceed to the survey

No, I would like to exit now

Role type

Please identify **<u>your role in BIM, which</u>** can be best described by one of the following five general categories:

1. Decision makers in planning, procurement, contracting, strategic development and financing
   (Typically representatives of Owner and Project Management organizations)
2. Decision makers responsible for design and engineering information input
   (Typically representatives of Architecture and Engineering firms)
3. Decision makers involved in the day to day management, implementation and coordination
   (Typically Project Managers/BIM Managers/Coordinators from General Contracting and Trade Contractor organizations)
4. Personnel involved in drafting and modeling of 2D and 3D, fabrication, construction & installation drawings
   (Typically those with the title of BIM/CAD modeler, Detailer or those performing similar duties from A/E, GC or trade contractor organizations)

Block 1 - Owner

The authors identify BIM as a process or an activity that encompasses three aspects: geometrical information, descriptive information and workflows (see table below). Please answer the following questions based on this definition. **Please answer the questions from the perspective of YOUR ROLE.**

Each option has an accompanying question as an example to help you think through the process

Geometrical information	3D parametric modeling of geometric information representing physical and spatial building components including dimension control
Descriptive Information	Project management information (cost, quantity, time) and management of information for decision making
Workflows	Workflows for BIM use and BIM implementation

1. On a scale of 1 to 7, what is the degree of importance of reliable <u>descriptive information</u> in a BIM, when making a decision about:

1.1 Contracting Method
(Is the contractors plan for managing information in BIM an important criterion in the contract?)

1.2 BIM capability of contractor
(Is the contractors plan for managing information in BIM an important criterion measured during procurement?)

1.3 Investment in hardware/software
(Is information exchange/management an important criterion when planning for investment in BIM software/hardware?)

1.4 BIM training
(How important is the inclusion of a section on information management in the BIM training material for your team?)

1.5 Developing an Owners BIM Facilities Management plan
(Is information management an important criterion when developing an Owners' BIM to FM execution plan?)

1.6 BIM standards
(How important is it to include standards for data structuring when developing a BIM standards for a project?)

2. On a scale of 1 to 7, what is the degree of importance of accuracy & control of <u>geometry</u> in BIM, when making a decision about:

2.1 Contracting Method
(Is the delivery of an accurate geometrical model an important criterion in the contract?)

2.2 BIM capability of contractor
(Is the contractors' capability of delivering accurate geometrical BIM models an important criterion considered during procurement?)

2.3 Investment in hardware/software
(Is geometrical tolerance an important criterion when planning for investment in BIM software/hardware?)

2.4 BIM training
(Is the importance of accurate 2D and 3D geometrical modeling emphasized in the BIM training material for your team?)

2.5 Developing an Owners BIM Facilities Management plan
(Is it important to consider the accuracy of model geometry in the Owners' BIM to FM execution plan?)

2.6 BIM standards
(How important is it to emphasize geometrical tolerances of the BIM model in the BIM standards for a project?)

3. On a scale of 1 to 7, what is the degree of importance of reliable workflows for BIM, when making a decision about:

3.1 Contracting
(What is the importance of items such as of 3D modeling workflow, information exchange and Information management in the contract?)

3.2 BIM capability of contractor
(Is the contractors' BIM work process considered during procurement?)

3.3 Investment in hardware/software
(Does the BIM work processes in any way influence the decisions for investing in hardware/software for BIM? Example common server versus cloud)

3.4 BIM training
(What is the importance of an education in BIM work processes?)

3.5 Developing an Owners BIMFM plan
(What is the level of importance of identifying a BIM workflow when outlining an Owners' BIM Facilities Management execution plan?)

3.6 BIM standards
(How important is it to standardize the workflow for BIM when developing a BIM standards for a project?)

4. Please define the value of BIM in your own words:

Block 2 - Design

The authors identify BIM as a process or an activity that encompasses three aspects: geometrical information, descriptive information and workflows (see table below). Please answer the following questions based on this definition. **Please answer the questions from the perspective of YOUR ROLE.**

Each option has an accompanying question as an example to help you think through the process

Geometrical information	3D parametric modeling of geometric information representing physical and spatial building components including dimension control
Descriptive Information	Project management information (cost, quantity, time) and management of information for decision making
Workflows	Workflows for BIM use and BIM implementation

1. On a scale of 1 to 7, what is the degree of importance of reliable of descriptive information in a BIM, when making a decision about:

   1.1 Spatial coordination
   (What is the importance of the reliable information when using BIM for coordination?)

   1.2 Visualization
   (How important is the 'information' in a 3D model when used for the purpose of visualization?)

   1.3 Constructability
   (What is the importance of reliable information in BIM when used for constructability analysis?)

   1.4 Energy Analysis
   (What is the importance is reliable information in BIM when used for energy analysis?)

   1.5 Engineering Analysis
   (What is the importance of reliable information in BIM when used for engineering analysis?)

   1.6 Facility Maintenance
   (How important is it to identify and include the information needs for facility management and maintenance at the time of design?)

