ABSTRACT

Title of Document: THE EFFECTS OF BUILDING INFORMATION MODELING ON CONSTRUCTION SITE PRODUCTIVITY

Douglas E. Chelson, Doctor of Philosophy, 2010

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Construction experiences low productivity compared to other industries, largely attributed to poor planning and communication. Building Information Modeling (BIM) is a process that is used to resolve these problems by simulating physical space and expressing design intent graphically, providing a clearer image of design conflicts or constructability issues so that they are resolved before construction begins. Productivity rates increase as BIM practices are implemented because rework and idle time are reduced for laborers.

Case studies of projects utilizing BIM indicate field productivity gains from 5 to 40%, depending on how the process is managed. Although the amount of savings is guarded closely by those who measure and track the changes in their productivity rates and unknown to many contractors, there are indicators that reveal increased productivity. *Key indicators of increased productivity are RFI reduction, amount of rework, schedule compliance, and change orders due to plan conflicts*. Each of these affect the various stakeholders of a project to different degrees but the overall effect is a net savings for the owner ranging from a few percent for competitive bid projects to

over 10% for integrated projects. BIM-enabled projects have 10% of the RFI that a typical project would have so that contractors realize an average savings of 9% in management time. Reduction of rework and idle time due to site conflicts savings for trade contractors are on the order of 9% of project costs. The abilities to prefabricate and automate site processes are also significant advantages of BIM usage experienced by trade contractors. The most significant savings are attributed to the clash detection process which eliminates conflicts in the field. These findings show that the strongest determinants of success on BIM projects in terms of site productivity are human factors rather than technical.

THE EFFECTS OF BUILDING INFORMATION MODELING ON CONSTRUCTION SITE PRODUCTIVITY

By

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Dedication

To my wife, Wendy.

An honorable mention to: my father and my children: Megan, Tata, Spud, Bug, Duke, Kekka, Meena, Fat Boy, Beast and Baby.

With gratitude to my sister, Debbie, who taught me to save.

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Chapter 1: INTRODUCTION

In the architecture, engineering, and construction (AEC) industry, diverse people, processes and materials are brought together to construct projects that are becoming increasingly complex. Stringent codes, sustainable design and equipment, high-tech communication systems, and environmental control systems installed in confined spaces under increasingly aggressive schedules make it necessary for each team member to be able to translate visual, written, and oral expressions and understand nuances to communicate effectively. This ability for each individual in the project team to visualize the design concept is crucial to create a finished product that meets the need of the owner. Communicating design intent from the *owner* to the *architect/engineer* and to the *builders* is a difficult task because of the various backgrounds, references and goals of these project participants. Building requirement definitions are frequently vague from the owner and/or the architect.

The standard design communication tools are specifications and two dimensional (2-D) drawings, but there are ambiguities endemic with these. When the plans and specifications do not communicate design clearly, builders must spend time asking for clarification, changing plans, and sometimes re-working components that were installed according to the builder's interpretation of the documents, but not in compliance with the owner's needs. These inefficiencies increase the amount of time and resources required to complete the product, thus productivity rates are lower and costs are higher. Proper communication of design intent and planning solves most of the problems causing the symptoms of unmet expectations, increased costs and delayed projects. When implemented properly, BIM is an effective tool in a planning and communicating process which results in increased productivity rates in the field.

1.1 Productivity in Construction

1.1.1 Production vs. Productivity Rate

Production is work that contributes toward achieving a goal. Installing a light switch is work, but is productive work only if it is done at the right place, at the right time, and in the right manner. *Productivity rate* is the ratio of unit input per unit output and is often given as a percentage. It is possible to be productive, but have low productivity rates. An example of this would be when additional labor is added to a project but proportional increase in output is not gained due to crowded conditions or improper planning. Per Figure 1 the productivity rate increases as the size of the crew increases up to a 7 person crew. After that the

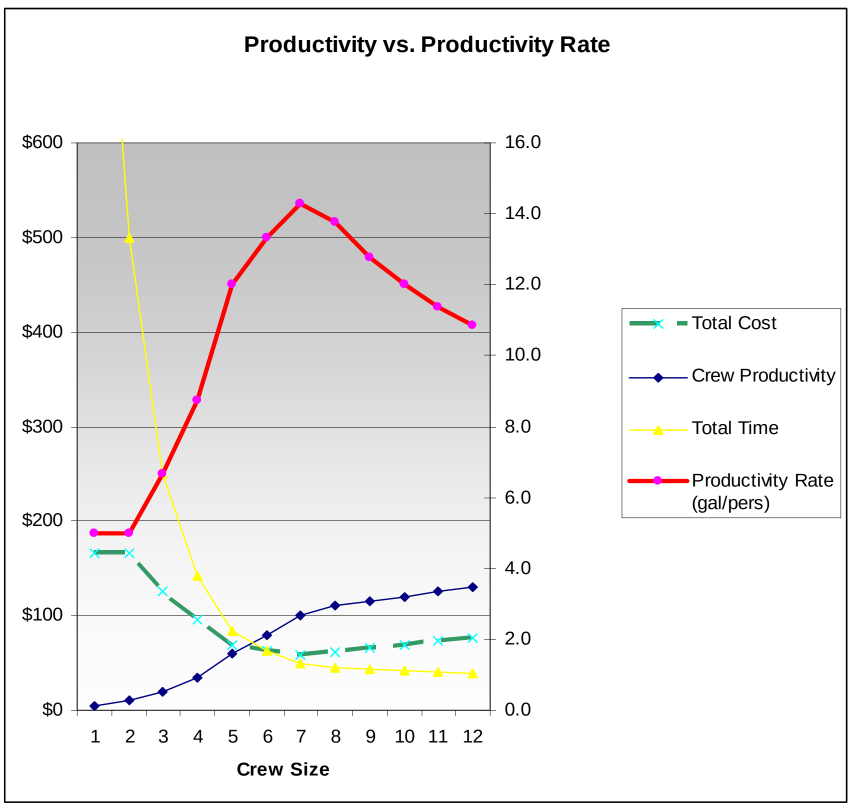

Figure 1 - Illustration of productivity vs. productivity rates.

rate falls because there is not enough room for each member to move efficiently so that output per person decreases. However, the amount of output for the crew continues to increase past the crew size of seven. Thus, despite the though total time decreases, the total cost to complete the task increases when more than 7 crew members are added.

The higher the *productivity,* the faster you are getting something done. The higher the *productivity rate,* the greater efficiency and therefore, total cost to complete the task is lower. The productivity rate is important because it is indicative of the amount of money that you are going to spend to produce the final product. This dissertation is concerned with construction site productivity rates.

1.1.2 Construction Productivity Relative to Manufacturing

The Construction Industry Institute (CII) determined in a study that the construction industry only contributed 10% of its effort to directly creating value while manufacturing contributed 62% (Eastman, 2008). Paul Teicholz of the Center for Integrated Facility Engineering

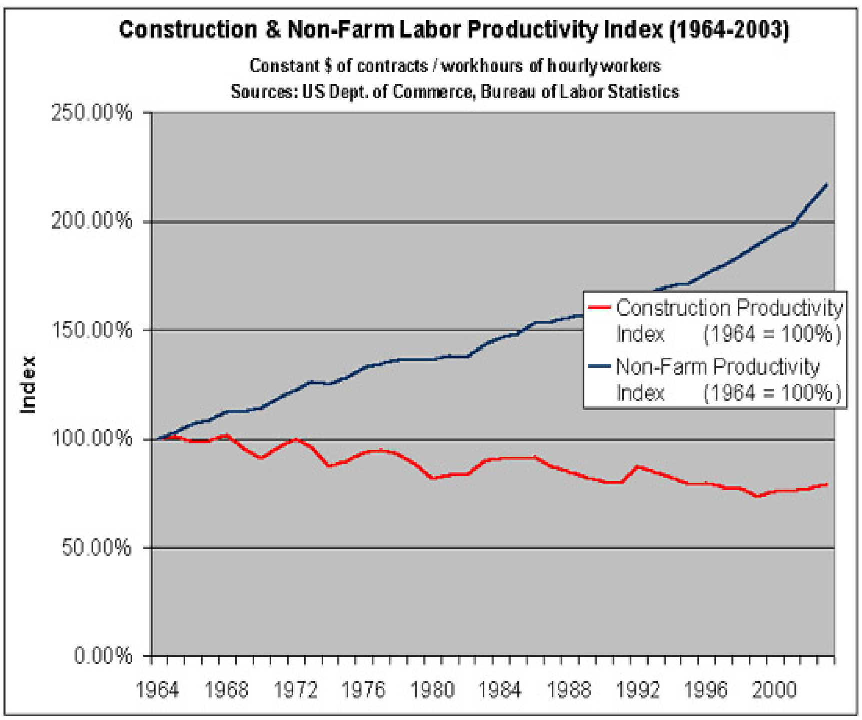

Figure 2 - Construction vs. manufacturing productivity rates. From US Dept. of Commerce, Bureau of Labor Statistics.

(CIFE) studied productivity based on contract dollar per labor hours input for both manufacturing and construction operations. He concluded that construction productivity declined approximately 20% from 1964 to 2003 while manufacturing increased by about 120% (See Figure 2). Teicholz attributes the increases in productivity in manufacturing largely to the automation and planning and coordination activities made more accessible by computerized processes that were available to manufacturing but not available to construction.

In addition to computerization, other factors contributing to the discrepancy between manufacturing and field construction are:

- Weather conditions on job sites make working conditions less conducive to time and quality control issues than in the environmentally controlled factory.
- Tools and equipment are superior in a factory over the mobile conditions on construction job sites where large machines are impractical due to the cost of mobilization.
- Work flow processes can be improved in factories but varying conditions from one job site to another preclude work layout optimization in many situations.
- Interrelationship of labor and processes from other trades working in close proximity adds scheduling and logistical problems at a job site.

The effects of each of these can be reduced by coordinating the materials and means of assembly on the site such that more complete parts are brought from a controlled factory environment and final assembly is done on the site. This turns the field constructors into the final assembly line component of building manufacturing.

Construction is manufacturing, but the factory is more mobile and thus not as easily controlled. The construction industry has not embraced the technology that has power to cause productivity rate increases for various reasons. A principle reason for this is that the more varied conditions on a construction job site make planning and modeling more difficult than in the controlled environment of the factory. BIM has the capability to aid the construction process in increasing efficiencies as manufacturers have done.

1.1.3 Poor Field Productivity Factors

The single biggest reason for low field productivity rates is lack of planning and control over the construction process. Construction typically sees about 40 – 60% productivity rates, depending on the trade (Eastman, 2008). Only half of workers' time is spent performing work that creates finished product and roughly half of their time is spent not creating value. Adrian (1987) showed that about 35% of workers' time is lost due to waiting for instruction, materials or other workers.

1.1.4 Cost of Poor Field Productivity

The cost of low productivity on job sites is large – especially when one considers that the construction industry is one of the largest in the U.S. at about 13% of GDP (gross domestic product), or about 1.6 trillion dollars in 2007. Traditionally it has been 10 to 11% of GDP (DOC, 2008). The typical rule of thumb for construction sites is that 40 to 60% of the cost of the physical product is labor, depending on the level of prefabrication and the quality of the material (Heldman, 2009). Assuming labor costs are 50% of the project cost and a firm can decrease wasted labor by one-third, then it follows that one-sixth of the project cost could be saved by properly planning, coordinating and communicating. The average house in the U.S. in 2008 was $88.55/SF (NAHB, 2009) and the average size was 2,459 SF (NAHB, 2009), making the average price of a house $217,744. One-sixth of that amount, about $36,000, can be attributed to poor planning, coordination and communication for field labor. Likewise, one-sixth of the 1.6 trillion dollar industry, $266 billion, is spent annually on wasted labor hours due to poor planning and communication. Kymmell (2008) states that the additional planning does take time and money to accomplish, but it has been shown that the cost of changes and planning earlier in the project before actual work in the field begins is far less expensive than making the changes or clarifications in the field.

1.1.5 Methods to Increase Field Productivity Rates

1.1.5.1 Prefabrication

Fabricating building components off-site in pieces reduces costs because the work environment can be controlled and quality can be more closely monitored. Prefabrication may increase productivity in the factory, but it can have the unintended effect of lowering productivity rates in the construction field because only the work that cannot be efficiently automated or systemized is left to be accomplished in the field. However, productivity rates increase on the project overall. Steel companies endeavor to fabricate as much in the shop as possible in order to reduce the number of more time-consumptive and costly welds and connections in the field. Fabrication in the shop is easier to perform and easier to inspect and verify. Southland Industries, a large mechanical firm, pre-assembles systems and tests them in the shop before delivery to the field. They even include wheels for easy moving (Sanvido, 2008). Cupertino Electric prefabricates because it can achieve much higher quality and reduce re-work in the field (Martinez, 2008). Prefabrication results in a net increase in productivity for these trade contractors.

1.1.5.2 Planning and Coordination

Construction firms use several different management styles in their efforts to improve performance and productivity rates. Management styles or systems such as MBWA, MBO, JIT, Lean, TQM and others vary based on corporate culture, but all try to organize systemic improvement by establishing goals, measuring results and directing further changes. Firms that formally establish goals or benchmarks and measure progress against these goals report increased performance (Young, 2008). This planning, however, takes time and resources up-front. Most firms are hesitant to spend much money before work starts because of cash flow problems. Planning to reduce conflicts and coordinate workflow done early in the project has been shown to save total projects cost from 4 to 8 times the initial investment in preplanning (Oglesby, 1989).

Pre-planning is done in construction by using scheduling programs for resource loading and task dependencies, a variety of spreadsheets or analysis programs to compare costs of various methods of construction, and document control programs to organize and plan communication. Design coordination has been done overlaying drawings or on CAD to determine conflicts and problems in constructing. More technologically advanced firms combine many of these tools into ERPs to streamline the data usage efficiency and web-based collaborative systems to further aid in obtaining input from stakeholders. The BIM process aids in pre-planning by increasing design communication effectiveness by visualization and coordinating the various systems and trades that will be constructed together.

1.1.5.3 Waste Reduction

Lean construction is a management method that looks for waste in construction processes and tries to reduce or eliminate it (LCI, 2008). Any activity that does not directly contribute to the finished product can be considered wasteful and should thus be eliminated. *Total Quality Management* (TQM) is based on the idea that every task contributes to compliance to the specifications or project goal. Improving not only the product but the process means that any activity that does not create value for the owner is wasteful. Quality improvement will drive wasteful tasks out of the project description until the standard operating procedures (SOP) are so organized that no inefficiencies are part of the plan.

Of course these are not entirely practical in construction due to the changing nature of projects, but there is much improvement that can be done. Koskela (2000) gives the term “suboptimal conditions” to describe a work environment resulting from interference between tasks. She found in her study that waste and value loss ‘primarily originated from prior phases of the project’ rather than from the task itself. Thus, much of the waste in construction arises from the lack of planning between tasks and not just in specific tasks. BIM enables planners to view conflicts between tasks before the conflicts become evident in the field.

1.2 Building Information Modeling (BIM)

1.2.1 BIM Definition

Managing building information has become more difficult in recent years as building systems have become more complex, project durations have decreased, and costs have become more scrutinized. In the days of master builders, the model of a building was in the mind of that master builder. Now, one person cannot possibly envision all the spatial relationships and requirements for all aspects of the building. Coordinating the many specialized fields involved in building has been difficult using 2-D because information is not centralized and communicating spatial relationships between the components is difficult. Returning to the concept of the master builder, BIM offers the single entity visualization and planning. The entity is a group of specialists who view and work a design concept made available by BIM software. Defining BIM is difficult because it refers to software tools, an independent created model, and to the process of designing and coordinating a project using BIM tools.

The term “BIM” often refers to the software that helps organize the data concerning the relationships of the building components and represents them in 3-D. BIM tools are often more intuitive and easier to use than traditional 2-D software tools because images are represented more realistically. When an element is changed on one view, all related information, be it in charts, schedules, elevations, details, etc., is changed simultaneously and represented accordingly in other views. The power of BIM tools is not limited to its ability to help visualize the design, but includes the amounts of data that are related to the objects in the design and its ability to communicate this information about individual project components (Kymmell, 2008).

BIM can be used as a noun to mean a Building Information Model which is a compilation of building information. The data are interrelated objects with all pertinent information on each object attached to it. A door in a model is not just a few lines *representing* a door, but contains all information that pertains to manufacturing, locating, installing, finishing and maintaining it. Users needing access to information view only information pertinent to their interest without changing the overall relational data. Thus, the power of the model is that many parties can work with a common database and have current information.

When used as a verb, Building Information Modeling refers to the act of simulating real activity relating to a building or construction project (Eastman, 2008). Similarly, the BIM SmartMarket Report by McGraw-Hill defines BIM as “the process of creating and using digital models for design, construction and/or operations of projects” (Norbert, 2008). Whichever the case or tense, BIM refers to a relatively new technology that supports visualization and communication of building design and construction processes. Rather than a software, BIM is “a systems approach to the design, construction, ownership, management, operation, maintenance, use, and demolition or reuse of buildings” (Smith, 2009). The most important part of BIM is not the software functionality, but collaboration in the design and planning process which speeds the process and clarifies design (Onuma, 2008). Depending on context “BIM” may be used to represent either of these definitions in this work.

1.2.2 How BIM Improves Productivity

BIM enables efficient productivity rate increase in *each* of the methods which increase rates in construction in general outlined in 1.1.5. It requires and causes collaborative design and coordination. It enables more efficient prefabrication, and reduces process and material wastes.

A major advantage of BIM is that it requires *earlier and better building design* which *increases productivity rates*, which causes compression of the overall project schedule. Figure 3 shows that the BIM process forces more design decisions to occur earlier in the project when impacts on cost are lower. Because construction components are detailed in 3-D, there are fewer conflicts in plans and greater understanding of what is

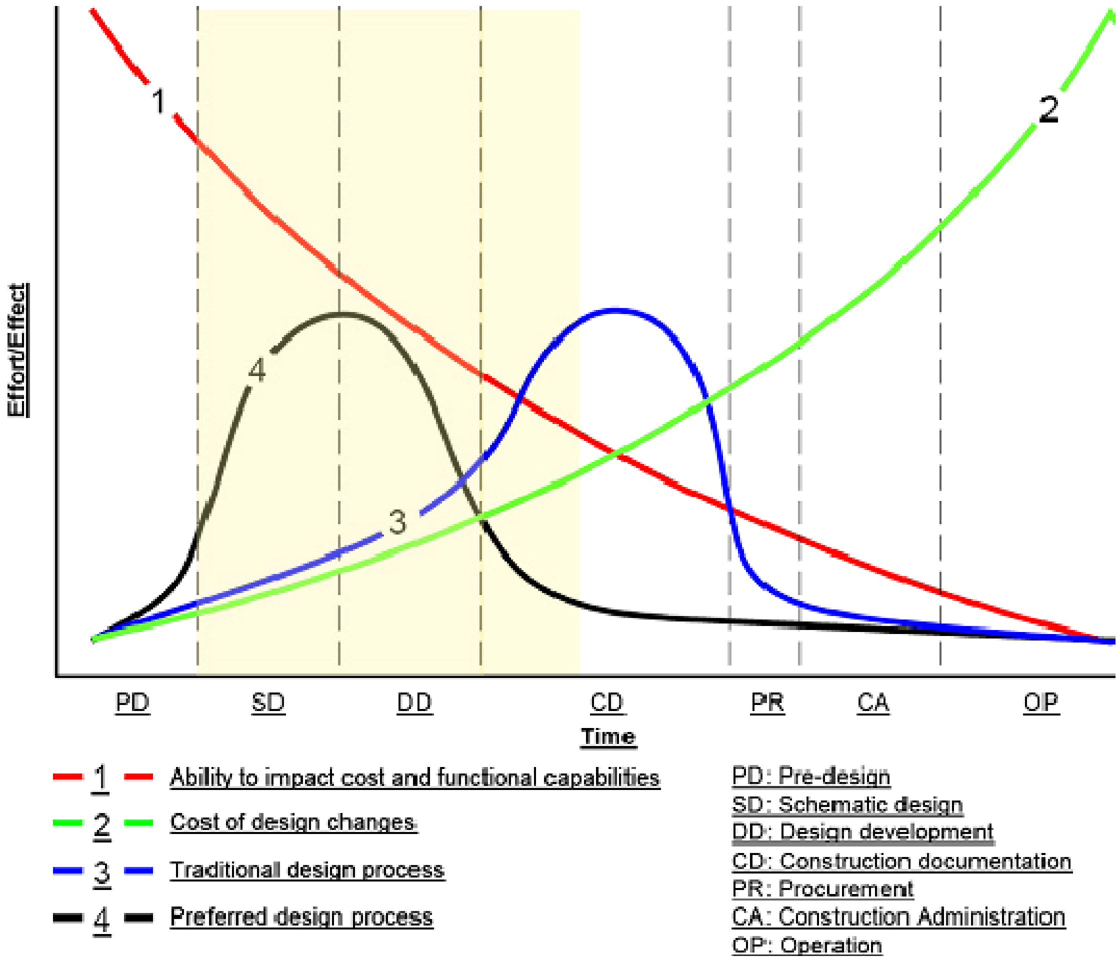

Figure 3 - Cost impact of shifting design curve to the left. (Source: CURT WP 1202, August 2004).

to be built prior to the actual construction process. BIM is used to coordinate complex building components and reduce the number of errors. This reduces the amount of delays and rework resulting in cost overruns. Case studies have shown that resources spent on the models before construction decrease the amount of changes and delays. (Smith, 2009; Kymmell, 2008; Hardin, 2009; et al) BIM usage drastically reduces requests for information (RFI) because the intent of the plan is more clearly understood. The resulting building product will be closer to the intent of the design and thus higher quality (Zeiger, 2008). Expending effort and money up front in the planning and design stages directly affects the *productivity in the field*, and thus the *profitability of the entire project.*

It is difficult to know exactly how much is saved by the use of BIM largely because, like health maintenance, prevention is stressed rather than the cure. Therefore, most reports of BIM's benefits concern cost avoidance or prevention of costly changes due to poor design. Productivity risk is a great concern to contractors and they bid projects based on how productive their crews have been in the past. Increasing planning capability should allow work to be installed with less confusion, delay, and re-work which should increase decrease labor and material costs. BIM is another tool that can be used by contractors to increase their productivity and thereby beat their estimates, thus turning a profit. Anecdotal results on one large firm's projects suggest that a 2 – 3 times payback is gained for the contractor for BIM expenditures (Post, 2008).

1.2.3 The Future of BIM

BIM usage is anticipated to continue to increase rapidly from the estimated 2-3% of the firms in the AEC industry that use BIM in a meaningful way (Bernstein, 2005). Since 2007 The Government Services Administration (GSA) and the US Army Corps of Engineers requires all physical facilities built for the government to be modeled. The effect of just these two government programs is enormous! More private owners are also requiring the use of BIM in order to increase efficiency of the building, lower costs and to enable more creative designs. High-profile projects such as the Ocean Heights Tower designed by Aedas in Dubai, 2008 Beijing Olympic National Stadium (the Bird's Nest) designed by Herzog & de Meuron, and the Frank Gehry designed Disney Concert Hall in

Los Angeles have brought more attention to construction styles and types that were impractical without the use of BIM.

Once BIM has been utilized on a project, its results speak for themselves and "firms that have switched to BIM don't switch back" to 2-D (Zeiger, 2008). Many jurisdictions are pushing to adopt BIM plan checking, which will further push architects and contractors to produce models for faster approval (Wible, 2009). Virtually all stakeholders are adopting BIM usage to some degree. Ideally, BIM will become a central part of the organizational structure of the design, build, and operation process including all aspects of the lifecycle of the building. All data pertinent to the project should be included and accessible to parties that need the information. Eastman writes:

> "A two-way interface to communicate with procurement, production control, shipping, and accounting information systems is essential in order to fully leverage the potential benefits… These may be stand-alone applications or parts of a comprehensive enterprise resource planning (ERP) suite. To avoid inconsistencies, the building information model should be the sole source for part lists and part production details for the full operation. Fabrication is performed over time, during which changes may continue to be made to the building's design. Up-to-date information regarding changes made to pieces in the model must be available to all of a company's departments at all times if errors are to be avoided. Ideally, this should not be a simple file export/import exchange but an online database link. Minimally, the software should provide an application programming interface, so that companies with access to programming capability

can adapt data exchanges to the requirements of their existing enterprise systems" (Eastman 2008).

This utopian system describes a model which is comprehensive, with robust software and users implementing the system properly. It sounds like an advertisement of a software company trying to vend their BIM tools. However, it comes from one of the leaders in BIM development and is more likely a prognostication than a sales pitch. Eastman describes a pervasive system of control here, and this is what is needed because waste in the construction process is pervasive. The technology will catch up with this vision as quickly as the culture changes to require it (Chelson, 2002). Increased usage will cause the market to respond to demand so that improved capabilities will become available.

1.3 Research Need

1.3.1 Understanding of the true value of BIM implementation

Because adoption of new technologies tends to be slow and difficult, it is usually only accomplished when required by government or owner regulations or when economic advantages seem so undeniable that the trouble, training, and expense of implementation is overwhelmingly justified. As mentioned in 1.2.3, many owners, including the GSA, are beginning to require models on their projects. Many general contractors (GC) contractually require key trade contractors to model their work and participate in collaborative meetings to resolve design and constructability conflicts. Turner Construction's approach, as well as a majority of GCs, to this includes placing the mechanical contractor in charge of doing clash detection for the construction team so that the clashes can be discussed in regular coordination meetings. Owners and contractors who include BIM usage in their contracts do so because of savings anticipated on the project.

Project leaders considering adopting BIM to gain perceived or possible advantages need to know the cost of implementation and the amount of expected savings through implementing BIM. *The value of BIM is the amount of money that can be saved by increasing productivity less the amount of the cost of performing the process*. Knowing this value will allow intelligent decision making regarding BIM. Currently, decision makers rely on testimonials and case studies to hear what *can* be saved or what others *have* saved. The citation of these testimonials and case studies would reveal that the variations in costs and savings are largely unpredictable. The AEC industry does not have the data needed to enable owners and contractors to predict an expected return on investment (ROI).

The hypothesis of this thesis is that BIM usage increases construction field productivity. Management choices will have an impact on the level of productivity increases and the savings gained are shared by owners and contractors. The productivity increases are expected to reduce construction costs such that total project costs to the owner should decrease.

1.3.2 Productivity Changes Associated with Specific BIM Practices

There is a need in the AEC industry for a benchmark of how much money is saved given an implementation strategy. The cost of implementing BIM on projects depends on many factors, which vary from project to project, including:

- type of software,
- level of model detail (LOD),

- expertise of the design and construction teams,
- sophistication and knowledge of the owner,
- complexity and uniqueness of project,
- when the process is started,
- time frame, and
- project delivery method (contract type).

The owner either directly or indirectly decides how these factors are managed. Knowing the expected cost savings associated with these specific practices would enable better decision making concerning BIM methodology. These causal relationships between the owner's and AEC team's decisions and the outcomes in terms of time and cost savings on the project need to be discovered and made available to the industry.

A BIM project that is properly detailed results in fewer conflicts and greater productivity during construction. Therefore, the decision *whether* to use BIM is only the initial decision and *how* to use the BIM model effectively up front to gain the greatest productivity on the field becomes the focus. Given current technology and the newness of collaborative BIM process practices, it is cost prohibitive to model every element on each project. Early in the project, the team determines which elements are likely to suffer conflict and require modeling. For example, does the toilet carrier need to be detailed or does a rough image of a toilet suffice? Because the higher the detail, the higher the model cost, it follows that if the detail is not useful because the installation is typical and no conflicts are expected, the higher detail should be avoided. This reduces costs when there is no expected savings from field coordination's reduction of conflicts. Too little detail will not sufficiently reduce field conflicts and the high costs associated with them. Too much detail and money and time is spent unnecessarily.

1.3.3 Net Effect of BIM Investment on Productivity Rates

BIM effectiveness is most often viewed in terms of cost avoidance – a reduction in the amount of change orders or project delays. This is only a part of the savings available. Contractors and owners are frequently missing out on additional savings available by productivity rate increases. Owners opt to use BIM primarily for faster schedules, earlier commitment of costs and the reduction of unanticipated costs or changes (Songer, 1997). When projects are appropriately modeled, the decrease in errors not only reduces the number of RFIs by a factor of 9 (Stanford, 2004) and change orders due to conflicts to near zero (Kymmell, 2008), but increases the productivity rate by reducing the time spent on tasks that do not contribute directly to the finished product. Time is not saved by simply adding resources, but by using resources more efficiently by proper planning with the aid of the model.

To understand the net savings one must know the additional costs of using BIM over normal preplanning efforts. The value of both the cost avoidance and the savings due to the increase in productivity rates for comparable BIM projects and non-BIM projects must then be compared to determine the cost savings associated with employing specific BIM practices. Thus, the net effects which specific BIM practices have on productivity rates can be known. With this information, more precise estimates for cost and time are probable such that more exact schedules and cost budgets can be made.

1.3.4 How much money can BIM save the AEC industry?

As mentioned earlier, the common evaluation of BIM savings is based on how many changes were eliminated and therefore extra costs avoided. The actual amount is not known. Anecdotal numbers and ‘general figures’ vary between software sellers, advocates and practitioners, but most fall in the range of 10 – 30%, although designers generally report higher increases. Following are samples of proclaimed savings:

- estimated returns of 2 to 1 and approximately 10% labor savings (Carbasho, 2008),
- design firms experienced 50% productivity gains by half of Revit users (Autodesk, 2007),
- labor productivity 15% to 30% better than industry standards (Khanzode, 2007),
- engineers had 47% decrease in labor hours needed to design and manage projects (Kaner, 2008),
- ROI on BIM is between 11 and 30% per AGC BIM Forum members (Young, 2008).

Using the information from 1.1.4 and assuming an increase in labor productivity of 20%, the cost savings available would be in the $160 billion range per year in the US. At a project level, this would represent an 8 to 9% reduction in costs that could be distributed between owners and contractors. This is not a re-distribution of wealth (from the laborers to the owners), but rather an elimination of wasted effort and costs.

1.4 Research Objectives

It is generally accepted by practitioners and evidenced by research that BIM usage increases design effectiveness and reduces total project costs. The question remains: how much is saved? The research should be able to provide data needed to determine how much time and money is saved in terms of field construction. The following indicators will be measured against the project and process variables to determine the causal effect BIM has on increasing field construction productivity rates.

1.4.1 RFI (request for information)

The number of RFI on a project is generally indicative of the level of clarity and completeness of plans and specifications. RFI take time from construction tasks – generally more than would be required to plan correctly during the design phase. One project reported having only a few RFI after using BIM procedures when that type of project would typically have a thousand RFI. This type of decrease in RFI, or decrease in confusion about design, is common on BIM projects according to the studies and advertisements about BIM. It translates to increased field productivity and decrease in wasted paper work. Knowing the cost of RFIs in terms of administration and lowered field productivity, and the number of RFIs avoided on a project by the use of BIM would be an indicator of the cost and time impact that better planning and modeling can have on a project.

1.4.2 Change Orders

Change Orders are extra costs paid to contractors by the owner when conditions differ from the contract documents. They are a common result of RFI. Five to ten percent contingencies carried by owners are not uncommon in anticipation for such extras. The *number of change orders* indicates the amount of confusion and costs associated with delays due to poor information, change of work, or re-work after a problem is discovered and resolved. The *dollar amount of the change order* is indicative of the scope of the severity of the changes. The change orders in question are those originating from plans and specification problems rather than unforeseen, differing conditions or design changes during the project.

1.4.3 Schedule Compliance

Construction schedulers should be able to predict work durations based on anticipation of how well the crews are able to meet productivity projections. If there are fewer delays because of more accurate and detailed planning, the schedule will not just be faster than on a standard project, but the anticipated target date will be hit more often. Scheduling accurately, as opposed to building faster or completing sooner, is important so that different tasks can be coordinated more closely. When contractors begin to see that the schedule is on track, they are more likely to be ready for work when it is scheduled to begin. Often, trade contractors do not believe that the space will be ready for them and will not follow the schedule closely. Schedule compliance is represented by how close the task is to its projected duration and is given as a percentage of time variance. Here, a positive or negative variance is not desirable because the issue is accuracy more than speed.

1.4.4 Delay Time

Delay is measured from the point when progress on a task is halted or slowed until progress is able to resume. In some cases, when there is a delay because of missing information or plan conflict, workers are put on a different task that may or may not be directly contributory to completing the finished product. In either case, the time required to change tasks makes the productivity rate for the project suffer. The delay time and cost includes time writing RFI, CO, getting materials, re-tooling and re-mobilizing.

1.4.5 Productivity Rate

If available, the labor productivity rate shows how effective the field personnel are at contributing effort to the finished product. This number may be represented in units/hour, units/dollar or in total hours/dollars expended on a task. By comparing these rates against projects that did not utilize BIM processes, the factor of influence BIM has on field productivity should be apparent in terms of labor.

1.4.6 Project Variables

BIM has been used on a variety of project types and sizes but there have been no studies found by the author showing relative savings based on project type. Construction projects are classified by size, cost, complexity, uniqueness, and project delivery method (PDM). It is expected that the most effective way to evaluate the changes in the key performance indicators (KPI) is against a matrix of these classifications, with complexity and size being the most significant. The result of the study is anticipated to show how different variables affect the overall productivity rates of construction projects.

1.5 Case Study

The author acted personally as project manager for the construction of a five story medical office building (MOB) addition to a hospital with a typical steel frame, concrete pan deck structure with a steel and concrete pan emergency exit stair case was built using standard design and construction techniques (see Appendix A for project information).

The budget was based on standard construction practices and plans from the architect showing the stair sections. Fabrication and connection details were done by the miscellaneous steel contractor. The shop drawings process extended over months because connection details were re-designed several times. The stairs were installed at a higher cost than had been budgeted by the contractor due to changes in the field installation situation, a more complicated work scenario, and additional labor hours spent re-working. As the process was nearing completion, the architect inspected the work and rejected it. At issue was a gap of 1/16th to 3/8th of an inch between the wall and the stairs at the perimeter of the landings and stair stringers. This type of gap is typical in stairwells of office buildings and serves the purpose of allowing tolerances for installation of the stair into a stairwell that is not likely to be perfectly square, plumb, and built to a tolerance of +/-¼". This type of gap is generally left or caulked, if needed. In this case, the architect rejected the gap because dust and allergens could become trapped in the gap – not acceptable in a hospital. The contract construction documents did not indicate requirements for no gap. The contractor assumed typical practices for office buildings while the architect assumed that since the MOB was attached to a hospital, it would be built to their idea of standard hospital stair construction. The requirements for the stairs were not clearly understood by all parties.

A solution to eliminate the gap was proposed and offered to the owner as an extra cost. The owner preferred to have the gap rather than spend the extra money. The balance between cost and quality were perceived differently by all parties involved in the stair problem.

Modeling the staircase would have communicated the design intent early in the design process and the cost could have been known prior to construction. A more cost-effective method would have been made available by starting the stair detailing earlier. It would also have allowed the fabricators to design components to a tighter tolerance so that the need for the gap was reduced. In all phases of design and construction, BIM would have increased communication and provided collaboration that would have reduced the time required to design, fabricate, and install stairs by preventing problems associated with the gap.

1.6 Conclusion

In the construction industry a higher productivity rate in the field will lower costs for the entire project. Productivity on the site is affected by the amount and quality of planning and coordination done before any work begins on site. Projects vary in complexity, team experience, budgets and other factors such that each has differing planning and coordination needs. Knowing how various BIM process elements affect these rates will enable owner and contractors to intelligently and responsibly plan the appropriate amount of time and money to be spent at the project level. The purpose of this work is to make a decision making model that will help in this process.

Chapter 2: REVIEW OF CONSTRUCTION PRODUCTIVITY THEORY AND PRACTICE

Productivity has different meanings in the AEC industry based on the perspective of the stakeholder. Owners may view field productivity as the *amount* of work being accomplished while the contractor understands it to be the *rate* at which the work is being accomplished. Following is a description of current views on the definition of construction productivity and a discussion of the interests of the various stakeholders and how they understand, measure and control productivity on a construction project.

CII (Construction Industry Institute) estimated in 2004 that 57% of construction spending is non-value added effort. This wasted effort does not directly contribute to a usable product. US estimated that out of $1.288 trillion in 2008 used for construction means, $600 billion was wasted in construction processes with the existing business model (CII, 2004). This inefficiency will not be completely eliminated because of the manifest variations in geography, owner requirements and cultural differences from project to project, but it can be vastly improved.

2.1 Definition of construction field productivity

Members of the construction industry differ in their definition of productivity. To some, productivity simply means “completion of construction work at unit rates more economical than the other, less than those published in estimating handbooks, and better than those used in producing the estimate for a given project” (Warren, 1989). Thus, if a firm is doing better than estimated, it is being productive. However, The U.S. Department of Commerce takes a more narrow view of productivity and defines it as “dollars of output per person hour of labor input". Adrian, however, refines the definition even more as he substitutes dollars input for labor input. This definition takes into consideration cost of equipment, materials, and other factors (Adrian, 1987). Heap defines productivity as "ratio of output to input, that is the ratio of the amount produced (the output) to the amount of any resources used in the course of production (the input). The resources may be land, materials, machinery, tools, or manpower" (Heap, 1987). This definition also takes into consideration any resources expended to produce the final project.

Production can be high when productivity rates are low. This often happens when labor is added to a jobsite when it is behind schedule, but required planning and work space are not provided for the workers. Each person working might only be spending half of their time effectively contributing to the finished product. This would mean a productivity rate or utilization rate of 50%. In other words, in this situation the firm is paying people full wages to work half of the time. Manufacturing firms would not find 50% acceptable, but this is the average rate in the construction industry.

2.1.1 Measuring Field Productivity Rates

Productive work creates value by directly contributing to the finished product. Building scaffolding for a mason is not directly productive work because it does not become a useable product for the end-user, but the mason installing bricks is creating value for the end-user because the bricks are part of the building. A mason waiting for an answer concerning what brick is supposed to be used at a specific location or how it is connected to the structure is not productive or effective because he is not actually installing bricks. Studies have found that about1/3 of a worker's time on construction sites is not effective due to waiting for instructions, materials or other workers (Adrian, 1987). Other studies indicate that only 36% of working time is value-adding (Oglesby, 1989). Levy estimates that only 32% of working time is productive (Levy, 1990). Eastman cites studies by CII that credit only a mere 10% of effort as value adding (Eastman, 2008). Field construction productivity rates refer not to the number of laborers on the site, but to labor utilization on the job site. The productivity rate is the ratio of how much time is spent directly contributing to the finished product to the total amount of labor hours spent on the site:

Labor productivity rate = Effective work/Total work

Many firms use a portion of contributing work, such as building scaffold or moving materials, as part of their productivity rate evaluations. One-fourth the amount of such contributing work is added to the amount of direct value-adding work and divided by the total amount of labor on site:

Labor productivity rate = (Effective work + ¼ Contributory work)/Total work

The advantage in evaluating work in this manner is that any work that is not directly value-adding is identified. This rate of effective labor hours divided by the total labor hours is the *utilization rate* and indicates how much of the paid labor actually is producing a useable product.

Different techniques are used to determine productivity of labor. Activity sampling merely requires the observer to watch a crew and record how many crew members were doing something – regardless of whether or not the work is effective. Five minute surveys and field ratings are used to evaluate amount of effort being expended by labor and the observer must record what the labor is accomplishing. A person waiting for another worker to finish his work is not effective. A person carrying lumber a long distance because it was stacked far from the work area would be considered ineffective or contributory depending on the firm. If a journeyman welder on a steel erection crew is observed carrying and placing metal decking, the work would be considered effective because it adds value, but it may not be totally effective because a less expensive worker could have done the same work, thus decreasing the cost of production which in turns increases the productivity rate for a value savings.

Man-hours are the most typical way to measure work in place because field management views work in terms of time rather than dollars. The most effective manner to evaluate true productivity is by costs of input to the value created. This takes into account the type of equipment used, prefabricated components, the cost of laborers and other factors which affect the total cost. When only man-hours or crew-hours are used, these other aspects are neglected. Labor productivity rates are among the most difficult things to estimate because they are unpredictable due to the insufficient knowledge contractors have about the project. Labor productivity can change by 30% from one hour to the next (Adrian, 1987). Unknowns such as weather, plan clarity, and interaction with other trades all cause the contractor to use lower productivity rates during estimating. Then, since money for poor productivity is in the budget, there is little incentive on the job site to plan better to cause an increase in productivity rates unless the field management has significant profitability bonuses.

Alfeld (1988) defines performance "as a ratio of accomplishment to methods." The worth of performance was given as the value of the accomplishment divided by the cost of the methods." This performance tells the worth of what they are doing, but not how well they are doing. Worth is the value of installed work and not the efficiency of the workers.

Tracking individual productivity is impractical since people fight it and most construction teams are fluid in their work task assignments. The use of aggregate measures to check overall performance for higher level tasks or trades is more accurate and indicative of the big picture. Task tracking at finite levels may tell more about focused work, but it often neglects how it relates to the big picture and often turns to one task improving at the expense of another. For this work, productivity of trades rather than individuals or crews will be evaluated.

According to Dana Smith, the construction industry has poor productivity for several reasons. One is that it is fragmented. Unlike big manufacturing where the customers and suppliers are controlled and companies can produce products in factories, construction companies deal with various owners, have many suppliers, and come from different backgrounds. There are also many small firms performing this work in different ways. There is not one group that can demand productivity at specified levels. One exception to this is the GSA. It is the largest facility "owner" in America and is able to demand a certain level of design proficiency and cost control in terms of proper design to eliminate field changes. This will be discussed in section 3.2. Building codes are a quality baseline in terms of finished product, but do not address productivity expectations. Another problem is that in construction the assembly is in the field rather than in a controlled environment.

Construction has no baseline data – other industries have productivity published, but not construction. Smith states that, "Lack of broad-based statistical data puts the construction industry at a significant disadvantage." If you cannot measure productivity, then it is impossible to assess the effects on productivity that result from changes or improvements in technology, skill, business practices, or production methods. When you cannot measure the impact of innovation, it is less likely to occur and the risk of implementation is higher. With this in mind, the resistance of construction industry to change may be viewed as a conservative, sound business decision. "The slow pace of innovation in the building industry is more likely the result of the lack of reliable business information" (Smith, 2009).

Paul Teicholz (2003) of CIFE proposed that productivity declined approximately 20% from 1964 to 2003 while manufacturing increased by about 120%. Several studies showing rise in productivity in construction are encouraging (Haskell, 2004) and many firms can show their own productivity rates rising. The cause of this incongruity could be that only larger companies who are concerned about their productivity are likely to study their rates. More components are being fabricated off-site in more controlled factory type settings where it is more efficient (Kymmell, 2008). Many of these tasks were produced relatively efficiently on the job site, but have been moved to an even more efficient factory setting. This increases the task productivity rate, but can decrease the on-site productivity rate by diluting the amount of more effective work performed on site. Additionally, the amount of safety regulations and other requirements have greatly increased the contract price.

Wasteful activity comprises over half of work expenditure while value-adding work is only 10% (Eastman, 2008). In this pessimistic view all work is not considered value-producing even though it is valuable to the process. Value adding effort vs. waste in both construction and manufacturing according to CII is shown in Figure 4 (See Eastman, 2009, pg. 331). Support activities are shown to be 1/3 of the work on a project. This includes erecting scaffolding, transporting materials, and other work that only aids others in performing their work. Productivity is an amount of work that is effective, or directly contributing to a finished product, plus a portion of contributory work, or work that helps but does not directly build a project, divided by the total hours spent on the project. In the construction industry, these ratings are typically 40 to 60 percent, depending on the type of work and project. Civil and concrete work both tend to be lower due to the reliance on the existing terrain and weather conditions. This corresponds with the idea that factory work is more productive since the weather and work environment is controlled. BIM helps planners create a more conducive work environment, thus increasing productivity.

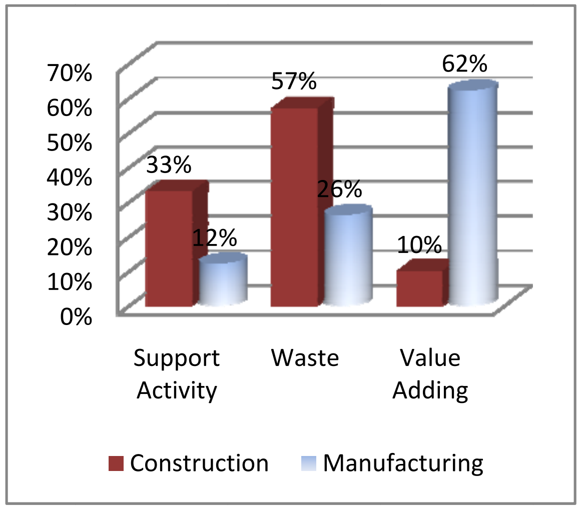

Figure 4 - Construction vs. Manufacturing comparison of waste and value-adding work. From: Construction Industry Institute.

2.1.2 Increasing Field Productivity

Because there are so many unknowns on construction sites, managers often minimize planning and set up only contingencies or response planning. Some of the unknowns, such as weather, cannot be controlled directly, but the effects of it can be controlled to a certain degree by scheduling or modifying work practices or adding environmental controls (Heap, 1987). Other unknowns, such as productivity rates, can be controlled to a greater degree. Managers should evaluate unknowns and separate them into categories. There are "known knowns, known unknowns, and unknown unknowns" (Rumsfeld, 2002). The first type is dealt with by traditional planning methods, the second type generally gets contingency planning and the last type only gets an occasional thought by risk analysts. There is more control over the first and, to a degree, the second type, but both need to be considered in a proper pre-planning session. Creative pessimism must be used to imagine what "unknown unknown" could occur that will affect productivity. This is where Murphy's Law is more than an amusing explanation of why things go wrong, and indeed, is the basis for developing solutions for potential problems. Productivity rates increase when such planning occurs.

Performance Ability Ratio (PAR) defines exemplary performance and makes that the standard for how efficiently the crew is operating.

PAR = exemplar performance/current performance.

PAR is calculated so that 1 is optimum and the larger the number, the lower the efficiency. Close to 1 means you are doing well but being at 1 continually is not reasonable since the average performance cannot be the best performance unless there is no variation. A wide variation means there are opportunities for management improvement. The PAR is dynamic because when a crew reaches a number that is higher than the previous high, that new number becomes the exemplar. The PAR should be lower for repetitive and uncomplicated tasks because the learning curve effect decreases wasted effort. PAR is valuable because best practices are the basis of measurement and improvement is made by emulating the practices of the exemplary performance (Alfeld, 1988).

The prevalent management technique of punishing low performers only shifts the low side of the productivity rate bell curve to the right, but does nothing or little for the average worker, which comprises the majority of work hours. The proper method is to shift the whole curve to the right to reduce the distance from the exemplar or high performer. This is done by emulating the exemplar and teaching methods to gain these increased rates (Alfeld, 1988).

One assurance of BIM is that planners can reduce errors in design and visualize the known unknowns. The cycle can be broken using BIM. Used as an information and communication tool, the constructors can visualize the construction product and process and send clarifying information so that the contingencies and waste levels of non-effective work are reduced dramatically. Thus, BIM can lower the cost of construction through increasing the effective time spent producing a product. The amount of hours or dollars expended to build the building should be able to decrease as the proportion of effort spent directly on producing the building increases in relation to the work that is not directly contributory.

The efficiency will further decrease as more items are brought in modular form. The work on-site then consists of assembling these modules together or building that cannot be effectively constructed off-site in a factory. Productivity rates will continue to decrease as modular construction increases unless BIM provides assembly efficiencies (Post, 2008). Levels of tolerance for design have changed from inches to sixteenths of inches. Modular panels now fit together better and come with instructions. The amount of dimensioning and information on the erection layout is substantially reduced. In the past, details were put on the layout drawings for the fabricators' benefit but it wasn't relevant to the erectors. An important result was that no repairs were required due to errors related to shop drawings (Kaner, 2008).

2.2 Capital Asset Management (Owners) Productivity

2.2.1 Capital Asset Management & Life Cycle Cost

Owners look at value based upon the usability of their building. Productivity for the actual users of the building is more interesting to them than for construction field crews because they will be paying for inefficiencies for the life of the building. An efficiency increase of just a few percentage points over the life of the building may represent millions of dollars. Owners ultimately perceive productivity by the amount of output the building gives relative to the input required.

Buildings must be valued by means more than square footage and quality such as might be labeled class A or B. A metric which gives information that is more capable of indicating the worth of a building based on its energy efficiency, productivity for occupants, health, and building components would be useful. These should be graded per expected longevity based on ‘quality’ of the components or method of construction (Smith, 2009).

Tenants or user satisfaction is another metric that is useful for valuating a building. Energy consumption and health of the building are important factors in this but there are many other issues that make a building good for the user. The ease of maintenance, accessibility, workflow in the structure, appearance, and other issues can be graded based on comparing the outcome to the goals. A balanced scorecard type approach can be used to evaluate how well the building's objectives are being met by the performance of the building (Rondeau, 2006).

2.2.1.1 Building Energy Usage

With the increased costs of energy and the threat of global warming, the energy consumption attributes of buildings are becoming a measured value. Non-industrial buildings consume nearly 40% of all energy in the US and 72% of US electricity production. The US Department of Energy's (DOE) Annual Energy Outlook 2007 forecasts energy consumption will increase 31% by 2030. Despite increases in available energy-efficient building designs, the DOE expects that buildings will still account for 40% of energy by 2030 (DOE, 2007). Although the number of buildings will increase, it appears that the DOE does not anticipate appreciable increases in building efficiency. The cost of operating a building is passed on from owners to the tenants, but the end users are becoming more conscious of total business operating costs and energy usage is becoming a larger and more visible part of that cost. Because of this there is more pressure from users to expect more energy efficient buildings from owners. The owners are responding by adopting more green building standards that will lower the tenants' operating costs.

Energy efficiency is one metric that is beginning to be used to determine the productivity rate of a building. There are now several groups or systems that are used to evaluate and document efficiency, including, but not limited to: CASBEE (Comprehensive Assessment System for Building Environmental Efficiency), SBTool, BREEAM (Building Research Establishment Environmental Assessment Method), Green Globes and LEED (Leadership in Energy and Environmental Design). The first three are used primarily in Japan, Britain, and various smaller countries, respectively. Green Globes was developed in Canada and is in the process of being accredited as an American National Standards Institute (ANSI) standard so that it can gain more recognition as a system to assess a building's energy efficiency. LEED is the dominant method in the US despite, or possibly, because its documentation onus is expensive, adding approximate 2% (NEMC, 2003; NRDC, 2009) to project costs while creating little direct value to the building. It has become more important in areas that are more populated with environmentally minded people. The US Green Building Council (USGBC) is issuing its 2009 version of LEED to reflect changes in environmental concerns and technologies available that increase the energy efficiency of buildings (USGBC, 2009). By the end of 2007, "two federal agencies, 22 states and 75 localities … instituted policies to encourage or require LEED" (Kamenetz, 2007). San Francisco, California has required all new municipal additions and renovations to be LEED Silver certified since 2004. Many other cities are adopting similar types of requirements for their buildings (cleanedison, 2009) and as of April 2009, 19,524 buildings have been registered and 2,476 have been certified (USGBC, April 2009). The adoption of these LEED requirements shows the trend in developing more environmentally friendly and efficient buildings.

Living Buildings is a new system for evaluating a building's "greenness". It evaluates what the building does, or in other words, how much of an impact it has on the environment. To be "living," the building must have a zero net impact on the environment, including energy consumption, water usage, pollution, etc. from both a construction and operational perspective (Krygiel, 2008). This was proposed at the 2006

USGBC (US Green Building Council) national conference but is more aggressive than LEED and will be more difficult to implement. USGBC is supporting the 2030 initiative to eliminate fossil fuel dependence in new buildings. Living Buildings may be utilized to advance that initiative.

The US Congress, in a typical attempt to quell normal market pressures to increase efficiency has attempted to dictate energy usage in buildings by the American Recovery and Reinvestment Act of 2009 enacted on February 17, 2009. This act provides government monies to stimulate economic growth including significant funding for infrastructure. One of the goals of the act was to develop a green economy. Billions of dollars were appropriated for spending on upgrading government facilities to be more energy efficient, four billion for the Office of High Performance Green Buildings, and billions for other construction energy related issues (Public Law 111-5, 2009). Clearly, the government is interested in creating a more energy efficient physical facilities infrastructure. A survey of architects in 2009 found that 58% believe that the stimulus funding will promote sustainable design and are adopting designs to do so (Baker, 2009).

2.2.1.2 Building Health

Dr. Lam of Carnegie Mellon reported that the Center for Building Performance and Diagnostics (CBPD) at Carnegie Melon University identified 25 studies that link indoor air quality improvements to productivity gains, with an average 3.3% productivity increase. Twenty studies linked improved temperature control to productivity gains, with an average 5.5% productivity increase. Thirteen studies linked high performance lighting systems to productivity gains, with a median 3.2% productivity increase (Lam, 2007). This is very significant considering that personnel costs constitute 92% of a 30-year life cost of a building. Operations and maintenance is only 6% and construction, 2% (Gottfried, 1996). Thus, a 1% productivity increase would save, over 30 years, four and a half times the total construction amount. This means that spending 10% more during construction to increase productivity would return 45 times the investment.

As can be seen in Figure 5, the building receives LEED credits when efforts are made to decrease operations and maintenance of the buildings, and the health of the occupants and the productivity improvements gained by proper design. Thus, LEED can be an indicator of the anticipated performance or productivity of a building in terms of both energy consumption and human productivity due to health and environmental issues.

CBPD Guideline ROIs for Office Buildings in Climate Zone 5

	Number of studies	Median Return on Investment (%)			Applicable LEED NC 2.2 Credits
		O&M Savings	Health benefits	Productivity Gains	
Increased outside air	11		69	1188	EQ 2
Energy recovery	4	172			EA 1
Filtration	3		5	48	
Individual air control	3		2	29	
Floor based ventilation	5	14		256	EA 1
Pollutant source control	7		20	50	EQ 4.1- EQ 4.4, EQ 5
Demand control ventilation	2	23		0	EA 1, EQ 1

CBPD Guideline ROIs for School Buildings in Climate Zone 1

	Number of studies	Median Return on Investment (%)			Applicable LEED for Schools Credits
		O&M Savings	Health benefits	Productivity Gains	
AIR					
Increased outside air	11		17	247	EQ 2
Energy recovery	4	172			EA 1
Filtration	4		5	28	
Individual air control	3		1	9	
Floor based ventilation	5	11		79	EA 1
Pollutant source control	7		36	19	EQ 4, EQ 5
Demand control ventilation	2	11			EA 1, EQ 1

Figure 5 – LEED credits as indicator of ROI of green building design and construction. (Source: Lam, Carnegie Mellon).

2.2.1.3 Efficiency and Adaptability

The ability to adapt a structure to changing operational requirements and new technologies is an important feature that needs to be designed into a building from the beginning. Many designs consider only the immediate workflow requirements. Companies design structural or functional features of the building around these rather than considering what may be required in the future. Churn, or the rate of change in structures, has increased from 8 to 4 year cycles since the 1960s and technology change has gone from 4 to 2 years in the same time period (Rondeau, 2006). The ability to adapt a building to new requirements is an important consideration for building owners so that usage and rent may continue much farther than the five or ten year lease with the first user.

2.2.2 Life-Cycle Costing

Owners are very concerned with the entire 'life' of their buildings. The owner of the land is ultimately responsible for all that occurs on their property unless transferred by a reasonable contract (Gray, 2000). Concept development, project definition, design, construction, commissioning, operations and deconstruction are all essential parts of the life to be considered. The construction phase gets much of the attention when decisions are made concerning the design and cost of the building, but that portion of the life cycle is typically about 2% of the cost of the building's life if personnel who use the building are included in the cost (Fuller, 2008).Without personnel, the design and construction costs constitute only 5-10% of costs while maintenance and operation is 60% - 85% (National Research Council, 1998; Eastman, 2008). Life-Cycle Cost Analysis (LCCA) is a process in which the owner and designer must "determine the economic effects of alternative designs of buildings and building systems and to quantify these effects and express them in dollar amounts" so that the best value proposition is gained (Fuller, 2008). Building Life Cycle Cost (BLCC) "software is used to evaluate alternative designs that have higher initial costs but lower operating-related costs over the project life than the lowest-initial-cost design" (NIBS, 2009). Properly considering total life costs rather than just construction methods and materials will reduce operating, remodeling, and de-commissioning costs by a far greater value than what was saved on construction (Hardin, 2009). Studies in Europe have shown that the loss of value to the owner due to exceptional maintenance costs are 4% of productions costs. Of this amount, about ½ of these costs are associated with design problems rather than construction or operations (Koskela, 2000). A separate study found that spending extra on carpet with a polyurethane backing saved $0.15/SF annually, based on increased life expectancy translating to fewer interruptions, carpet removal and landfill fees and reduced maintenance (Campbell, 2002). Understanding the materials and their relationship to other systems and to life-cycle costs is required for proper design and building productivity.

Sophisticated owners use capital asset management tools to plan and organize their properties and development. FIATECH is one group that has endeavored to increase construction and development efficiencies by the use of new technologies. Their focus is on the big picture in that they evaluate how specific practices affect the total life structure of the building, not just the construction project. The large amount of data created during the construction process has become more organized so that it can be accessed and used by owners. In fact, more forward-thinking owners are using the data to maintain the structure, plan for remodeling and for the deconstruction of the building when its useful life ends (FIATECH conference, 2009). Productivity for the owner thus considers much more than the finite design and construction process. It must be a function of total costs from inceptions to removal required to enable the output expected from the structure.

2.3 Design Process Productivity

Due to the complexity of modern buildings, it is nearly impossible for a designer to capture all of the details precisely the way the project will be realized. The role of the designer is to communicate the intent of the finished project while the contractor controls the means and methods of building the product. Because the various systems in buildings can be assembled using a variety of methods and using a variety of materials, coordinating the disparate assemblies can be difficult. Architects are responsible to design plans. These plans show *what* to build, not necessarily *how* to build. Contractors are responsible for constructability review because they are responsible for the means and methods (Jackson, 2004). Conflicts and confusion where design and constructability responsibilities overlap cause work stoppage so that discrepancies can be clarified and information disseminated. If the problems are not discovered until construction is underway, installed components may need to be removed and replaced so that the product is able to fulfill its intended purpose. These things not only cost money but add time to projects.

2.3.1 Architects & Engineers

Architects are primarily responsible for preparing documents that communicate the needs of the owner to the builders. Their task is to identify these needs and wishes and transfer them into drawings and specifications. They also are traditionally responsible to ensure that the intent of the plans is carried out by the builders. There are four basic steps in their service: 1) schematic design, 2) design development, 3) construction documents and 4) checking and coordination. A majority of their time is spent on development and construction documents (Autodesk, 2008). Frequently, all information is not available during the design phase because equipment to be used by the owner cannot be determined until the project is underway. This makes the process more difficult and requires flexibility and usually results in subsequent inefficiencies in the design process and product (Chapman, 2007). Ruber observes that "designers need to have the time to review the overall solution with the individual resolutions...Ensuring design intent or what many of us would consider cleaning up the design causes virtual changes. We as a design industry are being tasked with creating fully developed solutions in real time as the constructor's develop theirs in the big room environment. This seems antithetical to what IPD is about. It has been my experience that the BIM exchange process supporting a collaborative environment is best for projects with more collaborative agreements than a traditional delivery model" (Ruber, 2009).

Engineers are concerned with the details of structural mechanics and systems design. As buildings are becoming more complex, each system requires more specialized knowledge. Those that design electrical systems have more detailed knowledge about electrical engineering but are limited in their understanding of plumbing or structural design requirements. Given the many engineers, conflicts between the systems are common (Liebing, 2000).

Coordination between the different engineers is generally the responsibility of the architect. Since the advent of CAD systems, this has been done by overlaying layers to find and eliminate conflicts. The process is slow, cumbersome, and often inefficient because of the need for sequential design. Each engineer must use the design of other engineers to create their own design which in turns affects other engineer's designs so that much iteration is required before a suitable overall design is completed. Constructability surveys are often not performed by the builder until bid time. Collaboration in this process consists of some meetings and sending plans, either printed or electronic, to all design parties for approval.

The owner's role in this collaboration is limited because they frequently do not understand the documents that have been produced. They may not have enough experience reading plans or may just not understand their own needs. The inability for them to visualize the design prohibits them from assessing whether or not the plan is suitable. Therefore, the appropriateness of the design may not be known until the project is underway and the owner can observe the physical product being built.

Because builders are not included in the design process effectively costs are added to the construction process. In a case study of door installation at a prison, Schmenner found that walls and doors were designed as different systems, ordered by the contractor in different packages, and built or installed by different specialty contractors. As a result of not viewing the doors as part of the wall system, the project participants failed to find a value for the owner with a better design. According to Schmenner, "local optimization can be detrimental to global optimization.” In this case study the contractor used latex caulking rather than security sealant in order to reduce materials costs and thereby unintentionally contributed to grout blowout problems. “Project participants fail to learn across projects; they rely on “received traditions” (Schmenner, 1993). Installers may not see that process design problems can be linked to inadequacies in product design. Thus, they do not provide feedback to designers to encourage modifications of the product design to better support process design” (Tsao, 2004).

Shop drawings comprise 38% of labor in the design and production process for engineered drawings. They typically are done independently of the CAD drawings that are made so there is a great deal of re-work done which is not value-adding work. By using the base model to detail, the fabricators save many hours of shop drawing time. Engineers will also have more time to spend on design rather than on document production (Kaner, 2008). According to Kaner, [four] objectives of using BIM are to:

1. Improve productivity by producing schedules and shop drawing in as automated fashion as can be achieved.
2. Absorb design changes with minimal rework.
3. Harness the capabilities of 3-D visualization to avoid design errors.
4. Visualize the structure.

Given the large amount of advertising and reporting of how BIM improves the productivity of the *design process*, it is apparent that the industry perceives deficiencies in the current method of designing. The use of fast track tries to speed the process. However, the speed is gained because construction begins before all design details for the entire project are known. Coordination is actually more difficult because work in the field is being completed before all systems are designed. Once each system in the plan is designed and construction is started, other systems must conform to those requirements and therefore are hampered in their ability to design a more efficient system. The solution to this inefficiency and rework in the design process is a faster iterative process with more collaboration (Kymmell, 2008).