   1.7 Prefabrication
   (What is the importance of reliable information if BIM is being used for prefabrication?)

2. On a scale of 1 to 7, what is the degree of importance of accuracy & control of geometry in BIM, when making a decision about:

   2.1 Spatial coordination
   (What is the importance of the accuracy of the model geometry when using BIM for coordination?)

   2.2 Visualization
   (What is the importance of accurate geometry of a 3D model when being used for the purpose of visualization?)

   2.3 Constructability
   (What is the importance of geometrical accuracy of BIM when used for constructability analysis?)

   2.4 Energy Analysis
   (How important is 'geometrical accuracy' in BIM when used for energy analysis?)

   2.5 Engineering Analysis
   (How important is 'geometrical accuracy' in BIM when used for engineering analysis?)

   2.6 Facility Maintenance
   (How important is it to maintain geometrical accuracy in BIM at the time of design if the BIM will be used for facility management and maintenance?)

   2.7 Prefabrication
   (How important is it to maintain accurate geometrical tolerances if BIM is being used for prefabrication?)

3. On a scale of 1 to 7, what is the degree of importance of reliable workflows for BIM, when making a decision about:

   3.1 Spatial coordination
   (What is the importance of maintaining a standard workflow including roles and responsibilities when using BIM for coordination?)

   3.2 Visualization
   (What is the importance of identifying a standard BIM workflow when BIM is used for visualization?)

   3.3 Constructability
   (How important is it to identify a standard BIM workflow when doing constructability analysis?)

   3.4 Energy Analysis
   (How important is it to identify a standard BIM workflow when doing energy analysis?)

   3.5 Engineering Analysis
   (How important is it to identify a standard BIM workflow when doing engineering analysis?)

   3.6 Facility Maintenance
   (How important is it to identify a standard BIM workflow for modeling or information management, when preparing BIM for facility management and maintenance?)

   3.7 Prefabrication
   (How important is it to identify a standard BIM workflow if BIM is being used for prefabrication?)

4. Please define the value of BIM in your own words:

Block 3 - Project Management

The authors identify BIM as a process or an activity that encompasses three aspects: geometrical information, descriptive information and workflows (see table below). Please answer the following questions based on this definition. **Please answer the questions from the perspective of YOUR ROLE.**

Each option has an accompanying question as an example to help you think through the process

Geometrical information	3D parametric modeling of geometric information representing physical and spatial building components including dimension control
Descriptive Information	Project management information (cost, quantity, time) and management of information for decision making
Workflows	Workflows for BIM use and BIM implementation

1. On a scale of 1 to 7, what is the degree of importance of reliable of descriptive information in a BIM, when making a decision about:

   1.1 Project risk management
   (Can BIM assist in risk management? If yes, how important is the reliability of information in BIM for this purpose?)

   1.2 BIM Execution Plan (BEP)
   (When developing a BEP, what is the level of importance given to information management?)

1.3 BIM Level of Development (LOD)
(How important is 'information' in BIM in a LOD standard?)

1.4 Model library
(What is the importance of reliable information in BIM when developing a model library?)

1.5 Computing quantity takeoff
(How important is the information in BIM when performing quantity takeoffs?)

1.6 Labor headcount and flow
(Can the information from BIM help in identifying the labor headcount requirement? If yes, what is the importance of reliable information?)

1.7 Clash detection
(How important is reliable information in BIM when performing clash detection?)

1.8 Schedule control (4D)
(How important is reliable information in BIM for schedule control?)

1.9 Cost control (5D)
(How important is reliable information in BIM for cost control?)

1.10 Material tracking
(How important is reliable information in BIM when used for material tracking?)

2. On a scale of 1 to 7, what is the degree of importance of reliable workflows for BIM, when making a decision about:

2.1 Project risk management
(Can BIM assist in risk management? If yes, how important is the identification of BIM workflows for this purpose?)