2.3.2 Project Delivery Method Effect on Design

The Project Delivery Method (PDM) is an important factor in how the design process flows and on whom the responsibilities and risks are incumbent. Over the last century, the principle form of contracting in the US has been Design-Bid-Build (DBB) where the builder is not involved in the design process. Because problems in the constructability of the plans are determined so late in the game, they are more expensive and time consuming. The Construction Management (CM) PDM brings the builder into the design process to encourage constructability input from the party which will control the means and methods. Similarly, the Design-Build (DB) PDM involves the contractor earlier, but generally carries the responsibility to control design so the owner has only one contract. This puts a greater responsibility on all parties to develop good communication practices and means of developing trust in each other (Dorsey, 1999; Liebing, 2001). Owners choose to use DB primarily because they require a shorter duration project and lower costs (Songer, 1997). The project duration is shorter because the builder is able to begin construction prior to completion of final construction documents and the bidding process typical in DBB (See Figure 6). Most construction contracts are a combination of these basic delivery methods. From DBB to CM to DB,

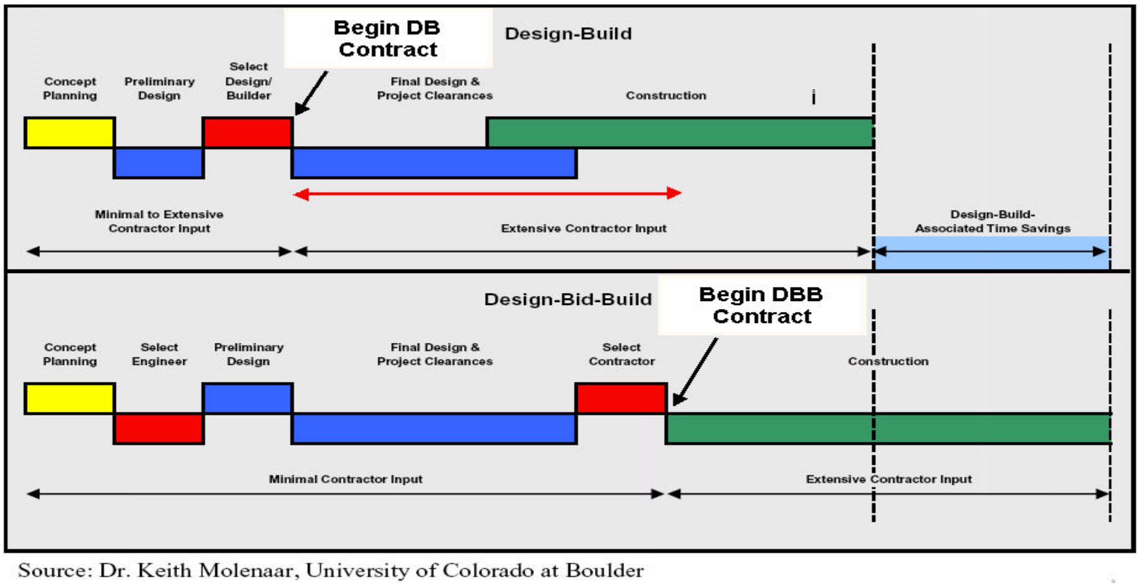

Figure 6 - Shortened project duration common to DB projects due to overlap of design and construction.

there is an increasing level of partnering in which contracting parties need to trust each other, collaborate and share outcome responsibilities (Fisk, 2000; Jackson, 2004).

In the last few years integrated project delivery (IPD) has gained more attention as a delivery method that contractually manages the need for increased collaboration for the purpose of solving problems in the design and construction process. “IPD structurally responds to the timing of when the constructor and trades are brought on to a project team.” This structure attempts to support the cultural process changes that require a “different perspective from individuals, firms and the team functionality to support success” (Ruber, 2009). The Construction Users Roundtable has encouraged the use of IPD because if should be better able to create better collaborative teams that will focus on the needs of the project – in this case the entire life-cycle of the building (CURT, 2004). IPD is “a project delivery approach that integrates people, systems, business structures, and practices into a process that collaboratively harnesses the talents and insights of all participants to reduce waste and optimize efficiency through all phases of design, fabrication and construction. . .[and] throughout the full life cycle of the facilities" (AIACC, 2006). To do so:

- "Members establish project Goals, project definition, and collaboration standards for the group.
- Members develop a risk matrix and complete integrated scope of services matrix to allocate responsibilities.
- Members establish a Project Management Team.
- Members provide Owner with a Target Cost no later than [at the] conclusion of criteria design"
- All decisions require unanimity, unless otherwise carved out in agreement (O'Connor, 2009).

Note that the focus is on the members establishing guidelines and process that help achieve the goal of creating a building for the owner's needs.

Savings in construction costs and time by the application of IPD and BIM are estimated to be in the range of 50%. This may be optimistic at first, but the growth in IPD agreements suggests that there are many who are willing to try for the promised savings (Knight, 2008). According to Eastman (2008), BIM is most effective with DB or IPD because collaboration in the design phase is fostered. DB and IPD contracts often include BIM usage requirements. Turner, like many sophisticated firms, includes on many of its contracts clauses concerning models and how they are to be submitted and used for the project good.

Noble of the American College of Construction Lawyers (ACCL) reported in 2007 that there have been only few such “alliance agreements” in America, but Sutter Health and University of Wisconsin pioneered the contract type where team members are tied to team performance and application of lean construction, and contingencies and incentives are shared by designers and constructors. BIM is considered important to the agreements because it aids in reduction of errors due to collaboration and visualization (Noble, 2007). Reed (2009) calls this type of approach “Lean Project Delivery” is now being used by a number of health care facilities such as Sutter Health, UCSF, ThetaCare, SSM, and BCJ Healthcare. It is noteworthy that these are medical facilities – some of the more complicated buildings constructed - requiring a great deal of interaction between the designers, builders and owners/users. It is anticipated that the use of IPD will increase dramatically now that organizations such as The Associated General Contractors of America (AGC), The American Institute of Architects (AIA) and Design-Build Institute of America (DBIA) have developed forms of agreement that their constituents can use with more confidence than by developing their own, untried contracts (AGC, 2008; AIA, 2009; DBIA; 2008). Historically, constituents of these groups trust documents issued by their organizations knowing they are created by expert lawyers seeking the interest of that group. Interest in IPD is strong in the private sector, but usage on government projects is less certain. Only one in six architecture firms feel that there is less interest in IPD due to the economic downturn while ¼ feel that there will be less demand for BIM due to the downturn (Baker, 2009).

2.4 Contractor's Productivity

Process engineering looks at reducing the amount of input required to make the output. Whether the savings accrue to the builder or to the owner is a business decision and determined in the contract. When a few contractors increase their productivity rates, they are able to keep the profit. As an increasing number of contractors become more efficient, more of the money saved by the contractor's ability to increase productivity will pass to the owner of the building based on market pressures. This is simple supply and demand. As more contractors become efficient they must compete with each other and the price subsequently lowers. The Church of Jesus Christ of Latter Day Saints has been able to maintain the price of building its chapels over a ten-year period despite inflation because the contractors that build the buildings become familiar with them and become more efficient (Reed Nielson, personal communication, 13 February 2009). The learning curve is enough that whereas material prices and labor rates have increased, the total cost of the buildings has dropped or remained constant because of the reduction in waste and increase in productivity rate.

2.4.1 Planning & Communication

Planning takes time and resources up-front. Most firms are hesitant to spend much money before work starts because of cash flow problems. As discussed in 2.3.1, the architect is responsible for *what to build* while the builder is responsible for the *how to build*. However, the increasing complexity of buildings and strict time requirements render this impractical as design concepts and methods are not separable. Planning to reduce conflicts and coordinate workflow can be done early in the project by using:

- scheduling programs for resource loading and task dependencies,

- a variety of spreadsheet-based analysis programs to compare costs of various methods of construction and
- document control programs to organize and plan communication.

Design coordination has been done by overlaying various drawings over light tables or on CAD to determine conflicts and problems in constructing (Kymmell, 2008). More technologically advanced firms combine many of these tools into ERPs to streamline the data usage efficiency (Chung, 2007). Collaborative systems further aid in obtaining input from stakeholders so that they can consult and agree on design and schedule. In this way optimal conditions can be achieved for the highest possible efficiency of the project.

Sophisticated organizations utilize processes such as WBS (work break-down structure). It is a "deliverable-oriented hierarchical decomposition of the work to be executed by the project team to accomplish the project objectives. . . It organizes and defines the total scope of the project" (PMI, 2004). The Project Management Institute (PMI) teaches formalized WBS development in the Project Management Body of Knowledge (PMBOK) such that project teams from different companies and cultures can work together in the framework established. It requires components of the project to be broken down by trade, category, time or some other means to develop relationships and dependencies and visualize them in a hierarchy. From these tasks, formal schedules are made. Ordering work packages and monitoring progress is based on these task definitions. It is a powerful design tool as well because "the WBS is a picture of the work of the project and how the items of work are related to one another" (Wysocki, 2009). The WBS process can hamper effective project- wide coordination by dividing work into packages before relationships can be evaluated. For example, the authors of a case study about installing doors at a prison determined that the “traditional WBS practice prevents project participants from seeing opportunities for systemic change” (Tsao, 2004). If the door manufacturer, installer and the contractor building the wall could have looked at the wall to door connection details, they could have provided a better design and saved costs and errors in the field. This process is generally iterative, but six different forms are used. Contribution from team members is important as relationships and scope of work are developed for the entire project.

General contractors must have a sophisticated system to manage the documents used to complete a project. It is important to get the correct information to the correct people at the correct time in the correct manner so that work is performed correctly. Document control software such as produced by Meridian, Primavera, Bentley, e.g. are used independently or as part of an ERP that helps manage the documents. These software systems are the most common way to manage documents. Many new programs such as Coreworx’s Interface Management were developed as web-based information control system but are used principally by large companies for which they were developed. Most complex document control systems such as Meridian’s Proliance and Bentley’s ProjectWise are underutilized because users deem them to be too slow and bulky to operate (Chelson, 2010; Fisk, 2000). This is largely a function of the massive amounts of information that users must get through to get to what they are searching for. Hierarchical organizations tend to dominate the industry and hand out orders rather than discuss ideas in a collaborative manner that the new systems are equipped to foster. This culture needs to change to a more open and collaborative one so that effective planning can occur. Rather than pushing documents around, the GC needs to coordinate the dissemination of information in a meaningful way to increase productivity.

All the effort to manage the work, including reporting and evaluating are non-value added to the building owner (Smith, 2009). This work significantly reduces the productivity rate of the project because these hours and resources used to manage documents are part of the total project cost, but not directly contributing to the finished product. By definition they are contributory, at best. Managing RFI, changes due to errors, and other 'paper management' necessitated by errors is not contributory, but non-productive per the definition of productive work (Adrian, 1987). Most firms streamline the document control process by computerization, but reducing the amount of error and the management of fixing errors is important to increase the overall effectiveness of construction operations.

Communications at a project level is regarded as a network of two-way channels and the number of channels is calculated using Metcalfe's Law represented by the equation $N=X(X-1)/2$. As project sizes have increased in complexity, more channels have been added (Kerzner, 2006). To illustrate, a project with 50 "players" has 435 potential channels of communication while one with 100 "players" has 4,950. Contractors have tried to control projects by controlling information and often restrict the channels available to members of the team. This is done by making all communication go through the contractor. This becomes burdensome and time consuming without computerized document control systems utilizing centralized data (Chelson, 2010). Using the collaborative approach the communication map becomes simpler in that all information is housed in a central location for easier access by parties that need the information. One party is still in charge of managing the process, but it is automated so that labor hours are saved and the speed of communication is increased dramatically. Figure 7 shows the simplified communication network. Although the relations and the channels are actually more complicated, they are automated and more user-friendly so that they are easier for the project participants.

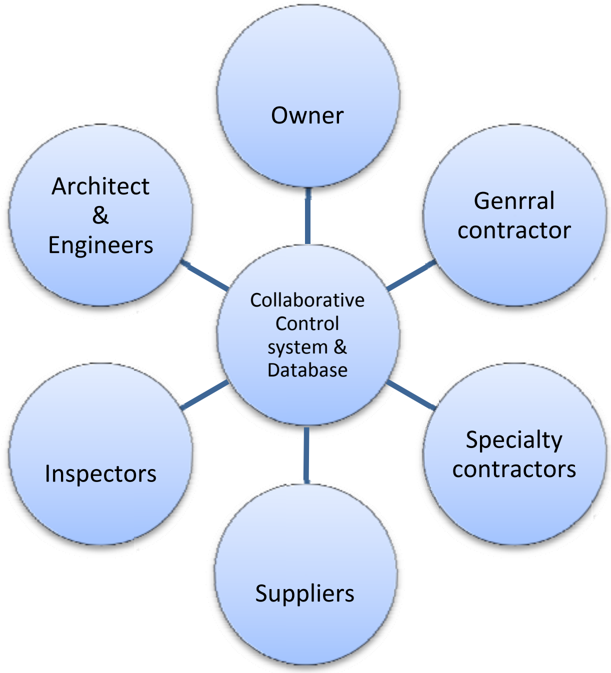

Figure 7 – A Centrally controlled collaborative communication system allows control by a manager and increases the ability for team members to communicate, but the process is automated and more efficient.

2.4.2 Workflow

Workflow planning consists of scheduling tasks that are dependent on each other and coordinating so that conflicts are reduced. Some of the dependencies are obvious such as a roof deck needing to be in place before the roofing material is installed. These are rarely missed, but critical dependencies are often missed or misdiagnosed such that conflicts in process slow progress. For example, one project required a sprinkler system to be installed in a building before it was completed. The actual predecessor to installing the fire suppression piping and sprinkler heads was a structure to hang them on. The walls and foundations were not actually required, but were typically done. Realizing the difference between typical and necessary allowed the project team to complete the requirement by building the columns and roof structure prior to pouring the wall foundations and building slab.

Scheduling is typically done by scheduling programs. Primavera's P-3 or P6 are the most common for larger projects, SureTrak for smaller projects. In total numbers Microsoft Project is used by more firms than all others combined (Primavera, 2008; Microsoft, 2007). Line of Balance is a technique used in scheduling that indicates a task's productivity rate by the slope of the line. Thus, the line shows both time and quantity of work as well as where the work takes place. Constructor's Project-Control uses this for its scheduling in models. This will be discussed in the next chapter. Critical Path Method (CPM) is the most widely used system with the Gantt chart being the most common method of visualization. The weakness of this system is that dependencies are not clearly evident and quantities are not apparent as they are with Line of Balance.

Schedule accuracy is important in the construction process not only because of the final project completion time but because of the interrelation of the many contractors and tasks that need to be planned. When a task is delayed, the succeeding task must be delayed. This causes problems for the team that had to be bumped as they scramble for other work to fill the void for their operations. Starting later will mean that other work they planned will be affected. Once a contractor has been delayed on a project, they are not likely to plan on ramping up for productivity on the project until they are assured that their efforts will be productive. This can add days or even months to the task schedule. Beating the schedule for a certain task may not be beneficial to the project if the succeeding task cannot be started earlier because resources were not planned for at that time. Thus, both late completion and early completion of tasks cripple the overall schedule.

Workflow reliability is the amount of times that tasks meet the projected schedule. Dr. Glenn Ballard, research director of LCI, measures the percent plan complete (PPC) by “dividing the number of near-term assignments completed by the total number of assignments made for the plan period.” This value is repeatedly measured at about 30% to 60% in the industry. This value can be increased to 70% if “shielding” is done in which effort is made to evaluate the reasonableness of commitment (Ballard, 1997). This process requires reviewing scope and assessing the conditions required for completion of the task and knowledge of productivity rates is essential for this. This can be accomplished when the parties that are required to make commitments work openly together rather than by a top-down approach that does not allow input from those who should best know what a realistic target is.

Dr. Ballard states that the fundamental causes of non-compliance are failure to apply quality criteria to assignments and failure to learn from plan failures through analysis and action on reasons. The activity definition model is a component of the Last Planner® system developed by Ballard and taught by the LCI. A crucial tenet of this system is that those close to the work – superintendents – are the persons who can best plan accurate schedules because they best understand the requirements and the conditions needed to obtain better productivity. In this model each activity or task needs to be defined, properly sequenced, in the right amount, and practical:

- “Well defined” means described sufficiently that it can be made ready and completion can be unambiguously determined.

- The "right sequence" is that sequence consistent with the internal logic of the work itself, project commitments and goals, and execution strategies.
- The "right amount" is that amount the planners judge their production units capable of completing after review of budget unit rates and after examining the specific work to be done.
- "Practical" means that all prerequisite work is in place and all resources are available" (Ballard, 2000).

Because there are variations in productivity – due to randomness and to the fact that construction projects tend to be unique – it is recommended that planners not load to 100% capacity (Ballard, 1999). Often, contractors feel compelled to either agree to an unreasonable schedule or to a best case scenario. This author has witnessed many times a specialty contractor say that their work can be completed in three weeks when there is only a small chance that the work will be completed. This is because their productivity is dependent on conditions that are not likely to be met, such as: no other trade workers on site, good weather, no material shortages, all workers are healthy, etc. Even if a team member uses average productivity rates rather than "optimal" or exemplar rates, the resulting time estimate would be accurate only half of the time. Optimistic estimates and unrealistic schedules result in tasks being completed late at least half of the time, delaying successors. Tasks completed early may be of no benefit to successor tasks since those performing the successor tasks may not be able to mobilize earlier without notice. Ballard (2000) stresses meeting schedule and Last Planner focuses on not being late, but completing a task much earlier than schedule creates lost opportunities to speed the schedule.

"Underloading" or "pacing" an activity can decrease productivity because there is a tendency for a task to fill the time that is allotted to it. Counter-intuitively, Ballard maintains that scheduling under full capacity or for optimal situations will help assure that tasks PPC is higher, "thus providing better advance notice to downstream [work packages or tasks] of work flowing toward them to increase their productivity." Whereas the first task may be under loaded, the downstream tasks should increase productivity such that the project as a whole benefits (Ballard, 2009). Interestingly, 30% increases in productivity of tasks has been observed frequently when PPC is improved by making sound assignments (Ballard and Howell, 1997). Collaborative improvements are needed to optimize the productivity of the project by balancing accuracy of the schedule durations for each task with the aggressive durations assigned to speed production.

Solutions to poor productivity reliability, other than making better estimates or reducing expectations are improving definition of tasks, consistent analysis of reasons for failure and giving planners the ability to refuse unreasonable timeframes to perform their scope of work. LCI continues to tout the benefits of the Last Planner system and it is gradually being used by more contractors who, despite initial misgivings, find that it facilitates more "reliable workflow in design as workgroup [leaders] adopt practices that trade foremen have learned" (Reed, 2009).

Most firms tend to underutilize the power of their software (Smith, 2009) by not entering productivity rates and costs and by not updating the schedule appropriately. Thus contractors do not gain understanding of productivity and its factors to use for more precise estimating and scheduling. The baseline schedule is the means whereby progress is compared to projections and evaluation of productivity is made. Earned Value (EV) is calculated by variance of budgeted schedule to actual schedule and the money expended versus the money budgeted for specific tasks. This evaluation indicates the status of the project based on time and money and allows projections for project completion (PMI, 2004; Badiru, 1995). A problem with this method is that the workflow sequences can be manipulated to decrease costs and increase completed tasks, making the project appear to have a positive variance. But, by so doing, work may be released improperly, causing sub-optimal performance and lowering productivity in the long run (Kim & Ballard, 2000). Currently, especially on government projects, the EV numbers are Key Performance Indicators. Most firms use scheduling programs independent of accounting program databases such that time and money are not directly connected. This is a major detriment to evaluating the time-cost relationship which is crucial in productivity analysis.

Procurement and material management systems account for considerable waste in the construction process. Procurement is difficult for long-lead items and is often handled separately, without adequate coordination. Inflation is difficult to predict and costs for labor and materials to be performed later in the project must be guessed by using running averages and projections on commodity prices and labor availability. Most agreements include a limited amount of labor and material escalation clause, but owners are expected to cover additional costs due to price increases beyond the control of or reasonable foresight of the contractor. One cause of the procurement problem is that poor plan coordination and shop drawing process necessitates prolonged procurement processes.

Various studies in Europe have found that around 10% of materials brought onto sites end up as waste (Koskela, 2000). Not only is excess material purchased, labor must spend time cutting, unpacking and handling this material that must be thrown out with a corresponding dump fee. This issue will be discussed in 2.6.1 as it is a clear example of waste reduction to eliminate costs. With rising dump fees since the 1990s largely motivated by government agencies wishing to minimize excess waste materials, the amount of wood and concrete being recycled has increased dramatically. LEED certification points are granted for reducing waste and recycling as further incentive to eliminate material waste.

2.4.3 Drawings & Coordination

Constructability review is an important aspect of contractor responsibilities. It is an assessment of the capability of a design to be constructed (The Construction Management Committee, 1991). Projects that specifically address constructability report 6-10% savings of construction costs (Constructability, 1986). Collaboration during the design phase between the consulting engineer (designer) and the specialist contractor could produce a cost savings of 20% (Latham, 1994, Koskela, 2000). Overcoming designs that cannot be built as drawn requires persons with knowledge of the building process being involved in the design process prior to bid and construction. This investment in time is made by contract in CM and by nature in DB and by process in IPD and has been shown to save costs during the construction phase.

Contractors are traditionally responsible for the “means and methods” of construction. Part of the fiscal responsibility contractors assume is performing constructability reviews of the plans and for coordination between trades. They are also contractually and legally responsible for safety on the job site. Several studies have indicated similar costs of accidents that occur of construction sites. As a percentage of projects costs it was estimated at 6% by Levitt & Samelson in 1987, between 7.9% and 15% by Everett & rank in 1996, and 8.5% by Dester & Blockley in 1995 (Koskela, 2000).

Suboptimal conditions are anything that reduces the optimal productivity that should be achieved if working "in heaven." These are generally avoidable extra work caused by poor planning or coordination of work. Installed components that interfere with components to be installed are a common problem. For example, after ductwork is installed, the plumber discovers that pipes cannot be installed due to the ductwork being in the way. Performance decreases by about 9% for every disrupted workday and on very poorly organized projects, cumulative labor performance reduction can average 60%. HVAC interferences are so common that 5% - 10% cost increase is usual and HVAC contactors increase their bids to account for the expected inefficiency (Gunnarsson, 1994; O'Brien, 1998). Hester found that productivity in elevated areas was 20% higher because "foremen tended to plan and prepare those works more carefully, and because the worker was less likely to be interrupted and shifted to other work" (Koskela, 2000; see also Hester et al. 1991).

Mechanical contractors suffer from low field productivity rates due to the many conflicts in space and time in regards to their ductwork and because the work environment is crowded and the parts are generally put together high above the floor so that access is difficult. Reducing the number of cuts and fittings for pipes and ducts increases productivity rates. Pre-planning cuts and supplying fabricated components saves much of the relatively inefficient field sizing, cutting and installation.

2.5 Industry Productivity Increase

Knowing the fundamental cause for low productivity in the construction industry is the first step in the quest to improve it. The construction industry is fragmented more than most industries that have relatively few large producers and/or consumers. At the end of WWII, the agricultural industry was fragmented and had no greater financial resources than builders did and no greater incentives to fund research individually, yet they have increased output 270% while construction has remained flat. Dana Smith and Michael Tardif explain that the exponential and differential growth in agricultural productivity can be attributed almost entirely to the vast amounts of state and federal funding for agricultural research over the past sixty years, which has supported and continues to support a nationwide network of agricultural research stations managed by schools of agriculture and land-grant colleges and universities." If construction had comparable level of research, it would have productivity increases too. The knowledge gained from government studies becomes public knowledge available to anyone who wishes to use it. As a result, innovation spreads rapidly (Smith, 2008; Eastman, 2008). Comparing the agriculture and construction industries is not entirely reasonable since the small farmers can get information from government sources and apply fertilizer or other improvements more easily than a contractor can manage a more complex project. Also, the increase in productivity in agriculture is more a function of bigger machines, irrigation and fertilizers/pesticides that are used in the same basic cultural context that farmers have used for years. The latter two have caused their own problems and there is a fight over how they are to be regulated. The implementation of these new productivity enhancing methods is not a disruptive technology, but intuitive and incremental in most cases. The increased complexity of building structures is disruptive because no one person can fully grasp the relationships and context of the process (Christensen, 1997). Additional levels of management, government regulations, and legal counsel were needed for control of the process. Contracts and litigation rather than collaboration and planning became management's focus such that documents are intended to protect against litigation rather than to communicate for clarity and teamwork. Unlike the construction industry, agriculture has not been hampered by litigation. A consumer will not sue a certain farmer for growing corn that is five inches shorter than normal corn and a farmer will not sue a consumer for not buying wheat that was grown using pesticides. This cultural difference between the two industries has created the situation that has hampered the ability of the AEC industry to solve the problem of low productivity – planning, trust, commitment and working together with a team approach rather than a litigious mind-set (Reed, 2009; Knight, 2008; Rogers, 1999). Nevertheless, the point is still very valid that more readily available information from sources other than salesmen from a few software companies is needed if there is to be a cultural change that encourages new innovations for productivity gains in the construction industry.

A study by the National Institute of Standards and Technology (NIST) found that incompatibility between systems prevents the sharing of information rapidly and efficiently. Double entry of data, errors due to lack of access to information and lost time due to waiting for information are all symptoms of inadequate interoperability and cost the industry, including owners, 15.8 billion dollars in 2004. Of this, approximately $1.2 billion was borne by architects and engineers and $4 billion by contractors (Gallaher, et al, 2004). Improper communication is not only cultural, but systemic in the AEC industry. The development of more robust document control programs will only help relieve this problem if the many programs can exchange data readily. Software and systems would likely change rapidly to reduce this interoperability inefficiency if the culture in the industry demanded it.

The government is requiring advancements in BIM and productivity through its contracts, but the energy usage requirements in buildings will likely have a larger impact as it makes owners require better designed buildings. The increase in productivity will be a result of owner's contracts driving improved design requirements and, out of necessity, the AEC will have to provide more efficient delivery and design systems.

2.6 Productivity Management Processes

2.6.1 Lean construction

Lean construction focuses not on increasing productive activities, but on eliminating unproductive work. It is a "concurrent and continuous improvement…of the construction processes with minimum cost and maximum value by considering the customer's needs" (Hardin, 2009). The idea is that is it easier to observe and identify waste than to visualize abstract solutions. Heaps of scrap lumber, or people who are idle while waiting for material are examples of obvious material and time waste. The construction industry produced 133 million tons of waste in 1997 (Krygiel, 2008). Turner Construction, in an effort to be more efficient, started controlling waste and on a project in Portland, OR experienced a net savings of $187,000. By reducing the non value-adding process of disposing of construction waste in landfills, they were able to increase productivity to the project in terms of $ output/$ input. Lean construction began growing as a process of reducing physical, material waste, but the process is more comprehensive and reaches all waste – which is anything that does not add value to the customer.

2.6.1.1 Waste Reduction

One obvious way to reduce waste is to avoid tearing out components and re-installing them. This represents a significant portion of labor hours on many projects. One mechanical firm reported that on projects where there is more time to plan and proceed at a slower pace, there is as little as a few percent of total labor hours attributed to re-work. On projects where there are plan conflicts, tight spaces, and where a "hurry up" attitude forces work ahead of planning and alongside other trades, the re-work portion of total hours can be as high as 50% (Christianson, 2009). The process of eliminating any work that does not remain on the project continues until no activity remains that does not directly produce the final project (Womack, 2003). The Shewhart cycle, which was renamed the Deming cycle because he taught the process, is closely associated with lean construction. In it the concept of Plan – Do – Check - Act is used to evaluate processes and ask why at least five times until an optimal process is engineered. The repetitive questioning of the system and re-designing until all material and effort that does not directly contribute to the project is eliminated. This is difficult to perform because of cultural resistance to change but is essential in creating the ideal process. This process will not end because technologies are continually advancing, making more improvements necessary (Bell, 2005; Gitlow, 1989; Pascal, 2007). Theoretically, through this process, activities that do not directly contribute to the building, such as scaffold set up and removal would be eliminated, and more productive methods would be implemented. This represents a large amount of money. The restoration of the

Washington Monument in Washington DC used a scaffolding system that cost $2.2 million – almost half of the total project cost (Mulligan, 2004). GPS technology is eliminating much of the need for surveying layout for equipment operations. Surveyors are used primarily in many projects as verification for GPS accuracy. Indeed, many jurisdictions use GPS as their dimensional survey method.

2.6.1.2 Pull Flow or Pull Construction

An important component of Lean Construction is known as *pull flow* (Eastman, 2008). Detailing and fabrication of components for a particular building section begins a short time before installation. This is important for several reasons. On high-tech or complex projects, equipment needs are frequently not known until later in the project or a changed during the project. Design and fabrication of these and related ETO components should be delayed until the latest possible point in time to allow for late decision making by the owner. By delaying decisions on uncertain tasks, changes in design and components do not need to take place and detail design only occurs once, thus decreasing non value-adding work (Laufer, 1997). The ability to do this is dependent on a clear visualization of component relationships and has only been made readily possible with BIM tools. With proper BIM usage, the design does not have to be modified but is done only as needed. A 50% reduction in shop drawing cycle time was experienced in the Flint plant for GM (Crowley, 2003.) Both the reduction in shop drawing time and the ability to delay design on some key elements are important to designing without waste. Pull production, whichever methods used, has a goal to “produce only what is needed, when it is needed, and in the right quantities so waste is minimized during the synchronization process” (Arbulu, 2006).

A principle tenet of lean construction is that each activity or task should optimize the project rather than the piece. Howell of LCI writes that the "project-side optimization, rather than a trade-level or silo focus" is needed and stakeholders need to have an 'all for one, one for all" mentality (Howell, 2008). This is one of the characteristics of BIM projects – they are collaborative and mandate sharing of information and responsibility if done properly.

2.6.1.3 Last Planner

The most common form of pull construction appears to be Last Planner. Many firms who are involved in Lean Construction Institute are also member of Last Planner communities of practice. Schedules are generally driven in construction hierarchically based on objectives handed down through the ranks. The person or group that determines the specific physical work that will be done in a limited time period (day or week) is the Last Planner. The Last Planner is the one that has the most control over productivity at the unit level and thus is considered pivotal in proper planning for effective and efficient operations. These finite work "assignments" are "unique because they drive direct work rather than the production of other plans" (Ballard and Howell 1994). Two key functions of this method are: "<u>production unit control</u> which coordinates the execution of work *within* production units such as construction crews and design squads and <u>work flow control</u> which coordinates the flow of design, supply, and installation *through* production units." Production unit control evaluates if:

- "The assignment is well defined.
- The right sequence of work is selected.
- The right amount of work is selected.

- The work selected is practical or sound; i.e., can be done."

The work flow is accomplished through constraint analysis, evaluation of related tasks, upstream needs, and matching load with capacity (Ballard, 2000).

Most construction firms use three week or five week look-ahead schedules, but the generally focus on what *should* be done. In the Last Planner system this process is far more involved as it incorporates a refining process whereby the Last Planner evaluates tasks and their place in the project and improves "assignments" so that they can be achieved in the time period designated. The Percent Plan Complete (PPC) is an important metric that gauges how often tasks are completed as scheduled. The lower the percentage, the more unreliable your schedule is. By shortening task durations and refining their definition, the reliability of the schedule increases so that plans for work tasks can be relied on so that less time is wasted in the field remobilizing or changing work tasks. PPC has been reported to increase to 40% to 80%, thus increasing productivity significantly.

2.6.1.4 CONWIP

Another variation of pull flow is based on continual evaluation of work in progress (CONWIP) with specific limits on WIP levels. This version has been used on large projects and differs from other pull production systems in how work tasks are ordered. The design function is signaled directly from the need to install a component rather than ordering through a production phase. On a large project the rebar process was studied and they found that "one of the first steps during the design of the rebar production system was to understand lead time including engineering, fabrication and assembly and installation." Through process re-engineering and BIM, the six week lead time for rebar was reduced to six days – or an 85% reduction (Arbulu, 2006).

2.6.2 Just In Time and Demand Flow

Just in Time (JIT) construction practices are used in conjunction with Lean practices to eliminate waste. JIT concepts have been used on projects with rigid space constraints, such as skyscrapers, where materials cannot be stored, but it was developed as a system as part of the "kaizen" (improvement in Japanese) process at Toyota. Ohno led the development of the system based on the teachings of Deming (Ohno, 1988; Reed, 2009). JIT helps reduce processing and storing of equipment and forces planning of labor and material coordination and has been widely adopted in the manufacturing industry. This enables "mass customization," or the process of building user specified product with standardized components, which speeds delivery and lowers costs (Pine, 1999; Gilmore, 2000). The work is directed toward the most cost-effective method to produce the end product rather than producing the individual components which often means taking delivery of components from suppliers as they are needed rather than having large amounts of inventory sitting on the job site that need to be processed and handled. The components are specified and ordered from the suppliers, but the delivery date is determined by project needs rather than by availability from the supplier (Nihon Nōritsu Kyōkai, 1988).

The old manufacturing process, in which parts are ordered from low bidders and stored until needed, is being replaced by demand flow manufacturing. Demand flow (pull flow) looks at total cost, rather than low price. This requires detailed planning and has been difficult to achieve until the last decade with the use of ERPs or sophisticated document and accounting control systems. The idea is that the production line (critical path of the construction schedule) pulls parts that are needed when they are needed.

Construction operations should not be concerned with inventory storage or ordering parts that they can manipulate to work in their product, but with installing the appropriate components at the right time in the right place. Products are built on demand rather than to stock. Adopting the demand approach reduces cycle time by an average of 75% and production costs are reduced by 10-20% (Mikulina, 1998). JIT has been possible with computerized control systems for nearly two decades but has not been widely used in construction due to the detailed logistical planning required on job sites. There is a subtle difference in demand flow taught in JIT and pull flow as used by LCI: whereas they both reduce material storage and handling costs, the former focuses on reducing costs from a supply side perspective while the latter plans to reduce rework and thus increase efficiency.

Productivity increase through JIT must be approached from a project level more than from the task level. For most firms, JIT requires a new mental approach to how they run the jobsite. "Responsibility for problems associated with the design and production of a product are always placed at the origin. For example, if a product is failing because the design is inadequate, engineering is the origin. Defects that are related to poor production practices have their origin in production. It is not uncommon for what appear to be production-related problems to actually be the result of a design problem" (Lubben, 1988). JIT practice for productivity has been difficult to measure for most firms because they do not accurately document the management time required to plan and the many interrelated aspects.

2.6.3 Total Quality Management

TQM (Total Quality Management) is a system that develops standard operating procedures (SOP) that ensure compliance to the specifications which define project outcomes. Deming taught the need for continual and systematic improvement of productivity rates as a critical part of a corporation's and indeed, a nation's ability to increase earnings and remain economically viable. His equation for quality is Results of work efforts/Total costs (Deming, 1988). Thus, activities that do not create value for the owner are inhibitors to the quality of the finished product and/or the quality of the process. Reduction of the amount of work that does not fall within specified tolerances equates to the elimination of wasteful practices, thus reducing the cost to produce a product (Mincks, 2004).

The ISO (International Organization for Standardization) 9000 family is a quality assurance system that puts the quality-management process into effect before work begins and detects and corrects problems before they reach disastrous proportions. It involves the development of quality manuals, general quality procedures, work instructions, and a plethora of forms that are used in a quality assurance system. It is a controlled systematic approach but the procedures need to be established to meet each firm's unique operational style and product. The guidelines are intended to supply basic minimum standards for firms that are endeavoring to meet quality requirements in their products (Ness, 1996; Kelly, 2009). By doing so, rework is reduced by clarifying specifications and defining the method to achieve the results desired. Construction and design firms tend to have difficulties implementing this system fully because the pervasive nature and the paperwork required are daunting. Many construction workers feel that they are turning to "checklist filers" and resist outside control.

Six-Sigma is yet another version of quality control utilized in manufacturing. There are several applications to the AEC industry, but the concept of reducing errors to 3.4 occurrences in one million is more than an industry based on unique buildings can fully grasp. The sigma refers to the efficiency of the operation by indicating how many outcomes will fall within a criterion range in terms of standard deviations from the norm. Construction firms that claim to use Six-Sigma must develop a system of measurement that is unique for their application and this is difficult to do. Because construction generally operates at 40% to 60% efficient in terms of labor productivity, the idea of achieving 2-sigma at 69% efficiency is an ambitious task. Attaining 3-sigma, or 93% efficiency, seems extremely aggressive for most operations in the field. Finding the production errors that fall out of the range and eliminating them is similar to the idea of lean, but this method uses statistical evaluation and process control more stringently. This process was developed from the work of W. Edwards Deming and the TQM movement.

2.6.4 Other Process Management Techniques

There are many types of management systems and software tools that are used to control production. The mindset of the management and corporate culture of the company determines which system is used. The following management techniques were developed by general business project managers and adapted for use by many firms in the AEC industry:

Balanced Scorecard, or score sheet, stresses the importance of a measurement system that provides feedback on key strategic priorities. A firm measures its performance on core objectives. Planning a system requires the articulation of a vision and strategy unique to the company and then the creation of methods to measure progress towards these goals (Kaplan, 1996).

MBWA (management by walking around) is used when management feels they can best improve productivity by aiding team members in achieving their objectives by helping them identify problems and working out solutions. Walking around and talking to people is better at identifying problems and solutions than studying productivity numbers (Peters, 1982).

MBO (management by objectives) is the process of defining and agreeing on objectives in an organization. Goal setting and establishment of procedures is to be done as a team instead of by edict from management. When those responsible for accomplishing the work are involved with the decision making process, they are more likely to buy in and be more motivated. Along with goals, measurable results are defined and monitored. This is where empowerment is given its chance (Drucker, 1954).

MBE (management by exception) is used when the leadership has defined goals and monitors activity to ensure that compliance is adequate to achieve overall project goals. Performance is monitored and compared to budgets and, as long as there are no major deviations, management does nothing so that the process may work without excessive and unneeded management control. Management works on strategic issues and not minutia. Problems are reported to a higher level manager when they are not solvable by the lower level manager. Pre-planning is not reduced, but follow up is done only when exceptions to the plan occur.

In variance analysis, baselines for schedules and budgets are compared against periodic progress reports to determine where productivity is lower than expected. Plans are made in which the performance can be improved and the cycle repeats. This is near the earned value (EV) approach taught by PMI. As long as KPI are good, then there is no reason for management to interfere with the work (Kerzner, 2006; PMI 2004).

Two principle causes for failure of firms to implement these value-adding management techniques have been lack of education and cultural resistance. They both are solved by management buy-in and commitment to implementation of the system. Without their teaching and progress review there will be no real incentive for those who are to carry out the tasks to perform. Setting goals and establishing standard operating procedures (SOP) is the beginning of management systems, monitoring and follow up are the more critical and usually neglected part of implementations (Luggen, 1988). Those firms that make the effort to measure and report progress see higher improvement than those that do not (Deming, 1986; Young, 2008).

2.6.5 Prefabrication

Increased prefabrication is made possible through the ability to manage the large amounts of information required (Eastman, 2008; Womack and Jones, 2003; See Howell, 1999). Lean construction will continue to drive more firms to prefabricate in order to achieve cost and quality requirements in a quicker manner (Womack and Jones, 2003; Howell, 1999, Carbasho 2008). Standard size materials increase productivity rates because they provide consistency for the workers and allow planning of materials to be accomplished more quickly and with less waste. Many firms assemble components on site but not necessarily in place in order to save labor costs. Engineered to order (ETO) components require a great deal of time on shop drawings and field verification. This slows the project frequently because components such as cabinetry, MEP (mechanical, electrical & plumbing) systems and fenestration are not produced until measurements of existing conditions are taken on the job site. Unfortunately, this is often the time when the ETO components should be installed and so there is a delay in the schedule. Careful shop drawing coordination and many coordination meetings by specialty contractors are performed so that these components may be fabricated prior to their being needed on the site (Howell, 1999, Eastman, 2008). Once approved, shop drawings are used to verify field dimensions. This is a very time consuming effort and is becoming less value-adding to the owner as BIM enables faster and more accurate detailed fabrication plans. The components are also able to be designed better with smaller tolerances and fewer errors, mostly due to the clash detection functions.

2.7 Productivity KPI

KPI are used by executives and managers in construction firms to monitor performance of crews and subcontractors. Each has various indicators that are important to them that are based on their own strategic goals and core competencies. Tracking too many reported numbers distracts from the important goals. If too many indicators are “key indicators” then no indicators are “key indicators” (Bird, 2004). As mentioned earlier, monitoring progress and costs should be done at the lowest possible managerial level and conglomerated to produce usable project or process level indicators of performance. Most executive dashboards report project level schedule and budget compliance by three or four measures: safety record, quality assurance systems and projected cost to completion.

2.7.1 Evaluation Criteria

2.7.1.1 Productivity

The rate at which a product is installed is evaluated in the field as hours per unit installed, but management should view this in terms of dollars spent to gain the finished product that meets the needs of the owner. Any work not directly going into the finished product is wasteful as it lowers the amount of finished product produced relative to effort. Contractor productivity rates are not reported externally but are generally guarded by the company management. The rate is not used to report billable accomplishment but rather reflects the efficiency at which resources are used to produce the billable product. Most firms are unwilling to share productivity rates because they are an indication of competitive edge. It is assumed that for the purposes of this thesis, the number will not be available for direct analysis.

Idle time is a significant factor in productivity ratings. As discussed earlier in this dissertation, one-third of laborer's time is spent waiting for instruction, materials or clarification. This idle time greatly reduces the amount of output per resource dollars input. Idle time is commonly recorded when a delay is discovered and the contractor believes that there will additional costs that will be claimed by the contractor. Idle time is generally recorded only when field management have reason to believe that laborers' time will be charged as an extra to the contract amount. It is not closely measured or reported otherwise. Most contractors know that there is significant idle time due to confusion or lack of direction and include some amount of money in their bid proposals to account for average idle-time expenditures. Contractors can make profit if they are able to plan better in order to reduce wasted time on the site.

2.7.1.2 Budget Variance – EV

Earned Value is used by many firms to evaluate how close the project is to the anticipated budget. This method is not entirely accurate in terms of understanding cost of construction because non-critical and less risky tasks can be completed earlier in the project, thereby raising the perceived productivity rate. Conversely, if risky or expensive tasks are completed early in the project, cost projections to completion will be inflated. Despite this, EV is used extensively for evaluating performance for tasks and predicting budget outcomes.

2.7.1.3 Schedule Compliance

, According to LCI, 55% of work promised to be completed each week is completed on schedule (Howell, 2006). Each delay causes a ripple effect on subsequent activities such that exact planning schedules are impossible to maintain. Materials arrive too early or too late and labor may not be available when needed. Meeting projected finish time is important for proper planning. It is not sufficient to be early on the time schedule, but to be on target – if early, then the next scheduled task cannot be started to take advantage of the early completion.

In 1970, it was found that government projects took 59 months to design and build while equivalent private projects took 24 months to design and build. Government projects took 1.5 times longer than private projects. In 1988 it was found that 48% of 268 projects valued at over $10 MM ran more than 6 months over budgeted schedule (Perkins, 2007b). The mean schedule growth for projects in an Australian study was 20.7% with a standard deviation of 28% (Irani, 2003; Love & Li, 2000). Research has overwhelmingly shown that Design Bid projects

2.7.1.4 Scope Creep

Scope creep is the gradual increase in the amount of work that is to be performed. It is typically the result of the owner adding requirements after the project has started. Unforeseen conditions, government regulations, or additional input from the end users can each change the amount of work required under the contract. This has the effect of throwing off planning of resources and decreasing efficiencies of effort for planners and workers.

2.7.1.5 RFI – Cost & Number

The number of RFI on a project is indicative of the clarity and completeness of the plans. A large number of RFI suggests that much time is being spent clarifying design intent rather than performing productive work. Most case studies and reports of BIM success indicated the amount of reduction in RFIs to be a significant advantage. The $611 MM project, Washington National's stadium, reportedly had less than 100 RFI on the structural steel portion of the project as contrasted to the expected 1,000 and 10,000 RFI on that type of non-BIM project (Fortner, 2008). The $100 MM Camino Medical Office Building project experienced only 6 RFI relating to MEP work. This type of project would normally be expected to have hundreds of RFI concerning MEP coordination (Carbasho, 2008). These projects experienced only 1%-10% of the RFI that would normally be expected. These numbers seem extraordinary but all reports indicate a reduction in RFI as a benefit of BIM usage. The actual reduction in RFI is not known, but it is apparent that it is significant.

The RFI process is: field personnel find and report the problem, the GC investigates the problem and then passes it to A/E, A/E investigates the problem and answers, GC studies, answers, and coordinates with applicable trades, trades get answers and develop method to complete, and any change order resulting from work different than anticipated in the documents is submitted. This is a time consumptive and costly procedure as illustrated by Figure 8.

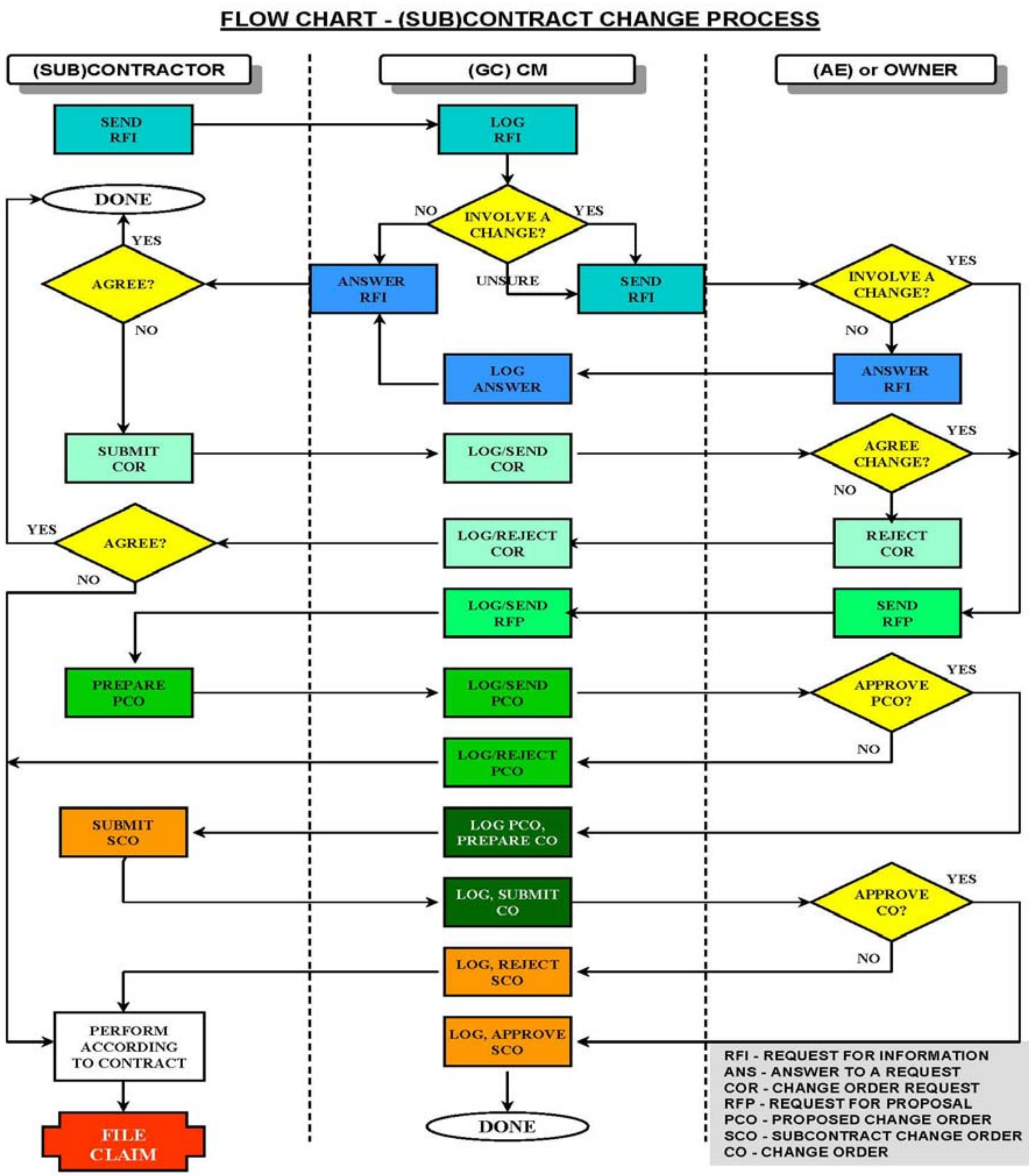

Figure 8 - RFI & change flowchart illustrating effort to manage an RFI.

According to the articles touting BIMs value, it is possible for projects utilizing BIM to have over 90% reduction in RFI compared to similar projects that do not use BIM.

The time and money saved on RFI administrative is significant and has been quantified by several major contractors including Kiewit, Clark, and Hensel Phelps. Figure 9 shows the official RFI process for the San Jose Airport Project as published by

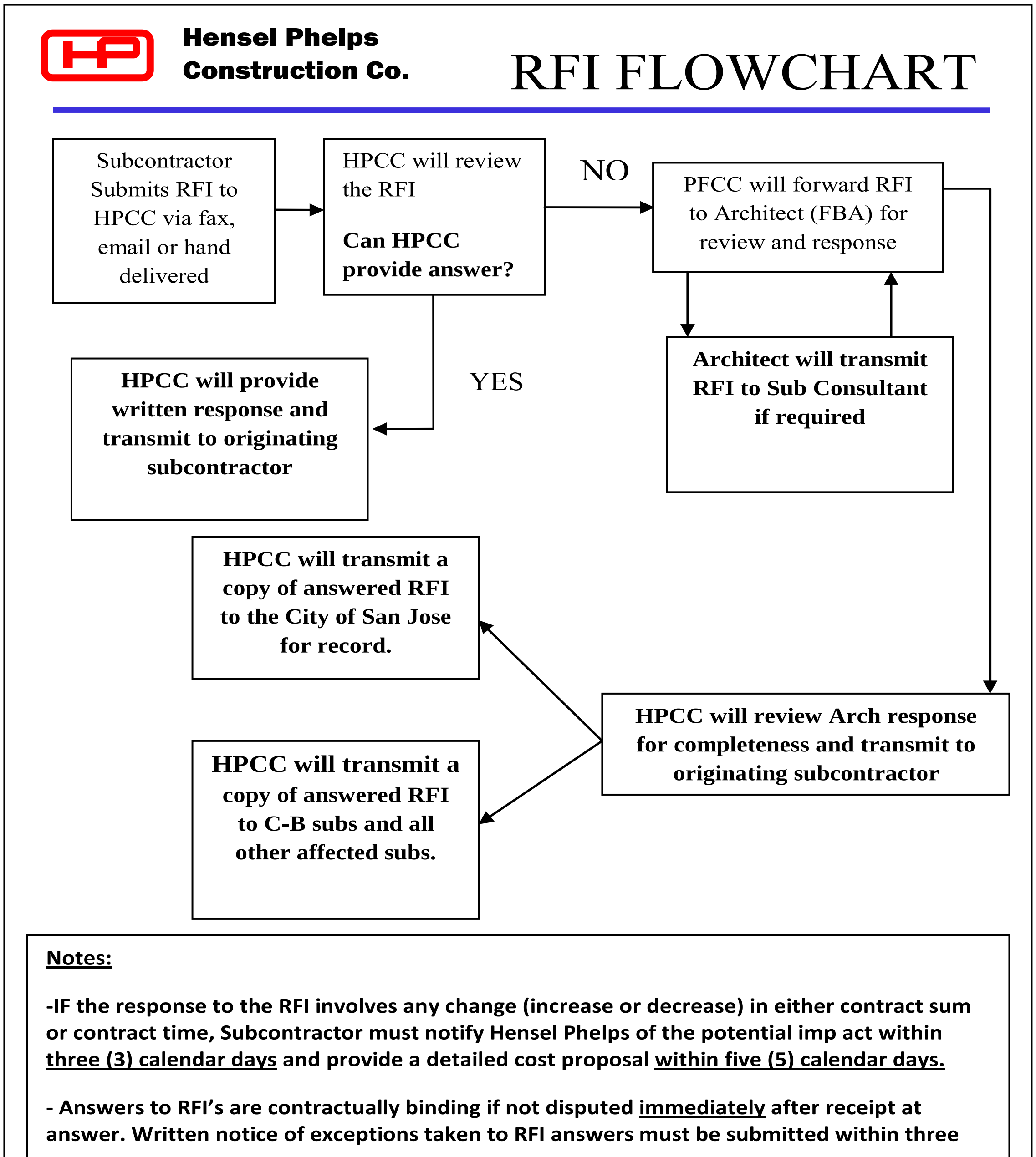

Figure 9 - Hensel Phelps (general contractor) simplified RFI flowchart. (Source: HP San Jose Airport project documentation).

Hensel Phelps. The average cost of administering the process and accounting for delays has been found to be in the range of $350 to $500 depending on the type of project. The average cost on buildings such as health care and education is $425 per RFI. This does not include extra costs due to re-mobilization of labor or extra work required by many RFI responses (see Figure 8). This $425/RFI is considerable, but not as significant as the time and labor costs of delays in the field due to confusion about the plans. The number of RFI on a job is indicative of the clarity of the plans and the coordination processes. Higher field productivity should be expected with fewer RFI because of the decreased confusion and waiting time in the field.

In a study of CM projects in Washington State that averaged $59 Million in contract size, the number of RFIs ranged from 188 to 2653, with a mean of 912 and a median of 410. The survey revealed that half of the respondents believed that the CM method resulted in fewer RFI than normal (Goldblatt, 2000). Using the mean RFI count, the average project experienced 155 RFI per $10 Million in contract price. Using the average cost of $425/RFI, the RFI administration cost for the "average" project of $59 Million is $387,600 or 0.65% of the project cost. This does not include all the field delays and loss of productivity resulting from the RFI changes.

2.7.1.6 Change Orders

Change orders are also indicative of inefficiencies due to poor planning. These often result in changes to conditions or scope. The more change orders, the less efficient the operation is. Design-Build contracts experience lower owner change order rates caused by plan error or constructability compared to DBB contracts. CII found that DB contract cost growth was 2.17% while DBB was 4.83% (CII, 2005). A study of mechanical contracts found that contract changes were 3.1% for DB and 6.6% for DBB, most of the difference being attributed to a reduction in design errors on DB projects

(Perkins, 2007). A study of Australian construction firms found that the average cost growth for the 161 projects studied was 12.6% with a standard deviation of 24.22% (Irani, 2003; Love & Li, 2000). A study done for the State of Washington showed that change orders on government projects utilizing CM contract type have shown 7.2% contract price increase. Other studies reviewed by Goldblatt and Septelka in this study were:

- "CII Research Summary 133-1 (1997) … reported a median cost growth of 4.8% for DBB projects, with 49% of the projects greater than 5%. It also reported that there is a 50% likelihood of a DBB project realizing cost growth between 2% and 11%. "CM at risk" … projects reported a median of 3.4%, with 44% of the projects over 5% and a 50% likelihood of realizing cost growth between 0% and 9%.
- Engan (1996) investigated change orders on 231 UW construction projects. She reported that the mean change order ratio for DBB projects under $10 million was 15% and the median was 9%.
- National Research Council's Building Research Board's committee on construction change orders (1986) reported—after looking at 59,155 private projects, 2200 VA projects, and $2.5 billion in Federal projects—that "contract modifications which increase contract value between 5 and 10 percent would reasonably be expected on most construction projects. (Goldblatt, 2000)."

One study by the USDOT showed that on transportation projects there were fewer change orders on DB projects, but that they cost more money. DB projects experienced a 6.0% cost growth while DBB projects averages 4.3% growth (USDOT, 2006). Several explanations were given for this exception to the typical study results showing that DB projects tend to perform better than DBB projects in terms of budget. The principle reason is that the owner recognizes problems with its requirements earlier in the project and is able to change the scope of work, making the project more expensive. If the problem is discovered later in the project, after construction is underway, changing the scope would be much more expensive and is thus not done. It was found that whereas the contract change costs were a little lower on the DBB projects studied, the owner was more satisfied with the finished DB product (Perkins, 2007).

Change order amounts vary greatly from project to project, but it is more common for commercial and educational projects to suffer from higher rates than transportation, industrial, and residential. Three to ten percent are generally expected by owners and held in contingencies for changes due to plans and design changes.

2.7.1.7 Quality & Rework

Quality is defined as adherence to the specification or how closely the product meets the owner's needs and expectations. Quality assurance programs are enacted by contractors to various degrees and architects play a role in ensuring that the product produced by the contractor complies with plans and specifications. Performing work the first time properly increases productivity because resources are not spent re-working non-compliant installations.

There is a difference between quality control and quality assurance. Quality control is based on post-production quality inspections and thus has increased costs without a savings for the firm (Jaafari, 1996; Preusser, 2007). This is the practice of finding errors after they occur and then repairing or reworking at a cost to the contractor.

Quality Assurance is the process of reducing errors rather than fixing errors after the fact. Barclay Construction is a typical firm that experienced rework costs estimated at 5% of their contract value. Once a quality assurance (rather than quality control) program was implemented, rework was reduced to less than 1% of the contract value in most of its projects" (Lomas, 1996). "Landin and Nilsson (2001) have stated that construction firms that make investments in quality systems do so based on 'acts of faith,' rather than on factual information. Consequently, they are often left questioning how much quality is actually costing or saving them" (Irani, 2003). If more contractors understood the cost of poor quality they would be expected to perceive that preventing errors is less expensive than fixing errors.

The tendency to repair damage rather than prevent it is a major factor in construction inefficiency and higher construction costs. Rework costs have been estimated to be as low as 3.3% (Fayek, 2003) and as high as 35% of construction costs (Irani, 2003). The Construction Industry Development Agency (CIDA) in Australia estimates that the direct cost of rework in construction is at least 10% of project costs (Love 2002). American mid-sized construction concerns were evaluated by the CII which determined that direct rework costs were 5% of project costs (CII, 2005). The direct cost of rework does not include indirect costs which most contractors viewed to be equal to the direct costs. Rework costs are not commonly measured in detail by construction companies (Tucker, 1996). To find these values researchers asked managers to estimate their direct and indirect costs associated with the rework performed on target projects (Irani, 2003; Love & Li, 2000). Irani found total rework costs to be 12% with a standard deviation of 35%. The respondent's estimates in his study reported direct rework costs of

6.4% with a standard deviation of 7.7% and indirect costs of 5.6% with a standard deviation of 7.19%. Irani was surprised “to find that respondents considered indirect costs to be of a similar amount as direct costs, especially as Love (2000) has shown that indirect rework costs can have a cost-multiplier effect as much as five times the actual (direct) cost of rectification” (Irani, 2003). Other studies have been conducted on the amount of rework performed on projects but most range from 4% (direct cost) to 14%. Love (2002) reports that 52% of project cost increases are attributable to rework, and Preusser (2007) teaches that contractors spend up to 30% of their profits on reworking errors. Whatever the exact amount, it can be concluded that rework contributes significantly to the amount of labor and material input to a project without increasing the value of the project so that productivity rates diminish with rework performed.

The most significant factors causing rework have been found to be poor design and coordination. A study by Burati indicated 79% of the problems originate in the design phase and that these quality problems can cost as much as 12.4% of the contract amount (Burati, 1992). The CII claims that 55% of the causes are design and engineering related (Hwang, 2009). Another study found that 51% of post construction quality problems were design related (Hammarlund & Josephson, 1991). According to all studies performed on the cause of rework, design problems and coordination were the predominant causes. Poor quality (non-compliance to the intent of the plans and specifications) is not generally noticed until the construction stage. By that point, money has been spent and more will need to be spent to rectify the problem. “Contractors, in many ways, act as quality buffers, that is, they check contract documentation before construction commences so that they can determine their construction programme as well as identify errors and foresee potential problems that may occur" (Love, 1999). Better plan coordination by designers would reduce over half of the causes of site rework.

2.7.1.8 Safety

Safety is monitored closely by management. Not only can safety infractions result in fines by OSHA or other agencies, but the threat of lawsuit and higher insurance rates create potential costs which do not add value to the finish product. Many firms report accident near-misses in an attempt to decrease their exposure to injuries and lost time accidents. These firms generally have fewer accidents and lower their Experience Modification Rate (EMR) which determines their workers compensation insurance costs so that they can be more competitive. This translates to increased project productivity because less money is spent on insurance rates and accident response. Costs of accidents have steadily increased on construction projects and a culture of safety is being implemented by many contractors to combat the high costs of poor safety. On one site, accident costs were 8.5% of contract the total contract price (Dester & Blockley, 1995). This is extreme, but the cost of safety is increasingly felt as insurance rates add costs to contractor overhead.

2.7.1.9 Capital Equipment & Material Usage

Knowing the location and usage rates of equipment and material is of great interest due to the capital investment required. Most sophisticated firms are beginning to track materials to be delivered to the site using RFID, scanners, or some other technology. Productivity rates increase with material tracking because time is spent installing rather than handling materials. Similarly, machines can be tracked to evaluate proper usage so that they are used more effectively.

2.8 Conclusion:

Productivity is defined and evaluated based on the expectations and needs of the stakeholder. For this work, it will be defined as the output per input in terms of dollars. Whereas productivity costs generally refer to the construction process and its associated costs, the focus should be on lifecycle cost, or the total expense associated with building, operating and deconstructing the building. The construction method and costs should reflect the optimal cost solution for the project rather than for the lowest construction cost just as individual tasks of the project should not be made more efficient at the expense of other tasks. Balancing the various task productivities and their impact on project as well as the building lifecycle requires a great deal of planning, coordinating and cooperation amongst all team members. All productivity should be based on the effectiveness of the inputs at achieving the requirements or specifications of the building.

Because the productivity rate is closely guarded by contractors, productivity at the project level will have to be evaluated by the following four KPI, based on the ability to measure them and because of their direct impact on the amount of resources required to complete the building product. These four are idle time (2.7.1.1), RFI (2.7.1.5), change orders (2.7.1.6) and re-work (2.7.1.7). Idle time and rework are field labor issues and are often conglomerated in labor reports so that they will be evaluated together when required. RFI and change orders are office generated and tend to be more accurately recorded. These KPI will be evaluated most closely in the research because they most strongly evidence the clarity of plans and the planning process – the factors that BIM is hypothesized to improve.

Chapter 3: BIM USAGE REVIEW

3.1 BIM History and Definition

Three-dimensional design based on solid modeling or 3-D shapes enclosing a volume was developed in the late 1970's and early 1980's. Early modeling software was difficult for users to use because they were used to 2-D design tools. It was also expensive and computers where often not powerful enough to support the operational needs of the software. Manufacturing and Aerospace needs spurred the creation of more useful design tools utilizing parametric object-based modeling in which each shape is defined and related to others so that components are represented and changed easily. Since the 1990's, mechanical and steel trades rapidly embraced the modeling tools because their fabrication processes utilized the model's output very efficiently. With the advancement of computer speed and memory, designers and other contractors began adopting BIM to integrate the various components of the building. In the last decade tools available to the AEC industry have been able to relate connected components in a defined space *and* include information about the object being modeled. BIM has only in the last five years, however, gained enough popularity and break into the mainstream market. For a more thorough discussion of the history of BIM see *BIM Handbook – A Guide to Building Information Modeling* written by Eastman, Teicholz, et al. (Eastman, 2008).

The AIA Building Information Modeling Protocol Exhibit defines the Building Information Model as "a digital representation of the physical and functional characteristics of the Project and is referred to in this Exhibit as the "Model(s)," which term may be used herein to describe a Model Element, a single Model or multiple Models used in the aggregate. This definition refers to the data organized to represent the project electronically. The document then defines Building Information Model*ing* as “the process and technology used to create the model” (AIA Document E202 – 2008). The product, or representation, is differentiated from the process of designing and organizing. As the axe cannot “boast itself against him that heweth therewith” (Isaiah 10:15), so the model can do nothing without a process for modeling. The analysis of BIM usage will refer principally to the actions and procedures that members of the AEC community are engaging in.

Some firms claim to be using BIM but are doing only 3-D images with no real ability to aid in construction planning. These are useful for visualizing finished appearance, but nothing more. Eastman (2008) defines what BIM is not. These are needed so that actual BIM usage by firms can be evaluated:

- Models that have only 3-D data but no object attributes or intelligence at the object level.
- Models with object definition but no proportion or positioning because they have no parametric intelligence.
- Models composed of multiple 2-D CAD that must be combined. Intelligence with respect to relationships cannot be guaranteed.
- Models that allow dimensional changes in one view that are not automatically reflected in other views.

There is no single software tool that performs all functions listed above, although several are approaching. Most firms prefer to use an authoring tool that is best suited for their needs rather than to work with a totally integrated systems which is slower and less intuitive. This will be discussed later. The most significant hindrance to the criteria given by Eastman is the level of training and understanding in the industry. There are still years of streamlining required for the BIM concept to be implemented in an effective way.

3.2 BIM Utilization

3.2.1 Owners

Owners weigh success of a project based on budget, schedule and meeting expectations. Research on the selection process shows that owners who select DB as their project's PDM did so in order to shorten duration, establish cost earlier, reduce costs, and reduce claims, in that order (Songer, 1997). BIM can cause marked improvement in each of these factors and is being used by owners for these reasons.