2.2 BIM Execution Plan (BEP)
(When developing a BEP, what is the level of importance given to BIM process mapping?)

2.3 BIM Level of Development (LOD)
(How important is the BIM workflow when identifying the LOD standard?)

2.4 Model library
(How important is the identification of a BIM workflow when developing a model library?)

2.5 Quantity takeoff
(How important is a standard BIM workflow when performing quantity takeoffs?)

2.6 Labor headcount and flow
(Can the BIM workflow play a role in identifying the labor headcount requirement? If yes, what is the level of importance?)

2.7 Clash detection
(How important is a standard BIM workflow when performing clash detection?)

2.8 Schedule control (4D)
(How important is a standard BIM workflow when performing schedule control?)

2.9 Cost control (5D)
(How important is a standard BIM workflow when performing cost control?)

2.10 Material tracking
(How important is a standard BIM workflow when used for material tracking?)

3. On a scale of 1 to 7, what is the degree of importance of accuracy & control of geometry in BIM, when making a decision about:

   3.1 Project risk management
   (Can BIM assist in risk management? If yes, how important is the accuracy of geometry of BIM for this purpose?)

   3.2 BIM Execution Plan (BEP)
   (When developing a BEP, what is the level of importance given to geometrical tolerances?)

   3.3 BIM Level of Development (LOD)
   (How important is the 'accuracy of geometry' of BIM when defining the LOD standard?)

   3.4 Model library
   (What is the importance of geometrical accuracy of the BIM model when developing a model library?)

   3.5 Material quantity takeoff
   (How important is the geometry of the model when using BIM for quantity takeoffs?)

   3.6 Labor headcount and flow
   (Can the model geometry play a role in identifying the labor headcount requirement? If yes, what is the level of importance?)

   3.7 Clash Detection
   (How important is accurate model geometry when performing clash detection?)

   3.8 Schedule control (4D)
   (How important is accurate model geometry when performing schedule control?)

   3.9 Cost control (5D)
   (How important is accurate model geometry when performing cost control?)

   3.10 Material tracking
   (How important is accurate model geometry in BIM, when used for material tracking?)

4. Please define the value of BIM in your own words:

Block 4 - Workface (modelers)

The authors identify BIM as a process or an activity that encompasses three aspects: geometrical information, descriptive information and workflows (see table below). Please answer the following questions based on this definition. **Please answer the questions from the perspective of YOUR ROLE.**

Each option has an accompanying question as an example to help you think through the process

Geometrical information	3D parametric modeling of geometric information representing physical and spatial building components including dimension control
Descriptive Information	Project management information (cost, quantity, time) and management of information for decision making
Workflows	Workflows for BIM use and BIM implementation

1. On a scale of 1 to 7, what is the degree of importance of accuracy & control of geometry in BIM, when making a decision about:

1.1 Creating an **as built** or background model of existing infrastructure
(Is accurate model geometry important when creating and working with a background model of existing infrastructure? If yes, what is the level of importance?)

1.2 **Detail drawings**
(How important is the accuracy of geometry and dimensions when creating detail drawings?)

1.3 **Quantity takeoffs**
(How important is the model geometry if BIM is prepared for quantity takeoffs?)

1.4 **Fabrication drawings**
(How important is the accuracy of geometry when automating spool drawings or fabrication drawings from BIM for the purpose of prefabricating at an offsite location?)

1.5 **Request for Information**
(Is inaccuracy of model geometry factor for issuing a RFI? If yes, how important is it?)

1.6 **Revision control** and change management
(How important is geometrical tolerance in BIM when managing changes in the model?)

2. On a scale of 1 to 7, what is the degree of importance of reliable of descriptive information in a BIM, when making a decision about:

2.1 Creating an **As-Built** or background model of existing infrastructure
(Is reliable information (apart from geometry) important when creating and working with a background model of existing infrastructure? If yes, what is the level of importance?)

2.2 **Detail drawings**
(How important is the maintenance of reliable project information when creating detail drawings?)

2.3 **Quantity takeoffs**
(How important is it to make sure the BIM has accurate information when preparing it for quantity takeoffs?)

2.4 **Fabrication drawings**
(How important is the reliability of information when automating spool drawings or fabrication drawings from BIM for prefabricating at an offsite location?)

2.5 **Request for Information**
(Is unreliable information a factor for issuing a RFI? If yes, how important is it?)

2.6 **Revision control** and change management
(How important is information management in BIM when managing changes in the model?)

3. On a scale of 1 to 7, what is the degree of importance of reliable workflows for BIM, when making a decision about:

3.1 Creating an **as built** or background model of existing infrastructure
(Is a standardized BIM workflow important when creating and working with a background model of existing infrastructure? If yes, what is the level of importance?)

3.2 **Detail drawings**
(How important is a standard BIM workflow when creating detail drawings?)

3.3 **Quantity takeoffs**
(How important is a standard BIM workflow when using it for quantity takeoffs?)

3.4 **Fabrication drawings**
(How important is a standard BIM workflow when automating spool drawings or fabrication drawings from BIM for prefabricating at an offsite location?)

3.5 **Revision control** and change management
(How important is the BIM workflow when managing changes in the model?)

4. Please define the value of BIM in your own words:

Figure F1 provides a screenshot of the survey as it would display for a respondent using the online web-URL. Figure F2 provides the survey flow showing the flow of questions based on the selections by the respondents.

Figure F1. *Screen-shot of Online Survey on Qualtrics.com*

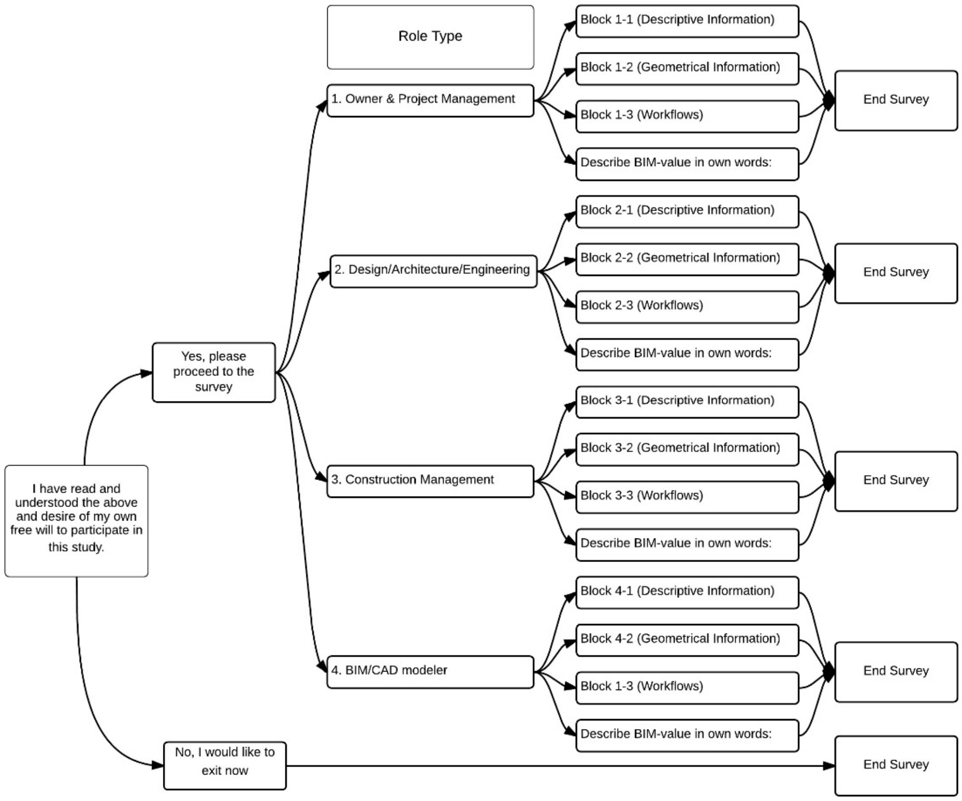


Figure F2. *Survey Flow*

FRIEDMAN TEST

OWNER

1. Friedman Test: P3. Contractor Selection-BIM maturity versus BIM-aspect blocked by Respondent

```
S = 1.40  DF = 2  P = 0.497
S = 2.00  DF = 2  P = 0.368 (adjusted for ties)

CATEGORY   N  Est Median   Sum of Ranks
G         10      6.0833    21.0
D         10      6.2500    22.0
W         10      5.9167    17.0

Grand median = 6.0833
```

2. Friedman Test: P2. BIM strategy-BIM-FM plan versus BIM-aspect blocked by Respondent

```
S = 2.15  DF = 2  P = 0.341
S = 2.77  DF = 2  P = 0.250 (adjusted for ties)

CATEGORY   N  Est Median   Sum of Ranks
G         10      5.8333    17.0
D         10      6.6667    23.5
W         10      6.0000    19.5
```