Schedule duration is shortened because of the parallel iterative design process, shortened design, and reduction in conflicts. It supports fast track building where the construction process can begin even without complete data, putting the project onto the fast track. Various studies on projects meeting scheduled budgets have shown weakness in the industry. One-third were completed on time, one-third were over by up to a month and one-third were over by more than a month. The overruns were the greatest dissatisfaction to customers (NEDO, 1988). In Australia 67% had time overruns and 22% had variations in scope of more than 10%, and all of those ran long (Koskela, 2000). About 45% of projects in the US finished over budget by more than 5% (Konchar, 1997). A similar British study showed that about 26% were more than 5% over budget at completion (Bennett, 1996).

Time compression is impressive when BIM is used. Kaner (2008) performed a case study where design was done by BIM and compared to a schedule for the work to be done in 2-D CAD. The schedule for design utilizing BIM on this one area was 23 days and it was estimated at 35 days for CAD. The design time only was a savings of about 33 percent. The Flint Engine plant project was compressed from an 80 week normal to 60 week typical fast-track to 35 week schedule by running design, engineering and construction in parallel. The BIM time savings were beyond typical fast-track processes, not just beyond traditional DBB. Not only is the BIM software able to speed design, but the process of shorter iterations with increased design collaboration decreases the amount of time that is spent re-designing and re-engineering due to work by other designers. This is in sharp contrast to the 2-D paper–based design process which must follow sequential steps (Eastman, 2008).

Some owners have created a model early in the project development stage for all prime contractors to use in their own designs during their DB proposal. One such case was for a skyscraper in Hong Kong. This tactic fostered a more open design phase in which various trades were able to think of how their work relates to others. The process was streamlined and shortened, but more importantly, the accuracy of the plans was increased such that re-work and delays due to insufficient plans was reduced on the order of 5% - 10% (Architectural Digest, 2007).

The Government Services Administration (GSA), the single largest facility ‘owner’ in the US, established the National 3-D – 4-D - BIM Program in 2003. Other federal agencies have followed suit and require BIM to be used for projects over 5,000 SF. In the program, the GSA (2009) made the distinction between 3-D and BIM. This helped establish the intelligent design concept rather than just 3-D pictures and this made a huge impact on defining open standards and interoperability since the data must be usable across the many programs and platforms in the market. In 2007, the US Army Corps of Engineers required Bentley to be used on their Center of Standardization prototype BIMs. There was concern that this would disrupt the industry and cause confusion about which system to go with, but the AEC industry has not changed dramatically with the choice. Owner requirements for BIM can be pivotal as history shows: Primavera scheduling tools were specified on government contracts and they subsequently became the predominant scheduling program in the industry. The GSA's approach to BIM requirement has been on defining their internal use needs and then seeking a BIM authoring tool to meet the requirements (Suermann, 2009). This type of approach will enable the most efficient BIM tools to become the predominant player because it is more efficient at meeting owner's requirements. Because needs vary, there will be many players in the market.

Costs are established earlier because the design curve shifts to the left as shown in Figure 3 on page 11 of this work. A higher investment up-front is required but the design is more accurate so that the overall project costs can be determined more accurately. The trade-off in spending more earlier to obtain a clearer view of the projected costs of the project is difficult for many owners who, if the project cannot be completed will have spent more on the initial design phase without gaining the benefits from the increased efficiencies derived from using BIM during the design concept phase.

The most widely reported BIM project is the Camino MOB project performed by DPR, Inc. It is referenced in dozens of articles and is the subject of at least six case studies. DPR, Inc. is one of few companies that spent as much effort evaluating their performance with BIM as they did when writing a case study of their experience. Most information concerning BIM is from very few case studies, and reports of users' satisfaction by proponents of BIM and software companies vending the products are limited. Most of the information concerns design productivity but when labor or project productivity is discussed, about 10% to 30% savings attributed to BIM is reported. These studies also report very few or no RFIs, COs due to conflicts, and incredibly reduced plan conflicts and rework. The case studies generally do not mention who retains the cost savings.

. Only 7 out of 246 projects mentioned in the 2008 Bentley Year in Review are residential and they are mostly visualization tools for owners. They include the following:

1. Kelderhof in Cape Town, SA designed 5 homes for development to adapt to various tastes, needs and budgets of the clients.
2. Johnnybro Development used BIM to model various apartments to help visual product and lighting effects in the interior. Helped communicate to the clients what the product would be.
3. Models used to create visualizations in order to show settings, views, orientation of waterfront properties in Netherlands.
4. Apartment building design gives superior product to the client. Environmental issues such as solar access, flow-though ventilation, and water reuse are incorporated into design along with siting of building to maintain natural

environment. In this case,, show and environmental and orientation issues seem to drive the need for BIM.

5. Tsai Residence – Johnnybro designed a house in New Zealand and changed design from visualizations presented to owners. In this way, they saved money and time in changes later.
6. BIM was used to design a residence because of the unusual demands in design and lay-out.
7. Eco-House for Nordic Conditions in Finland. Bentley Architecture and Tri-Forma were used to create design options for informed decisions. Design and construction documents are coordinated. Costs are predicted using model.

Of the cases here, 1-5 and 7 utilized BIM for visualization to the owner as a principle purpose. Cases 3, 4 & 7 had environmental considerations as an important reason for BIM. Orientation of the structure for both solar and vista views consideration were important. The 6th case used BIM mostly for uniqueness of design and constraints that were difficult to design in 2-D, but also energy usage was an important factor. In residential construction, the big seller seems to be the visualization that is available to show the client what they will be getting. This is both a sales feature and a money saver due to the reduced re-work that often occurs when the owner or user sees the potential finished product and decides that it is not what they had in mind. On typical low- rise residential the building technique is not as complex and the builders generally do not require the aid of 3-D visualization because they will be constructing the same basic housing unit that they have built many times before. Most structures built are small residential. The learning curve on each project is minor because each tends to be similar to many others that have been built by the various contractors. Owner satisfaction should be increased due to their understanding of what the final product will be prior to its actualization.

Productivity increases are not a hot topic when discussing BIM benefits in residential design and construction. They tend to be less complicated and are performed by firms that do not measure productivity as closely as large firms which contain a managerial level dedicated to such issues. Communicating what the finished product will be before construction starts seems to be the biggest incentive to utilize BIM.

3.2.2 Designers

Owners are requiring BIM usage in many cases in order to reduce errors and unexpected costs. BIM is touted as the way to save money by eliminating errors and waste. Owners are expecting to receive a bigger share of the savings so that designers and contractors will have to be able to prove their own value by managing the process. The group that takes the risk of implementation should be receiving the rewards of doing so.

Reports tend to overstate the usage and success of BIM usage in the industry. The CSI BLOG posted an article on Dec 15, 2008 which reported the McGraw-Hill SmartMarket BIM report. It stated that “45% of users report that they are utilizing BIM tools at moderate levels or higher” (CSI BLOG, 2008). Similar language is used in numerous articles and reports and leads readers to believe that BIM usage is very common. However, the “users” reported are those that volunteered to respond to a survey given to people who utilize BIM and the results are not conclusive in terms of industry-wide adoption or usage.

There are several reasons to begin implementing BIM practices in design firms. Owner requirement is not very common. Owners were the primary drivers of BIM usage on only 13% of projects. In fact, recent research indicates that when BIM is utilized, the primary drivers are architects 40% of the time, GCs 18% of the time and a combination 14% of the time. Interestingly, contractors do not view architects as the principle drivers but over half view themselves in that role (Young, 2008). The author found few instances where BIM was used at the behest of the owner without the design/construction team touting its benefits and including it as part of the contract documents.

Architects and engineers used BIM when a project was very complex and they didn't know how to design manage it with normal 2-D drawings (Kaner, 2008). BIM has been primarily used on complex projects such as petrochemical plants, process facilities, hospitals and other structures where close coordination is difficult with traditional 2-D representations. Using a model permits more difficult structures to be constructed as communicating intent is made simpler. Dubai is home to many such projects that could not be conceived or designed practically without the use of object oriented relational models (ENR, 2009).

Training is very important for designers. Knowing how to use the basic software functions does not mean that you can use it efficiently. This point is illustrated on a case study of a pre-cast shelter constructed in Israel. The engineering firm discovered that after formal training the design productivity increased by 600%. Levels of productivity and pace of productivity are highly dependent on the degree of formal training. Both companies reported that BIM operators have to undergo a significant change in thinking from their cad approach to their BIM approach (Kaner, 2008).

Productive use of BIM requires careful planning regarding how the building is to be modeled. During "much of the BIM workflow, the focus is placed on the building as a whole, with all the work performed on the model. Drawings are secondary, only modeled in the designers' minds. As such, design using BIM becomes largely top-down, as opposed to a hybrid, iterative approach using CAD (Sacks et al. 2005; Kaner, 2008, Kymmell, 2008).

The process of design and the productivity is greatly affected by BIM. Of designers and engineers that participated in the ENR survey, 72% of users say there was at least a moderate impact on internal project process and 2/3 report at least moderate impact on external project process. Half of users have a very positive impact while only 7% report negative impact (Young, 2008). During design phase of a power plant in Wyoming, 3-D model collaboration reduced the estimated 7,600 number of physical plant drawings that would need to be printed and handled by 85%. This represents thousands of hours of work saved and a reduction of paper and shipping costs as well (Bentley, 2008). Three buildings were studied where the engineering and design were done in 2-D CAD and later with BIM. The reduction in engineering and drafting hours for the jobs averaged 58% for the two larger jobs and 21% for the smaller project (Sacks & Barak, 2007). BIM allowed accurate equipment and pipe location which is very difficult in orthographic drawings. Design man-hours were reduced at a 2.5 to 1 ratio compared to traditional 2-D design process (Bentley, 2008).

Anecdotal reports generally sponsored by software companies and architects give ranges of from 10% to over 1,000% increases in productivity or returns on investment. It is difficult to know which because they are not scientific in their approach to throwing out numbers. Few negative reports of BIM are found. The McGraw-Hill report found that about half of current BIM users expect to be heavy users of BIM in 2009 (Young, 2008). Clearly the trend is for continued growth in usage due to the productivity gains afforded by BIM. Because of the fragmented nature of construction and the large amounts of small firms, adoptions will still take several years. It is projected that half of structural engineers will be using BIM by 2015 and not reach 80% usage rate until 2020 (McPhater, 2009).

LEED is a recent development with many owners requesting or requiring accreditation. This does not increase productivity or make a job more efficient, but the building becomes more efficient in terms of environmental and human impacts. There is a great deal of additional documentation and methods analysis that must be performed for a LEED project and in some cases, accreditation points can be granted by more efficient job site operations. For example, paperwork reduction in favor of electronic documents, waste material processing, and commissioning processes can all increase the efficiency of various aspects of the construction and turn-over process.

3.2.3 Contractors

The means and methods responsibility belongs to contractors. This knowledge is needed for proper design, but designers generally do not have this information when starting design concepts. Proper BIM involves the builders early in the process. This helps to include the means and methods information into the design so that it is more efficient and accurate. This information allows proper design in terms of sequencing and material usage (Smith, 2009). Some of the trade contractors utilizing BIM have found that producing models saves them enough money in re-work that they use BIM on most projects, regardless of whether or not other trade contractors, the general contractor or the designers opt to produce a model (Kymmell, 2009; Sanvido, 2008). By modeling, there is an increased ability to pre-fabricate larger sections of ductwork and install them in a more logical way. The ability to construct sections of work off-site increases the overall productivity rates because they can work in more controlled environments and plan material usage more accurately and use more specialized and efficient machines and equipment.

General contractors have begun to get involved in the coordination processes using models. Several are requiring that MEP, structural, building skin, and drywall contractors work together to incorporate their models into a single model used for clash detection and detailed planning. The clash detection finds instances of conflict in the plans. Ductwork or piping that runs through a structural member is easily discovered during the detection process. The savings available from this process alone is generally equivalent to a majority of the owner's expenditures on change orders resulting from plan conflicts (Smith, 2009). With the added advantage of not having to re-work, wait for direction, and pre-fabricate more logical components, the savings can be quite high, on the order of 10 to 30 percent for many of the specialty contractors (Eastman, 2008).

BIM is enabling contractors to model lifting equipment, material transportation and installation, and heavy civil work such as excavation and mass soil excavation. Excavation costs are decreased significantly by using BIM because the distance soil is moved, the depth of the cut equipment makes, and the number of passes required to gain proper level are reduced significantly by the model optimizer.

Contractors are reporting remarkable improvement in their operations because of BIM usage:

- Ghafari Associates on the GM Toledo Powertrain Transmission plant used 3-D clash detection to find and eliminate “thousands of interferences in the virtual model before they translated into costly field interferences, with 3 to 5 percent overall savings due to collision avoidance.”
- The Washington National’s stadium had only 100 RFI rather than the 1,000 to 10,000 that would normally be produced on that type of project. Only 2% of the steel members required changing when they expected about 10% for a typical project of this size and complexity (Fortner, 2008).
- CH2M Hill on the Pantex Processing Facility modeled down to ¾” conduit. This is more detail than normal but they found that it was useful in reducing the amount of conflicts in the limited space during remodeling at an occupied facility.
- Labor productivity rates on the Camino MOB were 15% to 30% higher than industry standards and there were no change orders related to field conflicts. Only two RFIs concerning field coordination arose on the project (Carbasho, 2008).
- The CCC Dubai Mall project used BIM and an automated tool to do quantity survey for concrete work and develop monthly valuation sheets. It did more than 95% of quantity survey, improving quality and efficiency of the process, and reducing the cost of the task by 65% (Bentley, 2008).

Dr. Victor Sanvido of Southland Industries reports that the mechanical systems were prefabricated off-site in an assembly facility based on designed specifications from the Camino MOB project model. There were 6 RFIs related to MEP and fire protection systems conflicting with other systems while there are usually hundreds of RFIs on this type of project. Only 6 equipment components had to be moved. Rework on this project took 43 hours or .2% of 25,000 hours of project labor. Thirty percent fewer sheet metal workers and 55% fewer pipe fitters than originally estimated were used. The HVAC contractor reported more than $400,000 in labor savings on a $9MM GMP and claimed a 2 to 1 net ROI. Southland Industries has used BIM since the 90's as the growing complexity of buildings has made BIM more essential for proper coordination (Sanvido, 2008). For specialty contractors and fabricators, "BIM supports the whole collaborative process of design development, detailing, and integration. In many recorded cases, BIM has been leveraged to enable greater degrees of prefabrication than were possible without it by shortening lead times and deepening design integration" Eastman, 2008).

On one precast concrete project the BIM design was structured properly and information was supplied only as needed. The fabricators received the information they needed to construct the panels, but were not given information that was not needed for their work. The erectors were given only information needed to perform their own specific work, but not other information not needed for their operations. The prints were easier to read and "the pieces and drawings were entirely error-free, a situation that [the erectors] had never experienced before" (Kaner, 2008). Supplying only needed information reduces information overload which makes the plans harder to read. Too much data has the effect of reducing the attention span and understanding of the people who are overloaded (Brown, 2000). BIM enables selective information release so that user of the model output receive only the information they need to be productive..

3.3 ROI of BIM usage

Design firms tend not to measure their ROI on BIM. They look only at cost of software and training. This misses much of the cost and big picture effects of BIM (Smith, 2009). Software and training are the tip of the iceberg. The principle costs are those associated with re-educating managing the culture shift that is needed for proper implementation of the proper software.

Without accurate information regarding the cost of implementation and the benefits gained from the new technology and process, firms will be apprehensive to commit to adopting it. Once firms do adopt BIM methodology they need to know what to base their performance on. There is a need in the AEC industry for a baseline model of how much money should be saved given implementation strategy.

The presence of waste in construction is pervasive. BIM reduces waste in the reduction of time and money spent on producing and using paper documents. In the case of the staircase, waste was evident in the design process as it was performed several times. This was because of lack of clear understanding of requirements, a fabrication process that would not allow complete components to be assembled in the shop, extra hours needed to install the stairs differently than anticipated, extra management hours needed to resolve the conflicts, paperwork and pricing and meetings with owners, architects and contractors. Each of these costs extra time and money. These activities were wasteful because they did not contribute to the finished product and, indeed, distracted attention from more appropriate work. A pervasive organizational system is needed to address this waste.

Evaluation of BIM is typically done by the reduction of errors. RFIs and COs relating to plan errors are indicative of the clarity of the design and cost of dealing with them. As seen in 3.2.3, several contractors evaluated the effectiveness of the BIM by how many RFIs were eliminated and how many members that did not need to be re-worked. However, this myopic view ignores the great deal of money which can be saved by evaluating productivity. Labor required to construct buildings designed with BIM processes should be compared to production of typical designs and methods (Eastman, 2008). Productivity gain for structural engineering drawings with rebar detailing has yielded gains between 21% and 59%, depending on size, complexity, and repetitiveness of the structure (Sacks and Barak, 2006).

The amount of money saved by avoiding conflicts and the amount of money saved by increasing productivity directly are summed to determine the savings gained by using BIM. Estimating productivity gain of BIM is difficult because there is little data other than what is provided from various design firms and software companies. As more historical data becomes available, contractors should be able to predict productivity rates for tasks given BIM design and compare these to non-BIM enabled projects so that a net change in productivity can be estimated.

The next step in ROI evaluation is calculating the investment cost of adopting BIM. Software and hardware costs are fairly straightforward to estimate, but training costs are more difficult. They are mostly a function of time needed to gain understanding of the system. According to Kymmell, BIM is more intuitive than CAD so that whereas the learning curve may be steep, it is not a huge consideration in the long run (Kymmell, 2009). Software and training costs must be added to any additional personnel and time needed to run multiple systems and learn a new culture and operational style.

ROI is determined by dividing the net savings by the investment cost. Autodesk teaches ROI as earnings/costs or as their equation reads:

$$((B-(B/(1+E))x(12-C))/(A+(BxCxD))$$

for the first year ROI, where A is the cost of hardware and software, B is the monthly labor cost, C is the training time in months, D is the productivity lost during training, and E is the productivity gain after training. The productivity loss and gain are the most sensitive variables. They are also the most unpredictable (Autodesk, 2007). The limitations of this ROI calculation are mostly in the unknown productivity changes and that it focuses on the designer's perspective. Autodesk performed a web survey in which respondents reported 25% to 50% productivity loss during training and ultimately 50% productivity gains by half of the users (Autodesk, 2008). To evaluate field productivity ROI, the investment is considered against the change in productivity. This will take the form of a scenario analysis. It is likely that labor hours are reduced and that there are no other costs. However, it is possible that the BIM process comes up with prefabricated components that may require additional shipping or equipment and handling costs that must be considered. Training may likely be the biggest cost of field work as the models are getting closer to the field all the time.

Of those firms that actively track BIM ROI only 2% perceive a negative ROI & 1/3 report more than 100% ROI. Of those firms that do not track ROI 10% perceive negative ROI and only 7% perceive more than 100% (Young, 2008). Tracking ROI appears to increase the ROI. It is likely that performance is actually better because firms that report are more likely to have a clear plan with a reporting system – most likely because of upper management support (Deming, 1986). Reporting productivity causes people to focus on work and do a better job, thus producing better results.

3.4 Factors Inhibiting BIM Implementation

3.4.1 Software and Process Maturity

BIM implementation has the capability to resolve many of the problems faced in construction. As bright as the possibilities are, there are a few issues that keep many from embracing BIM:

- Technology and standards are changing quickly so that potential users are wary of purchasing and committing to specific software.
- Data is not entirely interoperable such that not all software programs work together.

These problems are being resolved rapidly. Bentley and Autodesk products are emerging as the dominant players in the software field. The former is promoting and developing with FIATECH ISO 95126 standards and Autodesk (with many of the other smaller firms) supports IFC. Industry Foundation Class (IFC) is a standard that should help defragment the industry if a majority of players adopt it. It was developed so that there would be a standard way to code data such that different software packages could read and use shared data. ASHRAE has been working on a standard to help coordinate the mechanical information using the IFC format. The BuildingSmart Alliance, an independent body of the National Institute of Building Sciences is working to develop open information environment for collaborative processes. This alliance includes the

ICC, IAI and CSI (ASHRAE, 2009). In August 2008, Bentley and Autodesk announced an agreement to improve interoperability where they will exchange library formats so that each will be able to read data from the other. The DWG and DNG formats will be more compatible (Bentley, Aug 2008).

A common database or single operating system may not be a good solution owing to the many needs of the data and operators that need to manipulate the data. It is technically difficult to create one representation that works for every application (Bernstein, 2004). Another problem is that "one large database with unfettered access is incompatible with current fragmented building industry structure." The strategy adopted by Autodesk is to have "meaningful interoperability" which is "purpose-built conduits from one application to another that achieve a particular task" (Bernstein, 2004). The change to models will be difficult and will not likely be en-masse even though the productivity and accuracy increases are apparent. The change to CAD decades ago required external influences like owner demand and changes to risk/reward ratios. The same will have to happen here (Bernstein, 2004).

"Risk and responsibility will be managed and filtered by connection protocols between these models, whose authors will maintain ownership, and whose data will be distributed via interoperable conduits that support specific transactions and filter unnecessary information form transmission." The architect's model will be the control model for design and decision making but it will not contain all information (Bernstein, 2004). The leading developer of BIM software does not envision a one-stop shopping approach to BIM – largely because of the fragmented nature of the industry and the hierarchical nature. To develop a harmonious system as envisioned by Eastman, culture changes in the industry will be required or a huge system mandated by the government will need to be created. As per typical government programs, that would be very inefficient.

GSA is encouraging the use of open standards for information exchange. Industry Foundation Classes (IFC) data model by International Alliance for interoperability (IAI) is one standard for exchange that is becoming dominant. It is based partly on ISO 10303 product data modeling standard and, with Autodesk's agreement with Bentley to open libraries, the problem is becoming less of an issue.

As mentioned in section 2.5, interoperability inefficiencies add costs to projects. The NIST study found that there was \$6.12/SF of added cost to the design and construction phases of projects. Furthermore, operations and maintenance by owners suffered additional costs of over \$9 billion or \$0.23/SF (Gallaher et al. 2004). The study found that owners bore 2/3 of these costs of interoperability inefficiency. "When applied to GSA's \$11 billion of construction program currently in the pipeline, NIST's findings equate to \$460 million of waste or rework on GSA projects. This waste and rework comes from many sources: inaccurate as-built drawings, miscommunication among stakeholders and inefficient and inconsistent analysis of designs." BIM helps reduce these problems and is thus being required on GSA projects (GSA, 2006).

Smith proposes that one way to improve this loss of value is to have reliable information on the building. This not only improves the construction and operations of structures, but also allows better deconstruction and reuse of raw material. Drawings used by contractors are pictorial in nature, but facility operators use an alphanumeric system for running the building. The data produced by designers and contractors, if not lost, is not entirely useful to the owner (Smith, 2009). As shown in Figure 10, there is great inefficiency in the typical process of design. At each stage of design some of the information is lost or needs to be reproduced for the next stage. A majority of the documents serve no useful value during the facility startup and operations stage and more documents will need to be produced during retrofitting, deconstruction or demolition (Eastman, 2008).

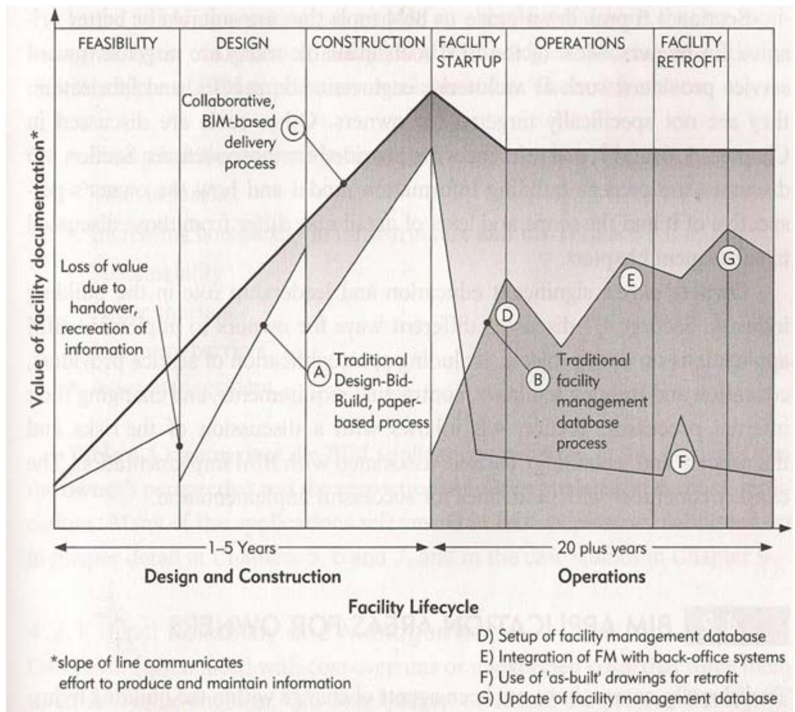

Figure 10 - Illustration of information loss at process phases (Source: Eastman, et. al.).

There are arguments that the BIM data interoperability issue could be solved by using open source for developing software. This requires a modular design for independent and concurrent work where the information can be exchanged easily because it is in smaller pieces. Each module works faster because it is not burdened with data from the other unneeded modules. A strong leader must coordinate the work because, without it, there is lack of direction and purpose to each module's work so that interoperability is still not achieved (Amor, 2002). Interestingly, the open source model is the basic way in which BIM should be run: work is performed in small packages and coordinated by frequent collaborative sessions and only information necessary to each modules task is included. The culture that keeps industry from open-source software makes it difficult to adopt the openly collaborative environment.

Interoperability has been difficult to achieve in the AEC industry because the diverse business models and operational styles have spawned the creation of many different software types to meet the needs. Rather than firms fitting their operations to meet a standard system, software is produced or modified to meet the needs of specific operating styles of individual contractors. This fragments the industry in terms of operations, and the various computerized control systems are not designed to work with each other in a systemized manner. As mentioned before, the two predominant BIM software tools' owners have agreed to exchange libraries to aid in this two-way communication between systems. Bentley's new platform is a method to interpret data from other sources so that it can be used in its system (FIATECH, 2009). Others will need to be developed for more complete interoperability.

The software tools are rapidly changing as new technology and user input increases. As with other new developments, there will be rapid growth in features and quality before the market stabilizes. The basic tools will become better understood, but there will also be more features that will continue to drive changes to the BIM and construction process. As long as there is waste and possibility to increase productivity, there will be changes. Many firms are offering new features to users. Autodesk will release Revit Architecture 2010 which will have the ability to produce precise conceptualization, visualization, and communication (Case Design, Autodesk 2009). This will enable more complex structures and more efficient management of them.

3.4.2 Experience and Training

According to the SmartMarket Survey on BIM usage, adequate training is the greatest challenge to BIM adoption. Only one-third of BIM users feel that they are "very adequately trained," suggesting a demand for more training (Young, 2008). Often software is underutilized because it is poorly matched to the firm's business needs or because its systems do not encourage proper usage of its technological abilities (Smith, 2009). Training is needed, but the system must match the work to be performed (Chelson, 2002). As more design and contracting firms adopt the software and practices, they will evolve to be more useful since the software companies will respond to user's requirements and market forces.

Productivity gains grow quickly when companies start using BIM. In one study, gains were 2% on the first project and 20 % on the second project for one company and went from 28% on the first to 47% productivity increase on the second project. They discovered that formal training is important to gain efficiency and that just learning key strokes does not bring the desired effectiveness of the system (Kaner, 2008). Sanvido indicates that the "most difficult aspect of using BIM is having team members who never used it and trying to get them to use it correctly…the industry is probably 15 to 20 percent of the way to where it needs to be" (Carbasho, 2008).

It is imperative "to have the model created by the people who will be completing the work" (Carbasho, 2008). There are few people who know how to use BIM that also know what they are modeling. If the wrong information is input then you spent money in order to create conflicts in the field. The "garbage in – garbage out" principle is especially applicable to BIM usage. Without proper information input, the only difference from the normal CAD approach is that you tried to instill confidence in a lousy plan (Hardin, 2009).

3.4.3 Legal Issues Concerning Design Risk and Liability

Contracts and project delivery systems are not established such that players understand the liability issues around design. Many designers and contractors are not willing to take the responsibility of the design if they do not understand how the courts will interpret the intent of their contracts. BIM, in conjunction with an ERP, should have the capacity to provide transparency so that all parties must work in a relationship of trust. Contracts have been issued by the AIA, DBIA, AGC and others that deal with BIM ownership and responsibility assignment. They are yet to be proven in court, but lawyers, owners and contractors are beginning to feel more comfortable with them.

Including BIM expectations in the contract is important. The key issues to be delineated are:

- What is the model used for?
- Schedule of deliverables.
- How is info shared with other models?
- How is process managed?
- How reliable is modeled information?

- Will model be used after construction? (Post, 2008).

These are addressed by various contracts that have been issue in the last year as mentioned in section 2.3.2.

The BIM protocol "helps define authorship and the level of refinement required for model elements contributed by team members" (ENR, 2008). Work is defined by CSI classification numbers and by level of development from LOD1 (Level of Development) which is early design stage to LOD5. Using these, responsibility for scope of design work can be better communicated, establishing responsibilities in the collaboration process. The architect may design to LOD1 and then work with the builder to complete LOD2 and then specialty contractors may be brought in to do LOD3 and LOD4 details. LOD descriptions are given in the AIA E202 Document:

LOD 100 – overall building massing indicative of area, height, volume, location, and orientation.

LOD 200 – generalized systems or assemblies with approximate quantities, sizes, shape, location, and orientation.

LOD 300 – specific assemblies that are accurate in terms of quantity, size, shape, location, and orientation.

LOD 400 – same as LOD 300 except that information is complete for fabrication, assembly and detailing information.

LOD 500 – constructed assemblies actual and accurate in terms of size, shape, location, quantity, and orientation.

Non-geometric information may be included in any of these LOD (AIA, 2008). Likewise, the CSI classification (MasterFormat, 2004) is used to define which elements will be detailed.

Traditional DBB arrangements cannot use BIM to its fullest extent because of the lack of incorporating design into constructability and value engineering. CM arrangements require the builder and the architect to collaborate earlier in the design process but do not substantially change risk allocation of design. IPD agreements are more commonly being used now but details are still being worked out on the contracts. AIA released agreements in May 2008 to help reduce or eliminate much of the adversarial nature of the construction industry. Both AIA agreements require BIM to be used to the fullest extent possible (Hurley, 2008). AIA's model E202™–2008, Building Information Modeling Protocol Exhibit is used to gain consensus on project teams concerning who is modeling what and it provides a roadmap of who will be modeling the next level of development (Rubel, 2009). BIM is viewed here as the collaborative tool that will reduce construction conflicts and streamline planning due to visualization of the product virtually prior to actual construction when workers interpret drawings. Six contract documents from various organizations concerning IPD and BIM protocol had been released by October, 2008.

3.4.4 New Way of Thinking

The BIM process is new and will require training, not just to understand the software, but to begin to view projects as required for proper BIM enabled planning and control. The BIM process is most efficient when data and information exchange electronically rather than in paper. Printing is actually the weak link in the BIM design communication process. An example is the BIMSTORM LAX experience where over 100 people collaborated remotely to design 50 million square feet of space in one day. The process produced 2.8 million pages of documents, but none were printed (Onuma, 2008). This ‘paperless’ aspect of BIM and its contribution to more environmentally friendly design make it invaluable in today’s more eco-friendly cultural and governmental environment.

Regulatory agencies are starting to use IT solutions to their processes. The ENR reports that only 10% of jurisdictions use IT in some portion of their regulatory programs. The article says that a 60% reduction in time spent to get projects through approval would translate to tens of billions of dollars annually (Wible, 2009). The need for technology here is increasing because of the more stringent requirements due to LEED, updated codes, and more complex structures.

All persons involved must be involved at regular intervals. This increases the openness and speed of collaboration. This type of open structure where information cannot be held to oneself is difficult for some users. Unfortunately, people in the construction industry who have the knowledge that is needed for BIM to work well have been working in an industry where collaboration to that level is not the norm (Kymmell, 2008).

3.5 The BIM Process

BIM is a process more than it is software. The principle benefit of using BIM is going through the process of collaborative planning. The software is amazing, but its real power lies in its potential as an instrument to get people to work together in real time.

The notion of collaboration on the level possible with BIM was not achievable until recently (Kymmell, 2008). The four steps in developing BIM capabilities are:

1. Lonely BIM where the user begins to tool up for BIM enabled projects.
2. Social BIM in which user collaborates with other firms using BIM.
3. Intimate BIM is when the owner, architect and contractor share risk and reward contractually via BIM enabled IPD.
4. "CheruBIM" is achieved when work finally gets heavenly (Nadine, 2008).

Some firms have reached level 2 in that they coordinate drawings, but few have been able to accomplish level 3 due to contract issues and culture limitations. These are becoming resolved by forward thinking AEC members.

3.5.1 Planning to Plan

Reducing the cycle time of all parts of a building's life is important and is accomplished with a consistent database. Construction documents do not have the information needed for the structure's maintenance. Thus time is spent producing documents for others that have no real value for the owner. The proper model should have the information that shows design intent, design method, building maintenance and usage information, and deconstruction or re-fitting information (Smith, 2009).

The short cycle iterative nature of the process is important to the efficiency of the operation because it reduces the amount of re-work that will need to occur in the design process. "The design process becomes iterative with high frequency cycle periods. The design progresses in small but tightly controlled steps, rather than the large open blocks of time associated with the traditional methods. This work flow is also carefully coordinated with all critical trades before it progresses into a new iteration. Lost time and wasted rework is minimized" (Kymmell, 2008). Working at the same time in short segments means that people do not perform much work that may be changed at a later time. This process only works when there is clear delineation objectives and LOD requirements.

3.5.2 BIM Team Protocol

Collaboration is the key to successful BIM implementation. Co-location of the owner, designer and constructors on site in a "big room" is becoming more common on larger complex projects.

> "Design intent questions are solved in real time, minutes instead of days or weeks…The formality of documentation is reserved for critical path issues requiring an interdisciplinary solution. RFI's have been replaced with a short walk from one desk to another and getting the question answered. The real benefit is that the questions are now two-way…A rigorous quality assurance, process…[is] needed to prevent process waste in the big room. The open environment of the big room needs structure for it to be successful" (Ruber, 2009).

Electronic meetings are good because there is an immediate report of the dialogue and results for all to see so that the system is more transparent. Turner uses SMART Board™ s during its BIM coordination meetings. A majority of the participants are located in one room with two screens and several other members join via conference call. The person hosting the model is at a remote location. As conflicts are reviewed using NavisWorks, resolution action items are written at the point of conflict so that the modelers responsible for resolving the conflict can do so by using the meeting model. Other benefits are that parallel communication promotes broader input into the meeting process and reduces the chance that a few people dominate the meeting. If there is process structure, it helps the group focus on key issues and discourages digression and unproductive behaviors (Shneiderman, 2005).

3.5.3 Beginning - Concurrent Operations

Experienced architects like Kling Stubbins say that you need to “jump in with both feet, halfway measures do not work best.” However, these architects are wary of selling unrealistic expectations to clients. BIM changes workflow and organization so that people need to get used to the new style of project design and management. Any implementation is difficult and needs to be supported by management in a consistent manner. Frequent program changes are not taken seriously by the workers so that they do not implement the new programs.

During the transition period, it is recommended that parallel systems are run. Parallel systems are better as they allow refining reports that give a comparative base to judge the effectiveness of the new system. This may be a quick process if the old system is inefficient (Alfeld, 1988). Mortenson Construction feels they are just getting to the point where they were getting valuable use of BIM and report that “most of our projects use 2-D documents and BIM on a parallel track because we are still learning” (Heller, 2007). Most firms have invested heavily into their present system and it should continue to be used while BIM protocols are implemented. There will be extra money spent running both systems, but the data used from running both will be able to help identify problems with the new so that it can be fixed before major problems occur. Using the old system to monitor progress will give users of the new system more confidence in their experiment and ensure that the project will be supported properly (Alfeld, 1988) and provide a back-up plan needed on complex operations (Laufer, 2000). Once several projects have been completed successfully using BIM, the old software and limited 2-D systems will not be needed to run similar projects.

"Drawings are no longer the primary tool but rather a report from the database. Those who design and those who solve technical problems become one and the same." Another user indicated that "BIM must be adopted incrementally." The lesson learned is that users must use BIM on a real project but set realistic objectives for gradual increasing of design capabilities and performance (Post, 2008).

3.6 BIM Software

3.6.1 Current Vendors & Users

There is no one application tool for all BIM processes. One reason that firms have been slow to adopt ERPs is because they do not perform all functions as efficiently as specific purpose products and are not flexible enough to adapt to project requirements (Chelson, 2008). Similarly, BIM software should be used as best suited for individual clients, users and project type needs. The GSA has adopted this mentality in that it recognizes that the tools should be used that meet specific job requirements rather than the other way around (Tuchman, 2008). So long as there is interoperability through ISO or IFC, the data can still be useful as a whole.

A good programming model will separate the "Process" from the "persistence." Pervasive computing service would "concentrate on defining behavioral interfaces that achieve business goals, independent of the persistence" (Amor, 2002). The interface should be set up to achieve business goals, not carried out the way people are used to doing things. The interface is adapted to make it more user friendly by making it look like things people are used to seeing, but when a new paradigm of operating is required, the interface may need to change.

3.6.1.1 Authoring Tools

3.6.1.1.1 Surface Modeler

Surface modelers are not true BIM in that they are not object modelers. "Components only look like objects, but actually are just collections of surfaces." They can act as a BIM tool in that information related to size, location, and look can be conveyed in a 3-D representation. These are used primarily as communication tools for specific issues (Kymmell, 2008; Eastman, 2008). Google SketchUp is the predominant player because it is inexpensive (free versions are available) and easy to use (www.sketchup.google.com). Models produced in SketchUp can be imported to NavisWorks® for clash detection but because it does not contain relational object-based information, it is not commonly used for serious modeling efforts.

3.6.1.1.2 Solid Modeler

Bentley's MicroStation TriForma and Autodesk's Revit® are the principle solid modelers. The former is robust and used on many larger projects but is considered 'bulky' to less trained or sophisticated users. Bentley has addressed data management by adopting the concept of a federated database because it is more adaptable and does not become difficult to manage on large projects like a centralized database would. Bentley's focus on large projects requires them to adopt a more flexible data structure. Their software is able to read almost any format and manipulate data directly in the original format (Kymmell, 2008).

Revit by Autodesk® is the most widely used solid modeler on the market (http://usa.autodesk.com/adsk/servlet/pc/index?siteID=123112&id=8479263). Revit has approximately 80% of the market and is used on a wide variety of buildings by architects and contractors (Autodesk, 2008; Chelson, 2010). It has gained its market position largely because of its marketing channels developed through the AutoCAD brand. Because it has gained a critical mass, many firms are using Revit because it is easily integrated with what other firms are using. An extensive library of objects is also available to users. If all members of the project team use the same authoring tool, it is easier to exchange data, but the process of clash detection for constructability purposes is not enhanced significantly for most contractors.

Vico Constructor™ is a modeler by Vico Software, Inc., a newer company whose products are noteworthy in their ability to work effectively with scheduling and estimating modeling tools. The Vico Office Suite coordinates the processes (http://www.vicosoftware.com/products/Vico_constructor_2008/tabid/84569/Default.aspx). It is, however, not used by many contractors. Other authoring tools such as Nemetscheck's Vectorworks Architect, (http://www.nemetschek.net/architect/index.php), Digital Project™ by Gehry Technologies (http://www.gehrytechnologies.com/), Graphisoft® ArchiCAD (http://www.graphisoftus.com/products_archicad.php) Most of the BIM software tools are solid modelers in that they are parametrically related and link characteristic information to the object.

3.6.1.2 Analysis Tools

NavisWorks is a viewer of models and is used to coordinate models that were produced using different authoring tools. It was purchased by Autodesk but can be used with nearly all types of authoring tools. It reads most types of 3-D file formats and is thus an interoperability tool whereby multiple models can be combined and solid objects can be viewed in order to discover conflicts in space (Kymmell, 2008; Hardin, 2009). This is the most commonly cited use for BIM in increasing productivity because it is here that problems are resolved prior to field work (Bennett, 2008).

This tool is used by nearly all contractors to resolve constructability issues. Each trade produces a model of its work and converts it to NavisWorks format. Each file is combined to make one model that represents the architectural and trade models in the same geometric space. Any surface that coincides with a surface from indicated in this combined model. The conflict causes and solutions are discussed by participants who can visualize the conflict due to the communication clarity of 3-D figures. Each discipline makes changes to their components as needed using their native authoring tool. The process is repeated, usually weekly, until constructability conflicts between building components are eliminated.

3.6.2 True BIM Application

Mortenson Construction teaches that in order to achieve the "intelligent simulation of architecture" six characteristics must be met by the model:

- "Digital,
- Spatial (3-D),
- Measurable (quantifiable, dimension-able, and query-able),

- Comprehensive (encapsulating and communicating design intent, building performance, constructability, and include sequential and financial aspects of means and methods),
- Accessible (to the entire AEC/ owner team through an interoperable and intuitive interface), and
- Durable (usable through all phases of a facility's life)" (Eastman, 2008).

There is no BIM software tool that accomplishes all of these tasks and there are very few firms that are achieving this level of BIM performance. Most teams use several different software programs that are brought together for analysis. The interaction of these authoring tools is discussed earlier in the interoperability section.

Chapter 4: RESEARCH METHODOLOGY

4.1 Current BIM Usage – Case Studies Review

The object of this research was to determine the amount of productivity change experienced when BIM is implemented. The first step in this research was to determine the levels of BIM usage by firms in the AEC industry. A review of case studies resulted in the review of current practices included in Chapters 2 and 3. The author found no independent or authoritative studies clearly showing the payback of BIM, nor any showing relationships between firms that have started BIM processes without having a robust planning system in place verses those that do not. The next step was discovery of what projects were being done with BIM and then determine their productivity based on the KPI. This was accomplished by both case study and survey. The former is preferred because the rapidly evolving nature of BIM usage makes it difficult to determine 'normal' practices and results.

Case studies have been published on noteworthy projects. Some of these are well-known only because the contractor or designer wanted to advertise to potential clients the advantages of BIM and hoped to acquire more business opportunities. The vast majority of the case studies show successful aspects of the project, and some include a "lessons learned" section. Most responsible studies indicate that there is a steep learning curve but, that after only a few projects, the users tend to be convinced that there are savings in time and effort. No accounts of BIM having a negative effect on a project were found, but this seems unrealistic that all BIM projects are successful. This study will include a broader look at projects that implemented BIM even if, or especially if, they were not deemed successful by all participants.

4.2 Ascertain AEC Firms' Current Usage of BIM – Pilot Survey

After the initial research, a short survey of practices by contractors and architects was administered in order to develop criteria for the research questions including:

- What percentage of projects are utilizing BIM and to what extent?
- What software tools are being used?
- Who are the principle drivers of use?
- What types of projects utilize BIM?
- What is the learning curve for BIM?
- What are the key indicators of productivity increase?

This portion of the study was conducted through informal interviews with practitioners rather than BIM champions so as to get closer to the reality of actual usage in firms. BIM professionals and project leaders tended to focus on the technological advantage of their system while the field personnel reported on the effectiveness of using BIM in the field and how it affected their operations.

4.2.1Targeted respondents

Firms interviewed were chosen from participants of Associated Schools of Construction (ASC) conferences, recruiters at CSU, Chico, active DBIA members, and FIATECH conference participants. This population was chosen because they seemed more likely to be involved with BIM because of their association with groups that foster development of new technologies and processes. ASC and Chico State recruiters are interested in recruiting from colleges and tend to seek those who understand the programs taught in universities. DBIA focuses on the relationship and collaborative process of construction and has espoused the use of BIM and IPD as a tool for achieving this goal. FIATECH is organized to develop new technology usage that improves the effectiveness and efficiency of the capital asset management process. These firms are assumed to be the avant-garde of BIM usage and a good source for BIM evaluation.

4.2.2 General Questionnaire to determine BIM usage

Managers and representatives of companies in the target audience were asked questions in informal interviews rather than filling out a questionnaire because more reliable results could be obtained. The newness of the process means that precise numbers were not known by the users so that perceptions of usage benefits needed to be evaluated. The following questions were asked in face-to-face interviews so that follow-up questions could be asked based up the respondent's attitude or comments:

1. Have you been involved in any projects using BIM and how many?
2. What BIM software does your firm use?
3. Who was the main motivator to use BIM (owner, architect, or contractor)?
4. Who is responsible for BIM – a corporate or project level BIM specialist?
5. What do you use BIM for (coordination, estimating, scheduling, design, procurement, or other)?
6. In your firm, who drives BIM usage, management or field personnel?
7. Did BIM make your job easier?
8. Did BIM save your firm money or just make you competitive?
9. Did BIM improve your schedule and trade coordination?

4.2.3 Results of BIM usage survey

The results of the informal surveys conducted by the author clarified what types of questions needed to be asked and how the data would best be collected. Some of the interesting aspects found during the interviews are specified below:

1. Contractors feel that the owners and architects are not adopting BIM fast enough and that they are resisting investing into the process during pre-construction even though it promises to benefit the project.
2. Knowing what the ROI of BIM usage is would be very helpful, but contractors do not know what the savings actually are. Those who do know refuse to report.
3. Field personnel tend to say that BIM is good, but that it is used primarily for communication.
4. Most contractors view BIM as the clash detection process done to plan and coordinate work. The idea of reducing errors on plans is the principle purpose for BIM implementation.
5. Contractors with larger amounts of labor to perform on a project tend to be more interested in modeling their work even if the designers or general contractor does not provide a model.
6. Despite the reporting of interoperability problems between BIM, software contractors are not deeply concerned. Their work is primarily done to reduce clashes. In nearly all cases this task is done with NavisWorks which recognizes almost every modeling tool.

4.2.3.1 Respondent profiles

Because the focus of this research is field productivity, interviewees were principally contractors who had interest in field operations. Representatives from twenty-six firms, most in the range of $250MM to $1BB in revenue, were asked the questions given in 4.2.2 and allowed to talk freely about their thoughts concerning BIM. Of the 26 firms, only three admitted to not having used BIM and only three claimed to use BIM on all their projects. The average participant reported to have used BIM on a few projects, but most of this usage appears to be schematics or trade specific planning.

As the survey questioned both upper management and field personnel concerning BIM practices, a common contradiction in answers arose. The BIM usage touted loudly by many companies' senior management had seemingly not filtrated from upper management to field personnel. The field users of BIM were not aware of what the BIM process is and were not aware that they were using this modeling process. This condition indicates that the firms starting to use BIM are early adopters by nature because the leadership is directing and orchestrating the BIM initiative. One exception is Mortensen Construction which encourages BIM usage in a systematic way but at the same time allows experimentation on BIM management procedures at the project level. New adopters are encouraged to try the new processes and do not need to fear reprisal for errors during the learning process. A top down approach seems to be met with resistance from the field and the user driven approach seems to be difficult to implement because funding is required to BIM and some framework for BIM implementation is needed. Because of the results of this survey, it was determined that case studies based both on management practices and field activity would be done on a project basis. This would make it possible to assess field productivity increases.

4.2.4.2 Comparison to published surveys

The results of the general questionnaire survey were different from the published surveys in that some participants expressed less enthusiasm toward the benefits than those reported in the published surveys. The overall results were similar in that there is a perception of increased productivity but several differences were noted:

1. Obtaining reliable data concerning productivity is difficult, if not impossible, because accurate reporting is not done by most contractors and because designers are not giving accurate models to contractors. Many large trade contractors were not able to identify their productivity rates or rework rates on different types of projects even if BIM were not being considered. There is a systemic lack of understanding of cause and effects for field productivity rates.
2. Some field personnel (generally union) reported that BIM is merely a communication tool that 'techies' are using to coordinate things that can be done by an experienced site manager or foreman.
3. Coordination is being performed by the lower tier contractors independent of architect's models and these contractors appear to be driving the adoption of the technology at the construction level.
4. General contractors seem to be driving the process planning but are assigning the work to specialty contractors – usually mechanical contractors who coordinate the MEP work.
5. The owners need to be convinced to support BIM usage. Many contractors will do BIM even if the owner does not require it, but most will not invest substantial

resources if the owner is not willing to pay for the service. The McGraw-Hill report (Young, 2008) indicates that contractors are the slow adopters but this research indicates that the owners lag behind the contractors in desire to use BIM.

6. The designers are not providing reliable models for use on projects. Contractors report that the architects may provide reference models but that they must produce their own models from 2-D contract documents provided by the architects. Engineers appear to be farther behind in adopting models as a method for transmitting contract documents. Designers tend to use models as a method to communicate concepts rather than intent such that re-entry is being performed by contractors. The issue is related to liability and reliability of contract documents.
7. The creation of documents from 2-D drawings by various subcontractors for coordination seems to becoming the accepted way due to a few distinct advantages it offers: One is that the process of creating a model from plans acts as a 'second set of eyes' on the plans so that conflicts and errors are discovered more readily. Another is that each contractor becomes responsible for creating their own work from scratch so that they take responsibility for their own design and are thus able to better control the means and methods of the construction process so that they can operate according to their preference, enabling increased productivity. Lastly, the creation of models by contractors causes them to look more closely at the details germane to their trade, fits into the bigger picture. These three factors enable contractors to produce plans that will enable higher rates of productivity by reducing conflicts and increasing the likelihood of having a layout or system that reflects their preferred operating style.

These differences can be attributed generally to the fact that the research is focused on contractors and field productivity while most research has been done from the perspective of the architects and owners. This work studies different stakeholder's perspectives on BIM, but focuses on the contractor's use and effects of BIM on their operations. BIM is seen mostly as a design tool now and the contractors' use of it now is to design the repairs for the errors in the plans produced by the architects. However, some contractors have been able to expand their vision of this tool to become a much greater tool in their individual companies.

4.3 Ascertain AEC Firms' Current Usage of BIM – General Survey

Two approaches were attempted to ascertain the amount of change in field productivity based on BIM usage. A survey designed based on the findings of the pilot surveys was performed. Secondly, case studies were performed. The purpose of the survey was to determine actual usage of BIM in a focused population. Rather than study success stories for advertising purposes, a more general sampling of the entire industry was to be evaluated at the project level. The population was all projects completed in a geographical area and the subset was to be the BIM enabled projects.

4.3.1 Distribution – Targeted Respondents

All BIM enabled projects found in the target area that were completed from 2005 to June 2009 were to be surveyed for this study. By surveying each BIM project, no margin of error was be expected. Any change in the number of BIM projects being completed over the three and a half year period would become evident through this study.

4.3.1.1 Location of Projects

The west coast of America and especially the Bay Area have a relatively large number of BIM projects compared to other regions in the USA (Young, 2009). A sample of projects in this geographical area was surveyed to find which projects utilized BIM. A few projects were sampled from Utah and Oregon to determine if there are any appreciable differences in those areas.

4.3.1.2 Size of Project

The vast majority of BIM projects reported are large projects of over $50 million. Some firms however are using BIM on small projects as experiments to learn the process. It was not expected that BIM is used on many projects smaller than $10 million, so these were not included in the project search. Smaller projects that use BIM are less likely to be done as a system, but more as a curiosity. Section 3.5 discusses the BIM process as an involved one requiring management investment in time. Smaller projects receive much less formal planning time than larger projects. BIM requires more up-front expenditures than traditional planning systems. It is assumed that those projects in which detailed planning is generally not performed will not receive extra BIM process expenditures and will thus not be considered for this project.

4.3.1.3 Method of Finding Target Projects

A complete inventory of projects completed in the sample area was attempted to ensure that all cases of BIM implementation –successful or not – are compared against traditional projects of a similar nature. The following information was requested from selected jurisdictions which grant permits in the study area:

1. Project name
2. Project Address
3. Owner name, address, email & phone number
4. Architect name, address, email & phone number
5. Contractor(s) name, address, email & phone number
6. Certificate of Occupancy date
7. Permit issuance date
8. Project valuation
9. Image of title page of permit plans

Each jurisdiction was requested to supply any of these known elements on all projects of over $10 MM in valuation that were granted occupancy between the dates of Jan. 1, 2006 and June 30, 2009, inclusive. It was expected that the address, name of at least one of the key members of the project team, and the answer to questions 7, 8 and 9 could be given for all projects. Each jurisdiction question in the survey creation process claimed to have a process whereby information on past building projects could be produced upon request. The data received from the participating jurisdictions would be compiled so that each project general contractor could be interviewed to determine if BIM was used by contractors or architects associated with the project.

4.3.1.4 Results of Search for Target Projects

Although city or county jurisdictions indicated an ability to provide information needed for this survey approach, few produced data when requested. Of the 17 contacted, only three sent data on building permits. Only one of those gave final inspection dates and none had information on when the certificate of occupancy was granted. In order to obtain more data a review of the building permit information was conducted at a building permit center and, although the staff members were willing to help, it was determined that the data needed could not be mined in a reasonable manner. Another jurisdiction was able to produce data for a price, but the data was too general as they did not have the means to sort and report only pertinent data. Thus, data was gathered from two jurisdictions, but at the cost of many hours of research. After compiling the information from five jurisdictions from which data was obtained, only four projects in the target price range were found and only one was non-industrial. This one project from five jurisdictions in a 3-1/2 year period in the target range did not use BIM. Given the limited budget for this research, and the scant results, the goal of obtaining sufficient conclusive information from BIM projects in a given geographical area was not realized.

4.3.2 Questionnaire to Identify BIM Users

A survey consisting of questions that would ascertain both the management processes used and the results of the project as a whole was distributed to persons who had expressed willingness to participate. The questionnaire is shown in Appendix B. The survey was not completed to the level desired because of the problems indicated in section 4.3.1.4 and because the preliminary results were not consistent. Response rate was low because of the following reasons given by those requested to participate:

- Not enough time to look up the data on projects.
- Cannot reveal information due to confidentially of competitive information.
- Do not know answers because the data is not measured.
- Do not understand the BIM process well enough to identify what was done.

The survey was used as the basis for interviews and case studies conducted for this research. Knowing the reasons that people did not respond influenced the way in which the interviews were conducted.

4.4 Interviews to Find Productivity Data from BIM Users

4.4.1 Distribution – Criteria for Participants

A sampling of contractors was chosen for interview from the same target population used in the pilot survey as described in 4.2.1. The survey shown above in 4.3.2 was the agenda for the interviews. Contractors doing BIM and non-BIM projects were unable to communicate known productivity rates or calculate productivity rates as a stand-alone number for comparison purposes. Of the sixty-three entities, mostly contractors, who were interviewed, 47 reported using BIM to some degree. More contractors were chosen because they are closer to the field and therefore should have more information on field productivity.

4.4.2 Format of data collection

4.4.2.1 Proprietary Information

Data concerning productivity rates and profitability are closely guarded by contractors. This proprietary information is generally not shared in the competitive and often adversarial contracting marketplace. Contractors who are in collaborative ventures with open books will not be concerned about this. However, most field productivity data comes from second or third tier specialty contractors who bid jobs as a lump sum or unit price basis. Their productivity rates and profits on the project are their 'secret' because the contractors view this information as their competitive edge. Reaching this data will require confidentiality agreements in many cases and the data will not be able to be associated with specific projects due to this agreement. Data in such cases will need to be combined into categories, but not released at the project level so as not to violate this confidentiality.

Some contractors fear that the money that they are able to make by bidding for average productivity and then managing the process to beat estimates will be lost if the information is widely known. BIM provides the ability to reduce many of the unknowns and possibilities for profit from this gamble. It also can virtually eliminate the changes that produce the change orders that many firms rely on to make a profit (ENR, 2009). Contractors that cannot share productivity increases may not be able to continue to compete in negotiated work with owners.

4.4.2.2 Survey/Interview Process

This portion of the data collection was done as interviews, using the survey as an agenda, with those participants that were directly involved in the project. It had been discovered through preliminary investigation that some firms (generally specialty trade contractors) know that their productivity is affected, but not to what degree. Specific data sought was:

- Number of hours/dollars spent on re-working.
- Number of hours/dollars lost due to waiting or inefficient work based on sub-optimal conditions and remobilization.
- Field productivity rate of crews.
- Frequency of meeting scheduled tasks (and reasons).

- RFI generated on the project.
- Change orders on the project.

The interview process focused on projects and how firms performed on specific projects. The results were recorded on spreadsheets but the data was inconsistent in that each firm was not able to supply accurate information for each category sought.

4.5 Case Studies of BIM users

Case studies were performed to evaluate the techniques that are employed by 'bimming' contractors. These primarily focus on contractors who are closer to productivity in the field and aware of actual consequences of BIM processes. Each study is an evaluation of the perspective of a member of a firm rather than an evaluation of a specific project. One or two projects were referenced as a basis for the study, but the focus was on the process and how the interviewee and their firm is evolving their BIM practices. One or more of the following was done on each case study concerning the varied stake holders:

1. Evaluate a BIM project and determine current methods used to manage the BIM process.
2. Research other projects performed by the contractor to determine how the practice of BIM has evolved.
3. Discuss the project with specialty contractors on the project and determine their productivity observations. Explore other projects performed by the specialty contractors with other general contractors to see how the practices and productivity compare.

4. Discuss the principle project with the owner or architect to determine impressions of project success and cost/schedule implications.

These case studies produce a more accurate appraisal of project team actions and associated productivity effects because the actions are seen from multiple perspectives. This cross-checking of information helps gain a better perspective from the project level rather than from the contractor level. The case studies provide the basis of evaluation of productivity rates given the various levels of BIM usage, experience, team usage, and project complexity. They focus on commercial and hospital because that segment is where most BIM usage has occurred to date.

In order to quantify the qualitative results of the case studies, Likert items are used to evaluate specific results. These are done on a one to five scale with a one indicating no relationship and five indicating a very strong relationship. These items will provide a numerical indication of how BIM affects different KPI used to evaluate productivity gains. Most participants could or would not indicate exact numbers when evaluating indicators, but their responses could be interpreted as numbers. This is explained in the results section of the case studies (section 5.10).

4.6 ROI monitoring system data collection

During the survey process I observed some of the methods that firms use to monitor their costs of using BIM and the savings that they attribute to the same. Research has shown that few firms attempt to measure their true ROI of such systems. Although ROI evaluation techniques are not the focus of this study, it will show if there is a relationship between the monitoring of ROI and amount of the ROI achieved (Young, 2008). As suggested by research, it was expected that firms that have a formal process for evaluating savings will report higher savings.

4.7 Conclusion

The four step survey process was intended to determine BIM usage and productivity effects on the projects level. Published case studies are evaluated to determine effective BIM implementation. Pilot surveys are used to determine level of use of BIM at the project level in the field. A survey/interview is done on those people most likely to use BIM to determine their BIM usage and productivity factors. The final case studies are a focused evaluation of field productivity on selected BIM projects.

Chapter 5: CASE STUDIES

Case studies have been performed for main stakeholders to characterize a typical sample of the BIM managerial practices and the stakeholder's perceived productivity increases. These case studies are meant to represent both the commonalities that run through a majority of the businesses implementing BIM, and also include diverse styles that bring success to the individual company studied. Therefore, the case studies have the dual role of illuminating not just the overarching commonalities of the factors affecting the efficient implementation of BIM, but also of the diverging characteristics that bring success to companies with differing objectives and abilities. The following eight case studies include the perspectives of the owner, the general contractor, and the trade contractor. Each case study includes a brief description of the company, the principle contact and:

1. each company's BIM management practices including shifts in management practices due to their learning experiences,
2. the observed consequences from using BIM,
3. challenges encountered in BIM usage or perceived limitations of BIM, and
4. a lessons-learned approach conclusion.

5.1 Case 1 – Target (Owner)

The Company:

Stephen Mekredes is the Project Development Manager for retail giant, Target. His experience and comments represent the owner's perspective in this case study. He is responsible to deliver the most cost effective method of constructing facilities. Because

Target has a large portfolio of properties, his role includes consideration that the design and construction process properly supports the facilities management side of the operational needs including sales, warehousing and distribution, and office space.

Information and maintenance requirements and records for Target's 2000 existing properties are housed in legacy systems. Target has modeled, to varying degrees, about ten projects ranging from a \$2 million remodel to a \$200 million distribution center and warehouse. Target employs internal BIM-capable architects and engineers, but also outsources some design to third party architects and engineers as needed. Conceptual design is performed with the aid of modeling tools on new projects. Some projects have been fully modeled in 3-D. Time scheduling (4-D) has been performed on some projects and manufacturing data for maintenance (6-D) has been included in some of their models. As an organization, they are keeping records of various practices and results that they are creating on their continuing experimentation with BIM.

5.1.1 BIM Management Practices

A typical construction project for Target is a negotiated design-assist CM contract made with a general contractor with whom they have done business with before. The GC is given typical 2-D drawings as well as a 3-D model as contract documents. A model manager is assigned to the general contractor's office to streamline the construction coordination and planning design process. Principle subcontractors of the general contractor are chosen competitively, but are brought in by the fifty percent design stage or earlier. In this way the builder's input is included in at least half of the design process, as would be expected in design-assist in order to obtain constructability input. As a team, the project members consider what needs to be modeled based on past modeling experience, prior conflicts experienced on similar projects, and doubt about component relationships. Thus, only items that need to be modeled are given resources.

5.1.2 Observed Consequences of Using BIM

Perhaps the most significant observation that Target has made concerning their implementation of BIM is an *expected* consequence that did not materialize. Target has experienced *no increase in design costs* when architects use BIM, as opposed to typical 2-D drawings in the design process. This contradicts the common belief by many owners that BIM increases up-front costs. This is often cited as a principle reason for not implementing BIM on their project at an early stage.

Some key indicators of productivity changes on BIM projects compared to non-BIM project are:

- A typical RFI reduction of at least 90% on BIM projects.
- The schedule is more accurate and of shorter duration. Target has only recently begun to measure these results and so does not know exactly how much of a percentage change is experienced on the project.
- There is less rework and far fewer change orders.
- The quality of the work is better in that fewer modifications and compromise in the field is done.

PointCloud3D has been used on some retrofit to model existing conditions, but Target's experience was the transfer of data was cumbersome and the process cost was too high. PointCloud3D provided features that were not needed on the project so that Target paid for unused items. Target may be able to benefit from these services on more complex retrofitting projects, but does not foresee modeling existing projects to that level at this time.

Target endeavors to avoid modeling unnecessary items by constant analysis of their results and refinement of process. If they find no clashes in the first run of the model and experience no reports of conflicts in the field, then the modeling for that item was not needed and they will not model it on future projects. With over 10 projects completed, they can rely on their past experiences so that they do not model details that are not warranted for the complexity level of the process.

Active measurement and evaluation of the processes is ongoing. Mr. Mekredes and Target feel confident that BIM has been effective at increasing value on each of the projects ranging from $2 to $200 million. Productivity apparently increases for the field but the company is not making the costs public. Target can say that based on the cost savings and the benefits to portfolio management they have seen in their experiences they will continue to utilize BIM as an integral part of their business practice.

5.1.3 Challenges of Using BIM

BIM is a road map to get to the 6-D, information-rich source envisioned for Target facilities management. Construction coordination and clash detection is a benefit and saves money, but the bigger and more comprehensive goal is to have regular, consistent data concerning maintenance, remodels, and portfolio management available to them. Consider a change in the refrigeration section in a given store. Many factors such as the following affect what can be done and the requirements to do it: weight loads on trusses, footing size and locations, location of existing piping and drains, and electrical supply. This information, centrally located in a visual format, would dramatically benefit the evaluation and design of common alterations in the stores. The road to this type of 6-D information is understandable, and indeed, Target is working to achieve this for the stores that BIM was used on in the recent past. The more difficult problem to be solved is how to cost-effectively populate this desired information from legacy systems into an intelligent and consistent 6-D model format.