Grand median = 6.1667

3. **Friedman Test: P4. BIM Standards Development – BEP versus BIM-aspects blocked by Respondent**

```
S = 0.00  DF = 2  P = 1.000
S = 0.00  DF = 2  P = 1.000 (adjusted for ties)

CATEGORY   N  Est Median  Sum of Ranks
G         10      6.5000    20.0
D         10      6.5000    20.0
W         10      6.5000    20.0

Grand median = 6.5000
```

4. **Friedman Test: M1. Workforce Training versus BIM-aspects blocked by Respondent**

```
S = 1.05  DF = 2  P = 0.592
S = 1.83  DF = 2  P = 0.401 (adjusted for ties)

CATEGORY   N  Est Median   Sum of Ranks
G         10      6.5000    17.5
D         10      6.5000    20.5
W         10      6.5000    22.0

Grand median = 6.5000
```

5. **Friedman Test: P1. Investment in BIM versus BIM-aspect blocked by Respondent**

```
S = 3.72  DF = 2  P = 0.155
S = 7.05  DF = 2  P = 0.029 (adjusted for ties)

CATEGORY  N  Est Median   Sum of Ranks
G         9      6.0000    17.0
D         9      6.3333    22.5
W         9      5.6667    14.5

Grand median = 6.0000
```

MODELER

1. **Friedman Test: I1. Existing Data Capture versus BIM-aspect blocked by Respondent**

```
S = 0.10  DF = 2  P = 0.951
S = 0.29  DF = 2  P = 0.867 (adjusted for ties)

CATEGORY  N  Est Median   Sum of Ranks
G         5      5.0000    10.0
D         5      5.0000    10.5
W         5      5.0000     9.5

Grand median = 5.0000
```

2. **Friedman Test: I6. Model Authoring versus BIM-aspects blocked by Respondent**

```
S = 1.60  DF = 2  P = 0.449
S = 4.00  DF = 2  P = 0.135 (adjusted for ties)

CATEGORY  N  Est Median   Sum of Ranks
G         5      6.0000     8.0
D         5      6.0000    12.0
W         5      6.0000    10.0

Grand median = 6.0000
```

3. **Friedman Test: I7. Resource Forecasting (quantity) versus BIM-aspects blocked by Respondent**

```
S = 0.70  DF = 2  P = 0.705
S = 2.00  DF = 2  P = 0.368 (adjusted for ties)

CATEGORY  N  Est Median   Sum of Ranks
G         5      6.0000    10.5
D         5      6.0000    11.0
W         5      6.0000     8.5

Grand median = 6.0000
```

4. **Friedman Test: I10. BIM to Prefab. versus BIM-aspects blocked by Respondent**

```
S = 1.30  DF = 2  P = 0.522
S = 3.71  DF = 2  P = 0.156 (adjusted for ties)

CATEGORY  N  Est Median   Sum of Ranks
G         5      6.0000     9.5
D         5      6.0000    12.0
W         5      6.0000     8.5

Grand median = 6.0000
```

5. **Friedman Test: I11. Revision Control versus BIM-aspects blocked by Respondent**

```
S = 0.10  DF = 2  P = 0.951
S = 0.29  DF = 2  P = 0.867 (adjusted for ties)

CATEGORY  N  Est Median   Sum of Ranks
G         5      5.0000    10.0
D         5      5.0000    10.5
W         5      5.0000     9.5

Grand median = 5.0000
```

CM

1. **Friedman Test: M5. Risk Management versus BIM-aspects blocked by Respondent**

```
S = 1.88  DF = 2  P = 0.390
S = 3.16  DF = 2  P = 0.206 (adjusted for ties)

CATEGORY   N  Est Median   Sum of Ranks
G         13      6.0000    22.5
D         13      6.0000    29.5
W         13      6.0000    26.0

Grand median = 6.0000
```

2. **Friedman Test: P4. BIM Standards Dev - BEP versus BIM-aspects blocked by Respondent**

```
S = 2.92  DF = 2  P = 0.232
S = 4.11  DF = 2  P = 0.128 (adjusted for ties)

CATEGORY   N  Est Median   Sum of Ranks
G         13      6.3333    23.0
D         13      6.0000    24.0
W         13      6.6667    31.0

Grand median = 6.3333
```

3. **Friedman Test: P4. BIM Standards Dev. - LOD versus BIM-aspects blocked by Respondent**

```
S = 1.65  DF = 2  P = 0.437
S = 2.87  DF = 2  P = 0.239 (adjusted for ties)
```