5.1.4 Conclusions

Target is taking the effort to pioneer BIM usage in property development and portfolio management. Their knowledge should give it a competitive advantage in its ability to maintain and modify its property but also decrease the cost of the construction operations and lower their risk exposure and subsequent contingencies over time. From the smallest $2 million remodel to the largest $200 million dollar project, clear advantages in terms of reduced RFI, change orders and rework were gained by the use of BIM during the construction and design process. Target is continuing to collect data on key cost and schedule indicators in relation to their BIM and construction management practices to determine the most effective manner of BIM expenditure. The ROI of BIM implementation is clearly positive since they are increasing BIM usage after completing 10 projects, but details on the level of productivity increase and ROI are prudently guarded because of the competitive advantage the information offers.

5.2 Case 2 - Layton Construction Company (GC)

The Company:

Damon Socha is the BIM manager for Layton Construction Company (Layton) which is one of the top 100 companies in revenue in the USA and in the top 20 in the hospital sector. Layton has been doing CM, CM at risk with Design-Assist, and DB projects but have a background in DBB. The majority of their projects are CM, but they also frequently perform DB. Layton has five different divisions housed under the holding company, but this study involves the primary construction firm which performs most types of commercial construction nationwide. The majority of its work is done in the intermountain west and California. One of their tenets is to compromise rather than go to court. They pride themselves in the fact that in nearly 60 years in business they have finished every project they have contracted to do. To manage their BIM dynamics, Layton employs a corporate BIM manager, two BIM project managers in the office, and two BIM operators in the field.

5.2.1BIM Management Practices

Layton has a general protocol as to which projects they consider are the most practical and productive to model. Currently, Layton fully models every healthcare project in BIM. Commercial projects generally use some element of BIM to a significant extent, utilizing BIM in coordination of work in about 75% of these projects. Tenant Improvements and smaller projects do not usually have any BIM usage.

Layton prefers to hire subcontractors who know how to BIM. If they are constrained to hire lower price contractors that do not have BIM experience they will train or assist the contractors, not teach how to perform the technical tasks of modeling (operating the program), but rather how to manage the modeling process concerning:

- What to model
- When to model
- How to coordinate modeling with other trades

- How to perform clash detections to ensure constructability.

Layton's preferred approach to managing the BIM process is to supply the trades with 2-D files and let them create models for the elements that they will construct. Although in the past they have furnished 3-D models to subcontractors, Layton found that most of their partners ask for 2-D drawings because they can create the model they need without interferences from other features that play little significance in their work. Layton works with Revit and prefers that other team members also use this program, but they allow trade contractors or other project members to use any program they feel is most practical for them. All project members must upload a NavisWorks model and a CAD file to a central ftp site controlled by Layton and assessable to all team members. In some cases where the subcontractor cannot model effectively, but modeling is needed for proper coordination, Layton will model the elements required for the good of the project.

The BIM process is initiated with a BIM kick-off meeting in which all the members meet together to discuss the parameters and rules of modeling the project. While the "big room" concept is mostly rejected, Layton will co-locate a few members in a common office on very large projects. Most of their workers and trade contractors prefer to do GoToMeetings® so that the operators can sit at their own desks with their own set-up and talk through the problems. This type of meeting also saves time for the operators because they can perform their work while in the meeting but not discussing items actively. Another concern with the "big room" is the legality issues which could arise regarding the absence of recorded, formal RFIs during designing and coordination. The trades generally work together to establish who will get to work in what zones, and disagreements tend to be self-policed to the point that the sub-contractors themselves make determination of conflict resolution. If there is a conflict, Layton may define certain areas as “no-fly zones,” and that area becomes limited to the use of one trade contractor. Layton becomes involved in disagreement matters only when there is a design issue involving the architect. Typically, on CM projects the subcontractors are brought in to start modeling their work at or before the 50% drawing stage, but earlier in DB.

Because each party tends to act in their own interest, there could be some inefficiency in the final design stage. However, each trade also acts to build their own segment most efficiently so as to reduce costs. Unless one party is overbearing or difficult, the overall project success will be more likely because they know they will be working with each other and start to trust each other after they have talked and worked together (Laugher, chap 8). Layton does not do incentives based on project results.

Layton’s typical project utilizing BIM is a CM project in which the subcontractors bid competitively and their contracts are tied to documents designed by architects and engineers. The level of detail is not defined in the contract, but rather each trade is responsible to model each of its own work and participate in the collision detection. The subcontractor is responsible to know what they should model. They are than held accountable for their level of modeling. If a specialty contractor elects not to model a specific detail and it ends up conflicting with something in the field that was modeled and coordinated with the team, then it is that subcontract’s responsibility to repair it in the field. This causes each subcontractor to evaluate what conflicts could occur and what would be difficult for them to adjust in the field. Mr. Socha states, “The person who causes the problem in the field because they did not follow the model or failed to model an element is responsible to pay for the fix.”

Layton also uses the compiled model with Syncro to perform schedule validation to aid in constructability and schedule refinement.

5.2.2 Observed Consequences of Using BIM

The overall result of Layton's BIM management style has proven to be such an increase in effectiveness that they have moved toward doing BIM on most of their projects. *They do not know the exact increase in productivity numbers, but believe that it is well worth it to spend the ½ to 1 percent of the project cost on the BIM process because it solves many problems in the field.*

Several of the evidences of the increase in field productivity follow.

- Reductions in RFIs approximating 90% when compared to typical non-BIM projects are typical. This is a significant savings. The standard cost of an RFI including administrative time to identify, input, process and evaluate, comes to hundreds of dollars depending on the type of conflict and the amount of time to provide an answer. The average cost per RFI could be about $400 and this does not include the additional cost in the eventuality that the response could require a change to the contract. More importantly, the process delays the planned construction workflow. On a recent fully modeled 85,000 SF hospital project, Layton experienced only 15 RFI from the field. A typical project of this type without the benefit of BIM would be expected to have hundreds of RFI.
- The process of completing shop drawings principally from the model is 60% faster than when using 2-D clash detection. There is a huge difference in planning/coordinating up front rather than in the field. The down time and

rework due to the conflicts that occur without the planning & clash detection are a very significant factor in maintaining schedule.

- Schedule performance is enhanced significantly on BIM projects. Layton simultaneously constructed two similar hospital projects in California; each approximately 250,000 SF. One hospital project was fully modeled while the other had no modeling. The BIM project was 2 months ahead of schedule compared to the non-BIM project which was 2 months behind schedule.
- Field personnel are reduced on BIM projects. The BIM project utilized 6 BIM operators for several months to model the project. Only one MEP coordinator working in the field was needed to manage the installation process. The other project had no investment in modeling, but 6 to 7 full-time MEP coordinators/superintendents/engineers were employed in the field during the MEP installation process. The field personnel were more costly than the operators so that the BIM investment paid for itself in the labor savings experienced by paying for planning in favor of paying to management. Typically, labor hours spent planning are less expensive than field labor due to the higher wages and overhead costs required for the field work. However, the greater number of field managers required indicates the greater need for those operators to assure compliance to an imperfect model and to correct expected inefficiencies in the field.
- Field rework is nearly eliminated and productivity is up so that the schedule is positively affected. Mr. Socha attributes the four month difference in schedule performance in these projects to the time invested in plan detailing enabled by

> BIM. This planning and clash detection reduces field confusion and re-work, thus increasing the amount of field resources needed to complete the project. In the non-modeled projects, field personnel tend to spend a large amount of time trying to figure out how parts will go together and be installed in conjunction with other trade's work on the site. Often workers are waiting for the proper part to arrive at the site because it could not be ordered until site evaluation and measurements could be taken. With proper BIM aided planning, these production holes in the schedule are minimized or virtually eliminated so that the schedules are accelerated. Foreseen problems can be mitigated to reduce schedule delays and increase schedule compliance. Whereas field management is generally considered good because it organizes work and solves conflicts, it is not directly beneficial to the finished project as required by Lean Construction principles. "The BIM process favors planning instead of field management and enables the reduction in total time needed to manage the process. Time is needed, it just happens up front as organizing actions rather than later as a reaction."

Mr. Socha indicated that the learning curve for a contractor who knows the technical operations of modeling software is 2-3 projects in terms of managing the process. If a contractor does not know how to run the software it will take 5-6 projects to master the process. If not managing BIM properly, 100 projects will not be enough to make a person an expert. Because the modeling depicts field installation procedures and requirements, the speed at which the person learns to model properly is very dependent on their practical experience in the field. A person who is learning to manage the BIM process must do projects with experienced people in order to avoid developing bad BIM habits.

There are two stages in the construction design - coordination of the trades and fabrication. During the coordination of work, trades should gain confidence and trust in the system and each other. BIM facilitates collaboration and trust. A company will not fabricate larger pieces to take to the job site or load the project per a schedule if they don't have confidence that they will be able to install the pieces in the field.

Layton self-performs concrete work. They generally don't model the rebar or concrete formwork for fabrication but they use their models of the concrete and import that into a total station for layout and benchmarks and this saves them time. The exact amount of the savings is not known, but thought to be several times faster. One of the things Mr. Socha noticed is that the generals need to control the design process so that any one of the subcontractors is not dominant during coordination. When the mechanical sub controls the coordination and clash detection they have more say in the design and dominate the process.

Layton has lowered their bid prices because of BIM, but their quality has gone up. The more they do with BIM, the cheaper, quicker, and better it becomes. (Typically the three elements of the project, quality, cost, and time are tradeoffs. Mr. Socha's impression is that, in the case of BIM, there is no trade off - when you BIM, cost goes down, time goes down, and quality goes up.) Once industry gets over the learning curve, then price will go down. On an 85,000 SF hospital project, ten to 15 thousand real collision or conflicts were discovered on each floor of this hospital. These were actual locations where different trades would be colliding into each other, and because they found these collisions that would have happened in the field based on 2-D drawings that they were given, *they saved $750,000 – $1 million in change orders*. Additionally, they gained productivity because people were not confused and didn't have to remobilize to other locations.

On the 250,000 SF, five-story hospital BIM project, OSHPD ([California] Office of Statewide Health Planning and development) only had five inspection issues during the construction stage. The OSHPD director actually paid a personal visit to the site, concerned that the inspectors might be being paid off because there were such few issues. Mr. Socha attributes this success to the fact that they modeled this project literally down to the nuts and bolts. A typical 2 year inspection process can be reduced to 6 months. Layton has used PointCloud3D to evaluate existing structures on OSHPD jobs but has found that coordination issues and the downloading of this information is difficult and can only be useful in very limited applications. While working on an MRI during the course of a particular project, the company found that coordination of a major run of piping should be modeled, but the connection details at some points were best left for specialty contractors in the field to work out. In some cases, modeling existing conditions may not be practical because obtaining specific information on the conditions may not be practical.

Owner's involvement is encouraged, as the process of intelligent design is able to start sooner. Even warehouse jobs are being completely modeled, and advantages are realized in terms of coordination and productivity increases.

Building the project team and encouraging open communication is the more important component of BIM. Mr. Socha says that 80% of problems in the construction process are people problems rather than technical in nature. BIM is valuable to the process because, when done properly, it can facilitate communication and team interaction, thus helping to solve people problems.

5.2.3 Challenges of Using BIM

One of the difficulties Layton experiences with the BIM process is finding operators who are knowledgeable about both BIM software application and the intricacies of how the work should be performed in the field. “How do you get a super, or person who has field knowledge to sit at a computer long enough to get information into it?” was his question. Persons who can operate BIM are typically younger, newly graduated from college, but lacking enough field knowledge to know what they are drawing and what the constraints in construction are. The problem with this is that they are representing items on a model, but often not understanding the particulars of what they are putting together so that the model will not reflect the way the work will actually be accomplished in the field. Because of this, conflicts in the field will occur. Layton’s field personnel tend to dislike the BIM coordination meetings because they are too long at a screen rather than out in the work areas.

5.2.4 Conclusions

Contractors that believe their role is to create value for the clients by organizing a project team and coordinating their efforts find BIM to be invaluable. Layton has found that allowing subcontractors to develop models based on their own expertise in construction will produce more cost-effective solutions to DB and CM design-assist projects because each is trying to maximize its own productivity. The general contractor is best suited to be a leader, encouraging and assisting team members to model well, but that they should not dictate method, as it will tend to reduce creativity and maximization of each trade's own productivity, thus reducing overall project effectiveness.

RFIs, which are an indication of confusion about the plans in the field and thus an indication productive labor achieved by field personnel, decrease by about 90% when BIM is practiced effectively. Re-work and change orders based on plan conflict are reduced to nearly nothing. Schedules are improved when modeling is done and they are controlled even more effectively when 4-D modeling is done to ensure constructability of means. The investment in BIM for these projects is typically less than 1%, easily compensated for by the increased efficiency and speed of the project. Given the positive aspects, the learning curve of only a few projects is not a significant enough a factor to inhibit implementing BIM as a tool for their business.

5.3 Case 3 – Hunt Construction (GC)

The Company:

Hunt Construction is a 2 billion dollar general contractor with several regional offices that are free to adapt some operating procedures based on local conditions and needs. Mark Bartlett is a regional manager in the San Francisco bay area and shared perspectives on the few BIM projects he has managed.

As a company policy, Hunt now utilizes BIM on all hospital projects. Hunt recently completed a hospital in which the contractors began modeling after the engineers had already completed their design stage, and because of the results of that effort, decided that all such projects should be modeled. Hunt is ramping up their in-house BIM operations and has two full time BIM managers and is looking to add one more BIM operator to staff a new hospital project.

Hunt includes BIM as an overhead cost rather than a direct project cost. They price the job in this manner to stay competitive. This practice reflects the idea of low bid contracting rather than qualification based contracting. The latter would include BIM as a value adding process to that particular project and therefore include it a direct cost. Tools and personnel needed for the BIM process would be a direct cost needed for the project needed to run efficiently.

The University of California – San Francisco (UCSF) project was a five-story, 162,000 SF laboratory research facility completed in 2009. Hunt was construction manager at risk (CM at Risk) and general contractor on the project. The trade contractor team began involvement in the constructability process at the end of the design stage when they began coordinating the work by using BIM.

5.3.1 BIM Management Practices

Hunt does not self-perform work except for carpentry for temporary conditions or safety, yet they still take an active part in the modeling in order to attempt to make coordination possible for other major trades. Hunt does not assign zones for different trade contractors nor specify how trades are to model because the trades know best how they operate efficiently and are already accustomed to working with each other to coordinate their activities. The weekly meetings keep the design iterations short enough that there is not too much wasted time designing pointless elements. For the UCSF project, the subcontractors were not brought in until the end of the design process, or at 75% of the total design. Mr. Bartlett observes that the trend for Hunt is to involve trade contractors earlier in the process in order to ensure constructability before engineers completely design the system. Clash detection in the BIM process is used as a constructability review of the design documents. NavisWorks was used by the construction team as the clash detection tool for this project. The designers were not efficient at integration and used differing means to coordinate. One of the designers used Revit for clashing rather than NavisWorks so that entire team coordination could not be done effectively.

To establish the level of trust needed to work collaboratively on BIM projects, a series of face-to-face meetings at the beginning of the project are conducted. At these meetings, the trade contractors discuss basic protocol, and a framework for conflict resolution is established. The essential requirements, of course, are specified in the contract. “Big Rooms” have merit, but too many meetings waste time and resources such that participants become upset and lose trust in the system. Rather than co-locating, Hunt has found that frequent regular interval meetings held with a strict agenda to control time are sufficient. There is a fine balance between formal, planned time and the open collaborative environment allowing members to share ideas freely.

At a minimum, team members model anything bigger than 2” or anything racked. They can model anything else they want in order to coordinate their work internally or to understand their methods better, but they cannot expect other team members to spend their time scrutinizing conflicts from the minor, typically inconsequential clashes.

The model for the project was maintained by Hunt. All members have access to it through a common ftp site. This is the stripped-down solid model in NavisWorks format. The information-rich models are maintained by the GC because it is not deemed to be of real value to the specialty subcontractors. Only necessary elements are included in the NavisWorks model since too much information makes coordination and clash detection impractical.

Many of the young BIM operators use NavisWorks with a checklist to do clash detections and feel that the longer the list, the more successful they have been finding potential problems. The more experienced managers follow a list but only do a “fly through” evaluation and identify major elements to work on. Fixing these principal problems generally automatically repairs a host of other clashes. At each meeting, a set of the most significant conflicts are identified and discussed so that time is not spent repairing minor clashes that will probably be resolved when the real conflict is dealt with. New BIM operators do not understand that some clashes on the screen are not an issue in the field – such as insulation on a pipe or a hanger on a pipe. A less experienced BIM operator will tend to think that identifying a great number of clashes is an indication of effectiveness, but to the seasoned team members this is a waste of their time in meetings.

Hunt uses models to show time relations and is also dealing with more 4-D modeling. On a recent project near a sports stadium, they created time representations showing how their work would affect game traffic accurately on game days. They built temporary structures and traffic controls to alleviate the hazards and increase user ease during sporting events. Because Hunt’s construction operations had to work around the game days, the models were used to ascertain what the traffic would be like on those days.

Whereas Hunt does not “blow the Lean Construction horn,” they do have interest in streamlining the construction process – especially in terms of scheduling to increase organization on the site so that trade contractors are able to work efficiently. They schedule back-to-front down to the superintendent level where workflow assignments are made. This start at pull-construction is helpful in planning the critical elements and is crucial to their planning efforts. Coupled with BIM coordination, this planning allows field labor to operate without disruptions.

Hunt has not integrated 5-D yet in field operations but pre-construction services are using the Revit models for quantities and use embedded conversion factors to obtain durations for export to spreadsheets for estimates. They will soon move to 5-D because owners are asking for cost loaded schedules.

5.3.2 Observed Consequences of Using BIM

Evidences of increased field productivity include the following:

- An estimated 50 percent reductions of RFI. Few of the RFIs were field generated.
- There was almost no rework and only a limited amount of unproductive field time for subcontractor laborers.
- Only 10% of the change orders were related to design changes and scope.
- Pre-fabrication of electrical components before final assembly on the site contributed to shortening the schedule.
- BIM was helpful in coordinating the work and running a better schedule based on the more detailed planning.

Although Mr. Bartlett does not know the exact numbers, he knows that productivity is increased when BIM is used. The return is probably significant based on observed performance of subcontractors, but since they do not self-perform considerable work, they do not have access to exact productivity rates.

Hunt's cost to model and perform coordination and clash detection for the project was $140,000, or 0.15% of project cost. This cost does not include the subcontractor's or design team's modeling costs. Hunt says that they will definitely never go back to working on these types of job without BIM. At first it had been used to propose projects at first but now is used more for planning operations.

Hunt feels that if they would not have utilized BIM, the work would not have reasonably been able to be accomplished. The project architect added a significant amount of scope to the plans after design and construction were underway. Hunt and the MEP contractors found it difficult to keep up with the changes because of the lack of BIM operators available to them. Integrating the changes into the model was not able to be done completely because many of the changes involved work around existing conditions which are difficult to model. On this project there were 2,200 field-generated RFI, but Mr. Bartlett estimates that there would have been twice that amount without the use of BIM. These RFI resulted in 200 field orders which were essentially the trade contractors telling the architects and engineers how to design proper construction methods. This is a clear example of the idea that the person closest to the work should be involved in the modeling process for that work.

The changes to this job amounted to $15 million, or 16.4% of the original contract amount. Hunt reports that most of these changes (over 90%) were due to design changes and scope creep rather than plan conflict. There was almost no rework and little stand-around time for the subcontractors' laborers. One subcontractor slowed work on the project by reducing staff. When there are conflicts in the schedule and/or plans, subcontractors frequently reduce labor forces on the project so that they do not have too many idle laborers. On this project the subcontractor was actually over-extended on other projects that had delays and felt that this project was more under control due to the BIM planning and assumed the project would be delayed because of the additional work added to the contract so that their delay would not impact the overall schedule. They were able to complete the work without over-staffing because of the additional planning up-front.

Some of the detailing may be hired out to a third party depending on the need. On the first of Hunt's projects they hired specialists to model the elements on the project. Some of Hunt's subcontractors that hire out the model detailing may not understand what should be modeled and improperly specify what the third party modeler should include. The third party is qualified to model but generally cannot discern what specific items should be modeled to meet the client's needs. In one case, the plumbing subcontractor over-specified the work to be done and the detailer modeled all the pipes that were not needed but did not include some of the needed hangers required for the clash detection. Modeling is more than knowing keystrokes. It involves knowing the trade and understanding the interrelations with other trade work. Third party modelers may be good for temporary needs, but cannot replace the in-house modeler that knows the company's means and methods rather than just industry standards.

Some observations relating to BIM usage on this project:

1. An electrician who was able to accurately coordinate their work with others' were able to prefabricate J-box assemblies so that the majority of the work was done in the shop rather than in the field, thus saving time and decreasing onsite construction

2. It was determined that the precast panels should have been modeled because they would have had a better understanding of connection points for coordination with all subs. There were a significant number of conflicts that could have been avoided if this visualization had been available.
3. The framing contractor should have been involved earlier in the modeling process to help detect conflicts associated with braces, soffits and other framing components. Hunt modeled some of the framing members so that the MEP could be coordinated with framing properly. The framing contactors should have started providing input when the MEP began their modeling and coordination. All members must be able to model their own processes and contribute to the model.
4. Some of the BIM operators do not understand the systems they are modeling and they cannot determine what should be modeled. On one changed condition, exhaust fans were raised eleven inches. They ended up clashing with braces and other elements and other framing elements, triggering field changes. When this change was represented on the model, diagonal braces were included because the modeler did not consider that they would be a problem. Because the part was not modeled a clash was not triggered. More experience is needed for the team to know what to model and what not to model - especially on changes to the plans. This is part of the learning curve.

5. Another demonstration of lack of knowledge of the system was manifest in piping that needed to be re-worked due to a failed OSHPD inspection. The BIM designer did not understand the nuances of OSHPD requirements and therefore included dead legs in the deionized water piping. Deionized piping requirements for dead legs are more restrictive than typical water piping, but a person who has not dealt with OSHPD may not understand the requirements that need to be met. Field experience is imperative to virtually create a system that will become physical.

One major change to the project was $13 million, of which ¾ was MEP changes. The construction team received no model of the MEP change. The MEP contractors each produced their own model and the process was coordinated from the architect's original model. The team had weekly meetings in the jobsite trailer for planning and class detection. All members of the team were present at the meetings – many sitting around not being productive. Later Hunt decided to use GoTo Meetings® so that all members can sit at their own desk and remain productive while 'at' the meeting. The fact that the team knew each other and had worked together meant that they were able to put a face to the name and thus increased trust and collaboration even though working remotely.

The site was very constrained for space such that there was no lay down space in the normal sense. Because they had the fourth floor empty shell, they could use it to avoid excessive warehousing costs but they still needed to plan the delivery of their materials. BIM was helpful because they were able to coordinate their work and run a better schedule based on the more detailed planning.

The learning curve associated with using BIM is fairly "short", according to Mr. Bartlett. He found that after one BIM job, a person can be a good manager. If the person does not have modeling technical ability, it will take a few projects to become a good operator. Outsourcing BIM to a third party is acceptable if done occasionally to meet time constraints, but a contractor who is in the business of coordinating construction should have their own capabilities in the long run. It is also helpful to have a set of "outside eyes" in the modeling process because it raises questions that might otherwise be missed, teaches new techniques, and also provides an additional layer to document the process in case of conflicts.

5.3.3 Challenges of Using BIM

Hunt is concerned about its inability to hire persons that can both operate BIM software and also understand field operations. Many of the people who know the software are newly graduated from school or have computer backgrounds rather than construction experience. Operators trained in BIM tend to think that "their computer screen is solving the problems. They get hung up on technology and computer screens and they don't understand the real world and how it works." Since a model is a representation of the real world, the modeler needs to understand the real world or they lose effectiveness as communicators. A person who does not understand the physical construction process cannot model effectively. One of the approaches that Hunt is taking to solve this problem is pairing experienced MEP coordinators with potential BIM operators so that they can spend time in the field. Thus, the operator visualizes the situation and the constraints and problems associated with the work they will model.

Mr. Bartlett expressed concern that technology has not kept up with demand. For instance, Hunt uses Revit for modeling and Primavera P3 for scheduling. Integrating model data into Primavera and other programs is difficult as they discovered on a recent project where Hunt performed some 4-D modeling but found that the interface was cumbersome. This is ironic in that many software vendors feel that contractors, in general, do not use the technology that is supplied.

When the subcontractors were doing their coordination they found it difficult to get the architect and engineer to review the models with them in the coordination meetings. In these meetings, if any of the contractors had a question about architectural finishes or design intent they were unable to acquire direct answers from the architect. Mr. Bartlett does not know if this is due to a liability issue or whether the architect was not comfortable with or was unable to make decisions quickly. The design team for the project developed the plans in the traditional method without builder involvement and did not seem to want to be involved with the means and methods planning component. Perhaps they were not paid by the owner to participate in this or perhaps they did not understand the means and methods well enough to take part in a way that would not put any liability on them. Whatever the reason, resistance from any team member - especially the designers, greatly diminished the value of BIM. A major change concerning the existing infrastructure on the project was given to the contracting team. The mechanical contractor quickly discovered 11 issues on the 2-D drawings of the changes and reported these concerns to the architect and owner. The contractor then modeled the work included in the change and found many more conflicts. A great deal of documentation was done by the contractor to show the issues and to protect themselves in case of a claim, but the modeling effort proved to be effective in that it communicated clearly enough that the costs of the change did not end up in claims.

Hunt does a project score sheet for their projects to provide tracking for problems encountered and to ensure open communication. Hunt performs this process in order to gain historical data to aid in future decision making as well as document the pro/con arguments at the time of decision making to understand intent. Some owners, including this project's owner, dislike the process, partly because of the fear of repercussions in case of claims made relating to the issue. On this project, the contractors used BIM to aid in this scorecard process by showing conflicts and the basis for decisions made in the field. Some of the concerns were ignored by the architect and owner and later cost additional money to repair, but the costs were minimized due to fact that the increased planning showed the proper course of action. BIM, when done properly, acts as a scorecard aid in that the intent of the plan is shown more clearly and is recorded as a decision-making instance.

If BIM is to improve overall productivity, the "owner must require designers to play nice." Architects are claiming that the model is not a contract document, which means other team members cannot use it with greater confidence. Architects are not working with the contractor's models during construction planning and clash detection because it is not in their contract. The failure is that the designers stand back and let the general and specialty contractors solve the problems without the designers' input. Owners need to change the contracts with the designers and contractors to reflect this need. This is a common response to the CM-at Risk PDM which is more litigious than DB because there is not a direct accountability of the architect to the builder.

5.3.4 Conclusions

Hunt is looking at integrated systems but is still performing these projects primarily as CM Design-Assist. Mr. Bartlett believes that the DB project delivery method would resolve many of the issues – including the architects working collaboratively with the construction team. Low-Bid contracting limits the value of BIM because the coordination process is not integrated in the design. Productivity increases with the use of BIM primarily because conflicts are drastically reduced. Even though Hunt does not self-perform, their fiscal obligation to reduce costs for the owner requires them to eliminate conflicts which cause additional costs in the field. BIM is invaluable in this regard such that Mr. Bartlett cannot imagine doing a large project without it now that he has experienced the positive difference of using BIM.

5.4 Case 4 – Diffenbaugh Construction (GC)

The Company:

Diffenbaugh is a general contractor with a high of $180 million in revenues. They specialize in concrete tilt and warehouses but also perform a fair amount of projects in the public sector. The majority of their work is delivered by DBB, but they also do CM and are venturing more into DB. Concrete installation is self-performed by their efficient unionized forces. Due to market forces and the hype about getting on the BIM bandwagon Diffenbaugh decided to test it out. To perform a good effort experiment with BIM they hired an in-house BIM person for coordination and modeling and did several projects using BIM to varying levels.

5.4.1 BIM Management Practices

Architectural and concrete features were modeled from 2-D contract documents on several projects. Diffenbaugh spent approximately 1-2 percent of the project cost performing this modeling using Revit. They had to rely on subcontractors to model their own work so that proper clash detection could be run, especially in the MEP trades where a majority of the clashes are usually seen. Most of their normal subcontractor base are smaller DBB companies and do not have the resources to begin modeling their jobs - the cost of hardware and software training to learn how to model is perceived to be too high for many of their subcontractors to take on at this point. It is unreasonable to expect the low-bid subcontractors to participate in modeling, and therefore the coordination and clash detection process involving principal subcontractors is not performed regularly. Because these subcontractors were not in a position to require BIM or to model extensively with their own resources, a concerted effort was not possible.

Benefits to the project when a few team members modeled or coordinated was not readily apparent due to conflicts with subcontractors, especially those that did not model. However, some advantage was seen when the MEP trades modeled and coordinated with others using NavisWorks. On jobs that were modeled, Diffenbaugh had the mechanical contractor be in charge of clash detection and doing coordination with the other MEP subs. Diffenbaugh took an active role only when conflicts could not readily be resolved and the architect needed to become involved.

Diffenbaugh recently began two DB projects – a community college building and a MOB (medical office building). The contract indicated that the designers build a model and supply it, along with 2-D drawings to the principle trade contractors. The MEP trades will each model their work and coordinate the drawings using NavisWorks clash detector in a process managed and controlled by the project architect. Diffenbaugh no longer employs their BIM person so they will not model their work internally, but any required modeling not completed by the team contractors will be modeled by the architect if needed for proper coordination. As a general contractor, they will be involved in the modeling process only as far as required to ensure that each party is doing their work or ensure that the project efficiency is increased as a whole. This prevents any subcontractor from gaining benefits of lowering its cost at the expense of others. Diffenbaugh will rely on its expertise in concrete work and does not expect to need to model this portion of the work. Since most the conflicts tend to center on MEP issues, they feel that letting MEP managers be responsible to coordinate the process and reduce clashes is natural. This plan supports their experience that architects should supply models and be more responsible for the design and coordinated contract documents. It could also prove to reduce duplication of effort if the models supplied to the subcontractors are done in proper layers such that they can be used as a basis for models to be produced by the subcontractors. No specific software type is specified for use by the various contractors.

5.4.2 Observed Consequences of Using BIM

Evidences of effects on field productivity:

- The RFIs were reduced to about half of what would be experienced on non-BIM projects.
- The productivity rates for their own forces did not change significantly on BIM projects.
- Reduces rework when plans are coordinated.

- Grater clash detection abilities for the MEP trades decreases conflict between trades. These reductions ripple out to other contractors and the general contractor in terms of managing conflicts.

One of the noticeable differences on BIM projects was the reduction in the number of RFIs. When BIM was used in any capacity to coordinate work, there were about half of the number of RFIs when compared to a non-BIM project. Diffenbaugh's perception, however, was that the time and money spent to prevent those RFIs was not worth it since "it is not our job to get rid of them anyway." Providing plans that are accurate and constructable should be incumbent on the architect rather than the contractor. Spending money on the architect's job without compensation does not necessarily save money for the contractor. The feeling at this company is that plans are becoming worse over time because the designers are sloppy and do not coordinate.

An advantage to the contractor was realized on one project where the waterproofing was modeled in an effort to understand how it was to be done given the phasing required for proper installation of the membrane. This is a means and methods issue, thus in the purview of the contractor. Net savings to the project because of modeling the solution prior to construction therefore contractually belong to the contractor. For this reason, modeling is perceived to be advantageous to the contractor only when the resolved conflicts are those of means and methods rather than plan reliability. Two observations concerning means and methods on past BIM projects were:

- The models did not include enough detail so that electrical contractors still hit footings because they didn't know how big they were or their exact location.

- Diffenbaugh experienced conflicts with the bolts being too close to each other or some other member or in the way of something else so that the desired finish result could not be produced.

Both of these issues involve means and methods questions and plan reliability issues. The models were not produced with enough detail of the concrete and structural work such that the conflict remained. The level of modeling performed did not eliminate these problems and therefore was deemed not a good enough investment to continue using BIM at this time on most projects.

Because much of Diffenbaugh's work is subcontractor management, they do not have direct control of the trade field subcontractor's means and methods and therefore, the productivity. So, except for their own concrete crew's performance, they do not have access to their trade subcontractor's productivity rates. The productivity rates for their own forces did not change significantly on BIM projects.