CATEGORY	N	Est Median	Sum of Ranks
G	13	7.0000	22.5
D	13	7.0000	26.5
W	13	7.0000	29.0

Grand median = 7.0000

4. **Friedman Test: P4. BIM Standards Dev. - Model Library versus BIM-aspects blocked by Respondent**

S = 0.73 DF = 2 P = 0.694
S = 1.23 DF = 2 P = 0.542 (adjusted for ties)

CATEGORY	N	Est Median	Sum of Ranks
G	13	7.0000	23.5
D	13	7.0000	27.5
W	13	7.0000	27.0

Grand median = 7.0000

5. **Friedman Test: I7. Resource Forecasting (quantity) versus BIM-aspects blocked by Respondent**

S = 1.42 DF = 2 P = 0.491
S = 3.08 DF = 2 P = 0.214 (adjusted for ties)

CATEGORY	N	Est Median	Sum of Ranks
G	13	6.0000	24.5
D	13	6.0000	29.5
W	13	6.0000	24.0

Grand median = 6.0000

6. **Friedman Test: I7. Resource Forecasting (Labor) versus BIM-aspects blocked by Respondent**

S = 1.65 DF = 2 P = 0.437
S = 2.32 DF = 2 P = 0.313 (adjusted for ties)

CATEGORY	N	Est Median	Sum of Ranks
G	13	5.6667	29.5
D	13	5.3333	25.5
W	13	5.0000	23.0

Grand median = 5.3333

7. **Friedman Test: I9. Coordination versus BIM-aspects blocked by Respondent**

S = 0.27 DF = 2 P = 0.874
S = 0.88 DF = 2 P = 0.646 (adjusted for ties)

CATEGORY	N	Est Median	Sum of Ranks
G	13	7.0000	25.0
D	13	7.0000	27.5
W	13	7.0000	25.5

Grand median = 7.0000

8. **Friedman Test: I8. Project Control (Schedule) versus BIM-aspects blocked by Respondent**

S = 6.62 DF = 2 P = 0.037
S = 9.05 DF = 2 P = 0.011 (adjusted for ties)

CATEGORY	N	Est Median	Sum of Ranks
G	13	6.0000	32.0
D	13	6.0000	27.0
W	13	5.0000	19.0

Grand median = 5.6667

9. Friedman Test: I8. Project Controls (Cost) versus BIM-aspects blocked by Respondent

```
S = 0.50  DF = 2  P = 0.779
S = 1.04  DF = 2  P = 0.595 (adjusted for ties)

CATEGORY   N  Est Median   Sum of Ranks
G         13      6.0000    28.0
D         13      6.0000    25.5
W         13      6.0000    24.5

Grand median = 6.0000
```

10. Friedman Test: I8. Project Controls (Material Tracking) versus BIM-aspects blocked by Respondent

```
S = 1.88  DF = 2  P = 0.390
S = 3.06  DF = 2  P = 0.216 (adjusted for ties)

                          Sum of
CATEGORY   N  Est Median   Ranks
G         13      5.0000    26.0
D         13      5.3333    29.5
W         13      4.6667    22.5

Grand median = 5.0000
```

		Respondents			Summary
	Q: Define the value of BIM in your own words	Theme 1 (red)	Theme 2 (black)	Theme 3 (blue)	
	priori classification:	**what is BIM?**	**expected value from BIM**	**requirement for implementation**	
	Owner				
1	A strong BIM program along with **defined deliverables** can define the **outcome** of a successful project or a failure. Defined by world class or not.	program	better project outcome	defined deliverables	
2	A tool that helps **realize field issues** before we get to the field. In an environment that requires **installation accuracy** down to fractions of the inch, BIM has acted as a great enabler.	tool	realize field issues, accurate installation	N/A	Program Tool Process
3	BIM **reduces overall cost** through **better coordination** and **reduction of changes**	N/A	reduce cost, better coordination, reduce changes	N/A	- Better project outcome - Reduce cost - Reduce schedule - Improve quality - Informed decision-making - Improve productivity - Better coordination - Accurate installation - Better sequencing
4	**Increase productivity** of contractors(trades); allows **shorter project durations** by doing fabrication of many different components in parallel (no need to wait for one component installed in the field to validate the details of subsequent ones); allows **better sequencing of work**, using pull planning; **better quality** of fabricated components (>95% of components fabricated off-site in controlled environment of trade's shops.	N/A	reduce schedule, improved quality, improve trade productivity, better sequencing	N/A	
5	BIM is the gathering and/or visualizing both project and lifecycle data for a building. This involves the use of **standards** and agreed upon **workflow practices** to ensure the integrity of the data for **future use and on demand decision making.**	process	lifecycle data for future use, on-demand decision making	standards, workflow practices	- Investment - Standards
6	I can see the value of this type of program, however, my company just cannot get past the **purchase price** and the associated maintanence cost.	program		investment and maintenance cost	
7	BIM is at the core of all of our preconstruction services and is a major component in the closeout of our projects. The way we look at BIM is as an all encompassing tool that allows our teams to make the **most informed decision to efficiently construct our projects.**	tool	informed decision making, efficient construction	N/A	
	A/E				
1	Taking all the information available to create a useful Model for every aspect of engineering/construction/maintenance side of buildings	tool	database of information	N/A	Tool
2	BIM is a tool that is growing in different directions and has several layers to it, but it will only be as good as the **owner and or users** make it. It is so powerful with its intelligence.	tool	intelligence	owner & user involvement	- Database - Intelligent modeling
3	The information is the key asset. The visualization and **BIM authoring interface is critical to developing the information**, but the model is really just the interface to the data.	N/A	information	N/A	- Owner involvement
	CM				
1	BIM provides a unique opportunity to construct virtually and evaluate the project at a new level. **Implementing work flow, accuracy, and details into a 3D model** before physical construction has occurred allows for **less waste, cleaner and safer install,** and provides a big pictures to the trades when installing. BIM is not a part of the project, it is a lifestyle for a project. In order to reap the full benefits that come with BIM it needs to be **implemented at the beginning.**	lifestyle (program)	less waste, cleaner and safer install	front-end implementation, accuracy, workflow	Tool / Technology / Model Process Program
2	BIM allows designs, ideas and concepts to be **viewed, analyzed** and **revised** in the 3D world as opposed to stick building and finding errors/clashes late in install.	N/A	visualization, analysis and revision of design issues, early detection of	N/A	Design - Early detection - Analysis - Revision - Detection of errors Management - Project Controls - Coordination On-site/Install - Visualization - Less waste - Less rework - Safe install - Reduced install time - Reduced headcount - Prefabrication
3	The value of BIM is its ability to **get the design kinks worked out** before construction begins. BIM alows us to work with smaller crew because we have **less rework** and helps us to derive a consistant schduel for instillation in the field. It allow field workers to look at a project and **what the need to do before they begin**, and helps with **safety** becuase the personal will only be going in to tight areas once. BIM allows for **prefabercation** cutting cost. BIM helps to keep a level number of people employeed so we don't have to do massive hireing and layoffs.	N/A	less rework, safety, prefabrication, resource allocation, resolve design issues	N/A	
4	BIM has allowed to perform full **fabrication** at our shop for electrical install. This leads to a **reduction in install duration and less manpower needed** on the job site which leads to savings for us and our customers. We are **not where we should be with generating cost, schedule, manpower information** but heading that direction. Once there the cost of estimating will also be reduced as it will be built into the model which will also be savings for all. BIM is the only significant productivity improvement the construction industry has made in years and we continue to share benefits from well planned BIM projects	model	prefabrication, reduced installation time, reduced headcount, savings	technology upgrades	- Front-end planning - Technology upgrades - Initial investment - Interoperability - Standards - Communication - Strategy - Accurate information
5	Proper use of BIM provides an efficient means for **real time coordination** identifying unknowns and **preventing rework**; additionally it **allows what-if evaluations** cost & time effectively when alternate solutions are considered; although it **increases time expended upfront**, it more than makes up for it in the long run. From my perspective it is an excellent example of the right tool for the right job when properly used, and has the advantage of being introduced for virtual design to benefit work prior to including logics for material, manpower, and cost. The only disadvantage is the **initial and licensing costs** of required for equipment and software, and **inability of some software products to communicate with others**, which is limiting for some organizations.	tool, VDC	real-time coordination, prevent rework, what-if evaluations	more upfront time, initial investment, interoperability	

6	Allows us to preperly staff the team, pull in **durations** and understand the contractor **cost.**	N/A	analyze costs, schedule	N/A	
7	BIM is a huge value to those who follow the process to the letter. This removes the constraint of having to hire numerous amounts of skilled tradesman during work ramps and puts the technical component of how to build something into a 3D world where they have a **picture** to follow and don't have to think on the fly off of 2D schematics. This allows projects to **stay on task** with **fewer issues** and lessens the learning curve during busy times of the schedule.	process	visualization, schedule control, reduces learning curve, reduces the need for skilled tradesmen	N/A	
8	This is a question with a depends answer. Normally when using BIM it has a specific purpose for a specific project. The most important value I've seen is **clash detection**. This allows products to be prefabricated and installed much quicker **without the fear of rework.**	N/A	clash detection, less rework	N/A	
9	Overall I see BIM as the binding force between Fabrication/Manufactured Equipment and the performance, installation and ongoing operations of buildings moving forward. As **standards improve** and become commonplace we'll see more and more usable BIM. Currently the value of BIM is only seen as a **clash detection tool**... as manufacturers share **accurate information** the BIM process will become a priceless asset for ALL players.	tool, process	clash detection	standards, accurate information	
10	The value of BIM resides in it's ability to produce **predictable outcomes**. This can be the difference in profit or loss; success or a lawsuite.	N/A	predictable outcomes	N/A	
11	BIM is a tool that allows the work to planned and **coordinated** fully with all stakeholders prior to commencing work. BIM enables companies to **prefabricate** in an controlled environment and reduce the quantity of workers in the field. By **reducing head count in the field,** overall **risk to the project is being reduced.** By following the BIM process, the **typical durations** for performing work are reduced significantly.	tool	coordination, prefabrication, less headcount, reduced schedule, risk management	N/A	
12	BIM is invaluable when used correctly (**execution, use, communication to partners, reference, accuracy**, etc.) in the **successful execution of construction projects** of today. In fact, firms that do not accept its value in their **planning and strategic processes** will eventually find themselves outdated, irrelevant and not competitive. Those that use BIM in planning, execution and operation of the built environment will continue to find value and return on a relatively small investment.	N/A	succesful execution of construction projects	communictaion, accuracy, part of strategic processes	
13	**Clash detection** and **sequencing** of work is the most important benefit. It is also very important for coordination of trades not only for clash detection, but to ensure that all building components will fit into the designated space.	N/A	clash detection, sequencing	N/A	
14	The value of BIM is all in the (I). Without the information contained in a BIM, the **project controls** and processes that have been developed all fail. It is even more difficult to go back to a pre-BIM process once you have truly embraced the use of BIM technologies. Not only more difficult, but also undesirable.	process, technology	project controls	N/A	
	Modeler				
1	The term BIM explains the importance of what it is used for. If any of the parts of BIM are lacking, the project can suffer significantly in time, cost and potentially even safety. Modeling a building based on **reliable information** can only work with a **complete buy-in from all the parties involved** in the contract, and with the understanding that **sharing information** is beneficial for everyone.	N/A	N/A	buy-in from all parties, reliable information, information sharing & collaboration	Process - Reduced time - Reduced cost - Reduced headcount - Coordination - Means & methods
2	BIM in my own words defines the process of saving time and materials in any construction process. The amount of steps that can be **reduced** by having a good BIM work-flow can not be explained exactly as every project requires a different work-flow based on size and complexity of the project. It is very important to have the **right people** in those positions to set up the work-flow for each individual project. That being said, I have been using **3D BIM and work-flow** for 8 years on two different software platforms with great success when used at it's full potential, but have also witnessed it's failure a couple times in those 8 years due to **infrastructure breakdown** of the work-flow because the wrong people are trying to control it. The BIM process must not be driven by a person in finance. That is usually who is deciding the amount of time that gets put into the work-flow due to cost. The issue with that is, those people don't understand the process and do not see the savings up front so they cut major steps out of the program. I have witnessed this first hand and it does collapse the BIM process. The companies need to have faith in the program and the people and invest 100% into BIM or it will fail.	process	reduce time, cost, reduce steps in worflow	right people, full adoption, identified workflow	- Stakeholder buy-in - Reliable information - Standard workflow - Information sharing - Complete adoption
3	A process that enables us **coordinate** together to make buildable models of almost anything.	process	coordination	N/A	
4	BIM is the process of creating and utilizing a 3D digital model of a project, including the **means and methods, design, and attribution data** of the products.	process	means & methods, design, data	N/A	
5	Taking Construction to the next level that will eliminate work force in the field, **increase schedule and overall save $**.	N/A	reduce cost, time and headcount	N/A	

Figure F3. *Qualitative Analysis*