5.4.3 Challenges of Using BIM

Many public owners have begun mandating BIM usage, but they do not give 3-D models to bidders or contractors so that contractors must start their models from 2-D documents. Some owners are specifying 3-D, data rich models for their uses after the project is closed. On DBB projects, there is little incentive to properly model for gained field savings, so creating the model is an additional chore. Contractors must anticipate what the models will cost to create and how effectively they can mend contract document problems and get a completed 3-D, data-rich model including maintenance information. These risks must be determined on top of the normal plan risk that they have to deal with.

The highly competitive market is now reducing margins so that spending money up-front on a project with the hope of saving on productivity is not feasible. The subcontractors competing for the projects do not all utilize BIM so that the general contractors cannot be assured of their ability to BIM - even if it is required. If the owners want the contractors to model projects in a competitive environment, they should include the money in the contract to pay for contractors to model up-front rather than expect them to take the risks and finance the modeling.

A lack of qualified people that know how to BIM is another challenge facing the industry. People that can both operate the software programs and know how to build are rare. Owners could help this by being willing to pay for the learning process for the contractors. Additionally, if the architects producing bid documents would provide models to the contractors, it would be less expensive to do constructability surveys and therefore be more cost-effective and practical to BIM these projects. The return would likely increase such that contractors could invest the resources into learning the BIM procedures and thus benefit the entire industry, eventually lowering prices to the owners.

5.4.4 Conclusions

Because Diffenbaugh did not realize an overall project cost savings for them, nor a productivity increase to their own self-performed work, they downsized and no longer have their own BIM manager. Now, with the severely restricted marketplace, especially in Southern California where they are headquartered, they cannot expend resources on any task that has not been proven to increase profitability. Several years ago, due to market forces they began using BIM to be competitive and keep ahead of the technology curve. This year, also because of market forces, they have discontinued the wide-scale use of BIM and now use it only when asked or it is expected by contract. Much of this pressure is due to the poor economy and dearth of projects to compete for. In Diffenbaugh's market, competitive forces are so great that they rely on low bid to secure jobs and issue change orders to make up for inadequate plans. Sadly, this market and contract type relies on finding errors in the plan and creating change orders as a way to compensate for lower productivity on the job. The only advantage for the contractor that BIM would have is finding means and methods conflicts in the modeling process. This often is an issue of 4-D scheduling – something that Diffenbaugh did not experiment with.

Smaller general contractors in the DBB market actually have somewhat of a disincentive to BIM a project effectively. It is not specifically required in the contract. By discovering errors in the plan and eliminating change orders, they reduce the amount of money they can make on the project. To make it worse, they spend money in order to reduce their income. In the DB and CM design-assist markets, there is impetus to use BIM, but for those who originate in the DBB market, the culture dictates that architects need to control the BIM process because they are the designers.

Architects need to give a model to the contractors so that they can use it as a basis for their own modeling efforts. Because contractors are builders, not designers, they feel that their responsibility is to install the work, not design it. More and more, owners want to pass off this clash detection function to hungry contractors and avoid paying the architects to solve these problems or take the risk.

5.5 Case 5 – Helix Electric, Inc. with Turner Construction

The Company:

Helix Electric, Inc. is the electrical contractor on the Sacramento Airport. Turner is the construction manager on this multi-prime project. Helix Electric is not new to modeling, but this is the first fully modeled project for the superintendent. Turner has modeled many of their large projects as well, but there may be differences in the way in which the projects are managed. This study looks at the results from the perspective of the electrical contractor's superintendent, Mr. Price, in relation to the management techniques of the construction manager. The meeting management style was observed several times by the author.

5.5.1 BIM Management Practices

The airport project has weekly BIM coordination meetings. The general contractor, each subcontractor, and the architects and engineers are all set up in trailers at the job site. The modeling is usually done at company offices rather than on-site in a "Big Room." The models are produced based on 2-D documents provided by the project architect but produced from a model of the project. Each trade contractor is required by contract to create a model based on those 'drawings' and to participate in clash detection meetings. The meetings are conducted in a conference on the project site with personnel for each trade involved but with some BIM operators participating remotely. The architect or the MEP coordinator for Turner conducts the meetings, but the mechanical contractor generally controls the image on the SMART Board™ in the conference from his office remotely. The mechanical contractor receives files from each team contributing to the model and merges them for clash detection using NavisWorks. When clash resolutions are determined, notes are made on the NavisWorks model by the mechanical contractor and that copy is sent to each trade's operator to make changes on their own models as part of their preparation for the next week's meeting. The process is fluid, with each member learning to work with each other in the process. Protocols, such as how the notations indicating which contractor would change their model to avoid conflict, were being decided during the third such meeting. Other changes were made as deemed necessary by the group. The architect participates in the meetings remotely from his Denver office in most cases. He refers to his model to ensure that the elements as detailed by the trade contractors meet the design intent and requirements for the airport. This spirit of cooperation was apparent through the project as conditions changed.

In a typical clash run, a very large amount of clashes are discovered – on one run 48,000 were identified by the program. Most of these are usually not clashes that are significant. For example, insulation or clamps on ductwork, pipes in a wall, brackets embedded in a concrete deck as needed, e.g. appear as clashes. During one meeting at the airport, over 10,000 clashes were identified. However, only about 20 of these were chosen for discussion. All clashes are not analyzed at each meeting, only the major clashes, as determined by the mechanical contractor, are on the agenda and are viewed from different angles on the clash model. Members from the trades generally refer to the 2-D drawings in the conference room to understand how to interpret the intent of the drawings and reveal any conflicts. Since the view on the board is from a clash detection program, it is not information-rich and is only surface modeled. The changes must be done by each of the trade contractors on their own modeling software. Although there is a duplication of effort involved here, some participants indicate that they believe this is better because it causes more people to look critically at the documents, increasing the number of errors found in the plan and reducing the chance of conflict in the field. Each week the participating contractors submit their models with updates to the mechanical contractor for further clash detection.

5.5.2 Observed Consequences of Using BIM

Helix Electric's superintendent on this project reported that he is not seeing big changes in productivity rates on this project. He would not expect them either because in the field they receive detailed schedules and budgets from estimating and work diligently to meet those targets. Their laborers are skilled and consistent and the estimators have a reliable database showing historical data on productivity rates. They have been doing BIM on other projects and can project the productivity rather accurately. The company did not share their productivity rates. However, these comments reflect a common misunderstanding of productivity in the field. The labor productivity rates alone are not conclusive evidence of increased project productivity because productivity is dependent on the amount of rework performed as much as is idle time.

The superintendent reports that he sees significant reductions in the amount of re-work and somewhat less time is spent standing around compared to a non-BIM project. The process seems to be catching errors in the plans and also finding conflicts where the major conduits and duct banks would run into mechanical, framing, or structural members.

Following are evidences of increased productivity on the Sacramento Airport project:

- Marked reduction in RFIs.

- Because the model eventually produces fabrication drawings, the shop drawing process is reduced which makes procurement easier.
- Much less rework due to reduced conflicts.
- Prefabrication of components makes them meet specific requirements so that the fieldwork is more precise and the finished product is better. This also speeds field installation.

The systematic approach to prioritizing and solving major conflicts first and leaving apparently less critical clashes for later evaluation saves a great deal of time in meetings because the resolution of one major clash often leads to the elimination of hundreds of minor clashes. Time spent in meetings discussing details can be wasteful for personnel who could be modeling or managing work in the field. The BIM costs for this project were less than one percent of project costs, yet the conflicts discovered and resolved prior to field work were important. One MEP contractor reported that since the model eventually produces fabrication drawings, the shop drawing process is reduced so that the net cost of modeling is significantly reduced.

Much of the electrical work is not greatly affected by BIM because the runs are small and usually not modeled anyway. Any conflicts and problems associated with these runs of less than 2" in diameter are easily and quickly solved in the field by the installers. On ductbanks and specialty piping, BIM is making the job more efficient because components are fabricated in their own shop or ready-made components are ordered from vendors. For example, the busway manufacturer can fabricate components to meet site-specific requirements that would normally be done less efficiently in the field. This improves quality and speeds installation. The superintendent says that whereas he can still see glitches in the BIM method, he would not want to go back to doing a project without BIM because it makes the process better, mainly in re-work reduction and pre-fabrication.

5.5.3 Challenges of Using BIM

"One problem with BIM is that you have to rely on others for accurate information," says Mr. Price. At the airport the soffit was not modeled properly by the framing contractor in some locations so that there were still conflicts in the field with Helix Electric's ductbanks. They have documented the conflict areas by digital photographs and are correlating them to the model so that they have documentation, but more importantly, so they can learn how to avoid these problems in the future by better modeling. This is an effective way of shortening the learning curve. Project team members who will review the process for 'lessons learned' and pass them on to their organizations learn to be more efficient modelers and increase institutional knowledge of the process.

5.5.4 Conclusions

On this project, a noticeable decrease in re-work and increased efficiency in installing pre-built or more accurately ordered materials is saving time spent on the project. In the larger sense, less time is spent on field work to accomplish the contract work due to the elimination of re-work and of implementation of lean tenets such as ordering material which is installed more efficiently and with less waste on the job site. RFIs are reduced as well. The biggest drawback to BIM is the challenge of being able to trust in the models and work of other contractors – especially when there is no direct contractual relation. There needs to be control of schedule and model that each team member can trust.

5.6 Case 6 – Southland Industries (Mechanical Subcontractor)

The Company:

Southland Industries is a large mechanical contractor, headquartered in southern California, but that performs work nationwide. Their capabilities in design and modeling and attitude toward collaboration attract projects that are almost exclusively design build. Dr. Victor Sanvido, a Senior Vice President, reports that Southland Industries prefers to be brought in early in the project where they can have a better opportunity to participate in design coordination. Because fabrication of sheet metal used in their installation is based on 3-D representations, Southland Industries has been modeling in 3-D their own ductwork since the 1980's. Their profit center is ductwork and HVAC systems, and BIM is one tool that enables more efficient fabrication and installation. Because they had been modeling in 3-D for their own operations, they were poised to begin BIM coordination with other members of the design-construction team when the software became more readily available in the 1990's. They have been involved in several highly visible projects including the Pentagon reconstruction with Hensel Phelps, the Camino Medical Office Building with DPR and are well known as efficient users of BIM. This case study explores proper BIM management practices through the experience and views of Southland Industries, principally from the perspective of Dr. Sanvido.

5.6.1 BIM Management Practices

Southland Industries' decision to model or not to model a particular project or part of a project is based upon their experience on whether or not certain elements need to be modeled for efficient field operation. Modeling is not done in response to an invitation from the owner or general contractor or because they will be compensated for modeling, but because they view modeling as an invaluable means of producing their own work more efficiently. Dr. Sanvido states, "Southland Industries' work is to install ductwork and we model first for that coordination." If an owner or another contractor does not wish to invest in the BIM process, Southland Industries will make an effort to show the benefits of doing so, but generally they are negotiating projects with owners and general contractors that appreciate the importance of this planning. They price their contracts based on what they perceive they will be required to do in terms of field work and in management work – including the amount of modeling and coordination they will have to do. On a team with more sophisticated and BIM experienced members, they will have to spend less time managing the process.

Southland Industries uses AutoCAD MEP for fabrication and prefers to model using this software. Coordination work is done using NavisWorks. The type of software required does not seem significant to Dr. Sanvido. The only major problems with platform issues emerged on the Pentagon rebuild project which was fully modeled. The architect had difficulties integrating their AutoCAD program output with the Bentley platform used by some members of the project team. In the last few years there have not been conflict problems because of the acceptance of IFC by the major software vendors.

Dr. Sanvido has discovered through experience that Southland Industries needs to understand the work of other contractors so that they can jointly create a more comprehensive model and improve communication concerning construction issues. Each contractor's model is its own point solution to the project coordination problem. Developing a relationship and a means for collaboration will enable the team members to work together. An opening planning meeting and then regular planning and coordination meetings are done to increase the accuracy of the project model. If the model is planned properly, most clashes are avoided. Dr. Sanvido views excessive conflicts between building components during NavisWorks clash detection to be a failure to plan proper placement rather than as an indicator of success in finding problems. Up-front planning about what level and where components are placed is vital in order to reduce waste in the detailing process. "It is better to find clashes in the model than in the field, but it is even better to minimize clashes in the model by better planning."

Southland Industries models to increase the efficiency of their primary profit center of installing sheet metal and HVAC systems. The first order of business is fabrication. This is supported by clash detection. The process must be managed properly so that important conflicts are dealt with and time is not wasted on unimportant details. There have been cases in which there are 45,000 - 48,000 clashes reported by the clash detection program - most of which are not truly problems that would be encountered in the field. Seismic support connections to the deck, clamps securing ductwork, pipes inside a wall cavity, insulation on ductwork are all included as conflicts because there are two surfaces touching each other. Southland Industries usually separates by layers elements that they are modeling so they can reduce clashes which are unimportant and don’t need attention. This crucial layout knowledge comes from experience. Proper layout during modeling will reduce the number of clashes discovered during coordination with other trades. Having a high number of clashes indicates improper planning and wasted efforts in designing. The key to this kind of efficient modeling is personnel who understand both how the work is performed in the field and how the work is modeled on a computer.

Southland Industries was involved in the Pentagon rebuild in which the entire project was modeled. They performed modeling on their own scope as well as for other trades. Hensel Phelps, the general contractor, did short interval scheduling for this multi-phase project. Each consecutive phase was rigidly scheduled so that the specialty contractors could expect that tasks could be performed without interruption when Hensel Phelps indicated. The modeling helped them understand exact material specifications, a schedule was written allowing for these needs, and the schedule was closely followed. Because they could rely on the schedule, they could plan for proper labor load to most efficiently complete the project. On this project, 10 percent of the cost of the work was available as an incentive if it was done properly. This project was closest to an IPD than any Dr. Sanvido can recall. Because the performance was tied to their compensation, intensive planning, including BIM usage was an integral part of this program. Coupled with the general contractor’s successful organization and scheduling, the project was a success.

Southland Industries is currently involved in a project that is ostensibly IPD. The owner uses incentives as a way to motivate good modeling practices and is involved closely in the development of the project. Designers and trade contractors are combined so that the project can be built virtually using input from those individuals that will actually perform the work. The designers are not just determining what will be placed in a location, but consider how it will be accomplished. Scheduling and cost loading is being included in the process to ensure that the entire process of construction is included in the virtual construction process. Contract price for the actual construction will be based on the model results. Involvement and acceptance of the model as an accurate representation of what will actually occur in the field is crucial for the success of this system.

Lean construction is an important aspect of Southland Industries' effort to become more efficient. A principle tenet of lean construction is the reduction and elimination of any work that does not directly contribute to the finished product. If the design was not planned properly, the detailer spends time drawing something that will need to be fixed later. Time wasted in design is cheaper than the time wasted in the field, so Southland Industries errs to the side of better planning but is continually seeking to streamline its design operations to better support the field operations.

5.6.2 Observed Consequences of Using BIM

Evidences of field productivity increases observed by Southland Industries:

- Reduction in rework to less than 1%.
- Increases of 20% to 30% in field productivity.
- Reduced injuries and lower EMR.
- Field layout time reduced by 75%.
- Virtual elimination of field-generated RFI.

Being involved in the schematics phase is very important because design efficiencies are lost otherwise. Fifty percent of the cost is determined in the initial program phase. Seventy-five percent is done in the schematics and design phase. [This is also cited in various articles on the topic (Carbasho, 2009)]. The last 25% of the design is done during the shop drawings phase. Therefore, the owner and architect have a greater effect on the total cost of the project by involving the builders early, not just to carry out clash detection, but to design the most effective method to create and locate zones. For example, smoke dampers cost a great deal of money and time to supply and install and also affect the framing, electrical, and other contractors. When more smoke dampers are installed, more controls are needed for building control systems and more maintenance panels are required. This in turn affects architectural design. The smoke dampers add cost and complexity to a building but they add no real value to the building because they create no real benefit to the occupants of the building. Using BIM to design a more streamlined smoke damper installation system is a good way to reduce costs on the project. By sharing ideas through models, the procedure can be made more efficient. However, realizing that there is no real value in the smoke damper, getting rid of as many as possible seems to be a better contributor to a leaner building. Using BIM to model alternate zones and routes of ductwork, they were able to eliminate about 30% of the smoke dampers. This example shows the benefits of involving the builders in the early schematic stage of the design process. The parties close to the work know the complexities of installing smoke dampers and, if given plans that include them, will try to streamline the installation. But, given the requirements of the space, Southland Industries could use models to determine ways to eliminate the construction elements that are more costly. Models impact overall productivity because they graphically show the detailers how the components affect other trade work and thus the overall effectiveness of the system.

When retrofitting existing spaces, too much time may be spent mining information about and modeling existing conditions. Southland Industries has been involved in PointCloud3D usage to gain accurate digital models of existing structures but found that the work was cumbersome. The complexities of renovations mean that all work cannot be modeled without an inordinate amount of time spent on the model. “Spending fifty percent of your budget on BIM will not translate to that much savings in the field,” observed Dr. Sanvido. Unusually complex remodels are usually not cost-effective to model. One noteworthy case is a hospital project in 2000 where they spent 2 - 3 times the price on modeling than on the installation. The cost of the model was about equal to the cost of the sheet metal alone. Southland Industries spent $1.5 million on modeling and $1.5 million on sheet metal. Generally, detailing is about 15% percent of the cost of the project. This project was a loss for them because they could not be compensated for the excess time modeling. Indeed, the complete modeling of the project was not a net value to the project team.

The human element of the “Big Room” is crucial to its success. The greatest advantage to the “Big Room” is the people are always close to each other and able to develop relationships and solve problems together. However, being in a “Big Room” may be cumbersome and, when too many people are present, conflicts may be hard to resolve because too many decision makers turns the process democratic.

A knowledgeable BIM coordinator is very important to the process. Some general contractors have coordinators who may understand the software but can't manage the process well. MEP coordinators with experience need to be managing jobs, rather than people with mere technical ability of modeling. General contractors or construction managers often want to have Southland Industries do the coordination and head the modeling effort.

BIM enabled planning increases the ability to prefabricate. Properly coordinated, the models are deemed to be more accurate such that Southland Industries' shop can build larger pieces of their ductwork for installation in the field. The confidence that the actual building will be like the 'plans' is essential in prefabrication. Traditionally, in construction, each specialty contractor builds components in their shop for final assembly in the field. In the case of mechanical contractors, ductwork and assemblies are fabricated from field measurements of existing conditions and then brought in small pieces to the jobsite. Each piece can be adjusted by field personnel, but the process is longer and the quality is generally lower than if the work is done in the shop. With a trusted model, larger pieces are fabricated and brought to the site because the adjustment ability is not needed and shop fabrication can begin earlier since they are not waiting on the measurements from the field. Thus, through prefabrication the building process is more efficient.

Some advantages of prefabrication made possible by BIM:

- Rework is reduced dramatically. On BIM projects rework amounts to a fraction of one percent – remarkable when compared to industry average of 14% of the cost of the project attributed to rework. The reduction is attributed mainly to the increased coordination between other trades and the increased accuracy. Rather than being within a ½" with paper planning, tolerances are generally within a 1/16 of an inch– limited primarily by human ability rather than by the software.

- The quality is better when materials are fabricated in more controlled conditions of the shop. Tighter tolerances means that the parts will fit better in the field so that there are fewer leaks, cracks and connectors. A joint assembled in the shop will be higher quality than one made in the field where it is hard to reach.
- Injuries are reduced because more of the work is done at waist height with specialized equipment in the shop. The larger pieces sent to the site are not able to be installed by one person on a ladder so there are fewer injuries involving falls from ladders or back injuries from improper lifting. Since the implementation of fabricating larger and heavier pieces Southland Industries has experienced fewer injuries and their EMR has dropped to 0.45 from 0.68 – a remarkable accomplishment and a significant savings in worker's compensation insurance costs.
- Field installation time is reduced. The larger pieces are assembled more quickly and inspections are faster.
- LEED credit for waste reduction and clean work environment are available. Certification for clean ductwork is faster because the larger pieces can be protected easier than the many small pieces.

Information from models is used to lay out work through the use of total stations. On a recent project the 25,000 point deck layout was accomplished with three to four people working seven days. This amount of work would normally be budgeted to take a larger crew of 6-7 people one month to complete. However, it took a couple of people one month in an office to prepare that information on a model. The time spent on fieldwork was cut by 75% but the modeling took additional time. “The general contractor cannot tell us to cut 75% of our layout time off because we need time to model before that work in the field can happen.” Less than half of the hours required for traditional layout were required with the use of the total station. The estimated savings on the layout of that floor on that project is 500 hours. Other advantages of modeling the layout points to decrease time in the field are:

- The field layout is on the critical path while the preparation work in the office may be able to be accomplished off of critical path.
- The field labor hours are reduced by about 75%. In terms of total hours, including the office hours spent preparing the data for the total station, using the total station is about 50% less. It is important to note that the time needed to fully model may not be available on some retrofit projects because the time to model through existing conditions is too great.
- The field labor exposure to hazards is reduced, thus contributing to fewer injuries and a lower EMR.
- Overall layout time in the field can be reduced if properly scheduled with the general contractor. Because mechanical work is generally on the critical path, this could reduce project schedule duration.

Southland Industries has been involved in projects in which some members, usually steel, concrete, or framing/drywall contractors are not modeling their work properly. Often, the job of modeling these other contractor’s installations has been taken on partially or wholly by Southland Industries so that proper coordination can be done. When doing this, Southland Industries’ modelers must learn about the other trades’ work. This greater knowledge allows them to design better systems that consider the various elements of the project so that, as a whole, the building and process is more efficient. With greater institutional understanding of other trades’ work Southland Industries has been able to explore new methods of prefabrication. With a detailed model produced collaboratively, they are able to invite other trades to come to Southland Industries’ shop to prefabricate complex assemblies for delivery to the project location. The framer brings a constructed box into Southland Industries’ shop where they install the piece of HVAC equipment, ductwork and connectors. The piping is installed by the plumber, some electrical work is done and other connections made while on a table in the shop. This operation is safer and higher quality can be expected because the connections are made at ground level rather than on a ladder, twisting and reaching to reach hard to access spaces.

When the assembly is done, OSHPD inspects the work in the shop where they can more quickly approve of the work. The entire assembly is placed on, or in some cases designed with, skids for easy transport to the jobsite. Final connections in the field are designed so that the workers can more easily perform the work. The larger pieces require proper equipment and labor planning to lift and install in the final location. This not only increases quality, safety and saves time in the field, it also decreases the time required to inspect and certify. Thus, BIM enables not only prefabrication of trade materials, but the coordination of work by multiple contractors in remote locations for the benefit of each contractor. This requires a great deal of trust between the contractors and in the schedule and model. Each trade must therefore contribute to and be responsible for their portion of the coordinated model.

5.6.3 Challenges of Using BIM

Acceptance of the model as a contract document sometimes is difficult because some contractors do not want to take responsibility for their contribution to the total model. On most projects, Southland Industries' technicians consolidate and finalize the coordinated model that each team member must sign off on. If each contractor has participated intelligently in the modeling process, they should accept it. A fear to accept it suggests doubt in their modeling ability or lack of faith in the process. Without buy-in to the model, there is limited trust, which diminishes the ability to prefabricate and follow the modeled installation plan. It is based in a lack of trust of other team members, lack of trust of their own planning and modeling, and/or fear of taking responsibility

Dr. Sanvido said that Southland Industries does not want to be the project leader in terms of modeling because "saying you're the leader makes a target on your head." The work must be done as a team or else the leader may fear the risks incumbent on the manager of the process; or the other team members may fear that the leader could take advantage of others. In the absence of a strong BIM leader Southland Industries will lead the process, but by example – coordinating and working with other members. Being the center of the coordination process allows them to create better conditions for them to build in, but it is done with consideration of how the project as a whole will be affected. Getting into a space first and getting the best space so that their work can be done quickly and easily should not be the reason to control the model process. People that want to work in this type of collaborative manner will come together and develop relationships such that this type of project planning will become more effective. When team members are picked later in the project so they cannot be involved in the design phase, the relationship of trust which is instrumental in solving field conflicts is diminished.

5.6.4 Conclusions

Architectural design is a trade. Architects draw and communicate intent and indicate what is to be built and the final appearance. The builders have traditionally been the ones that actually draw the details of how they are going to build what the architect has envisioned. So long as these requirements are met, trade contractors should determine how to construct the building because they are the ones who best understand the building process from the production point of view. To do this, the trade contractors should be brought into the design process early. A good model from the architect gives enough information to show where finish elements are located and to be coordinated with the structural drawings. Each trade should model its own work based on its experience and understanding of efficient practices. A very detailed model from the architect and engineer may limit the ability of a trade contractor to design an efficient installation method. The example of the smoke damper design shows that the builder can design HVAC zones that will be less expensive to install and/or operate if given the ability to do so. Involving MEP contractors during the validation stage rather than after the architect and engineer have designed the entire project will increase efficiencies in construction and overall building effectiveness.

Much of the information on intelligent models cannot be transferred back and forth during this design phase. Clash detection is performed in NavisWorks by converting solid models into surface models and overlaying the surfaces in one space. When the conversion is made, data other than special relations are lost so that it is not available for usage in the shared model. Additionally, during the design and construction coordination phase, an excessive amount of information on the model makes it so that modelers cannot see the things they are concerned with. In many cases, models are stripped down so that the trade contractors can view only the things they want to look at rather than sift through the massive amounts of information on them. At the end of the project, however, owners are starting to want to have much of this information turned over to them in a unified, intelligent model. The owner needs to be involved in this design stage to be assured that the information they want in a completed model is included in the design model and so that duplication of effort is avoided.

Incentives are important to help the team work together, but controls for monitoring how each is ‘playing in the sandbox’ cannot be made effectively for this type of project. Only relationships of trust will allow people to work with each other on the level required for BIM to really work in making the projects leaner and to gain the productivity wanted at the project level, not just at the trade level.

To be useful, BIM requires a reliable schedule. To achieve the productivity gains available because of cutting down rework and having better prefabricated parts, you have to be able to get into a jobsite and have the space available to you when you were told it would be available. If the CG does not enforce or maintain schedules that can be relied upon, then the contractors may not be able to supply the proper resources when needed and may have too much labor on site when they can’t be used. An important part of the modeling procedure should be schedule validation and proper scheduling.

5.7 Case 7 – Kinetics Mechanical (Mechanical Subcontractor)

The Company:

Kinetics is a large mechanical firm with different groups running various types of projects for diverse clients. Joshua Lynn is a project manager that oversees projects in the high-tech sector in the northwest. Whereas the company models much of their work where it is deemed important to do so, Mr. Lynn's work involves smaller projects that are very fast-track fit-outs. These have demanding specifications and, like the high-tech industry where time to market is critical, there can be no delays in making the space operational for client use. Much of this work is process area and clean rooms. BIM is not used on most jobs unless the owner requests and sponsors the work. This study looks at the effectiveness of BIM on extremely specified and time sensitive projects.

5.7.1 BIM Management Practices

It is typical that mechanical contractors get first consideration in installing their work because their ductwork and piping requirements are generally bigger, more exacting and more expensive to route around other elements. In most cases, on the types of projects that Kinetics performs in this division, there is no time to do coordination and planning with other trades. Kinetics has only a few weeks to perform their share of work from the time they receive their drawing until the time that it should be complete. Rather than spend time coordinating, material is quickly brought to the field and installed before other trades install their materials. In this way, the smaller piping of the other trades can be worked around the larger piping of Kinetics. Most conflicts in location of their work and other elements in the field are solved by field personnel based on their experience.

The firm has an in-house BIM department that models work on large, multi-story projects in which the ductwork will be fairly repetitive and needs to be coordinated with structural and other trades' elements. This time to plan is not available to model on the smaller, but intensive projects in which they are generally functioning in existing environments. "BIM is a good communication tool, but a good foreman will envision and order the right material and install it without too much problem," says Mr. Lynn. BIM is simply not needed and there is not time given the way Kinetic's projects in that division are contracted and operated.

Kinetics is starting to use total stations for layout on some of their larger projects. These points are modeled and uploaded to the equipment for layout. This could only be done effectively on projects that are already being modeled and do not have too many existing constraints that would need to be accurately entered into the model. Most BIM work on their projects are done only when asked for by the owner or general contractor rather than because it is seen as a positive productivity booster for Kinetics.

5.7.2 Observed Consequences of Using BIM

Scope, not size of project, is the differentiator as to whether or not the project is modeled. In a high-rise that can be planned in advance, the model makes sense because the duct runs can be predicted and coordinated. However, on the high tech, fast track projects common to Mr. Lynn's department, there is not enough time to model. The foremen on their projects can visualize the fit of the material and equipment because of their experience installing. No real advantage is expected by modeling this type of work. It is believed, in fact, that it would slow the project and cause productivity to decrease because they would be working with other trades in the same space and time.

5.7.3 Challenges of Using BIM

The work performed by this division of Kinetics is segmental, complex and requires advanced technical ability, but is hard to model because they do not get detailed models of existing conditions and because of the intricacy of the work. Many of the pipes on these projects are even smaller than typically modeled. Even more advantageous than having a model from which they can produce detailed, prefabricated pieces and discovering clashes with other trade work, getting into the workspace first in order to install their equipment before other trades clutter the area up is the factor that increases Kinetic's field productivity on these types of projects. On these smaller, involved projects, letting each trade solve their problems with their specialized laborers is perceived to be better than trying to have them communicate with each other in an office to plan the work in advance. BIM operators that understand how the work is done are rare and the installers that know how to do the work rarely communicate with BIM software.

5.7.4 Conclusions

Fast track projects where the owner's requirements are not defined until immediately before the work is supposed to be installed do not have the luxury of being able to plan in advance in order to shorten the field work time. Similar to observations by other contractors that perform retrofit work, it is easier to have experienced field personnel "just make it work" rather than plan everything for them. Larger projects with time to plan the big ductwork should be modeled. Primarily this is done to aid communicating with other trades to avoid conflicts between the several trades' work. Secondarily, it is done to plan within its own scope.

5.8 Case 8 –Raymond (Framing/Drywall Subcontractor)

The Company:

Kim Lorch is Vice President of operations for Raymond, a framing and drywall contractor which performs work in the commercial sector, including hospitals and other high-visibility public spaces. They perform BIM services using their in-house operators when requested by owners or general contractors to do so but do not utilize BIM on all of their projects. BIM is part of their service package, not as a stand-alone profit center. Their engineering capability is one of Raymond's competitive edges. Mr. Lorch indicated that there is concern that rather than being a tool to further leverage that capability, BIM may competes with their engineering capacity in terms of engineering hours. BIM is a tool used to successfully compete for the jobs that are more technically challenging.

5.8.1 BIM Management Practices

Raymond models when they are asked to do so for the more complex projects they are involved with. They participate in the coordination meetings and clash detection process when called upon. They use Autodesk's Revit Architecture and AutoCAD 3-D to model and use NavisWorks for clash detection, depending on what the general contractor or owner specifies. Raymond's in-house modelers will model their own work in detail in limited areas as needed to clarify their own framing requirements. Once they understand their own framing requirements, it is quicker and generally as useful to other trades to box out areas that Raymond will need for their framing support. Because adding additional detail may actually interfere with other trades designing their individual details assigning work zones to subcontractors may be as effective as actually spending the time to detail all framing members throughout the entire drawing. Drawing their work is generally 2-4% of their total costs and BIM can add another 1-2% depending on how much detail they must model to properly coordinate with structural and MEP.

Raymond is currently involved in an IPD with a sophisticated team that is expending a great deal of effort in modeling the entire project before costs are established. The owner is investing an estimated 5% of the project cost into modeling with the anticipation of saving time and money by the reduction of errors and conflicts in the construction process. Each team member works closely with others to coordinate their modeling efforts and perform frequent clash detection procedures. Co-location is important in this process because the speed at which the design iterations and communication concerning planning and coordination occur. There are incentives to the project team to encourage design accuracy. The price of the actual construction work will be mutually agreed upon by the several prime contractors and the owner based upon the model. A great deal of confidence in the model is required to allow this type of agreement. Generally, contractors assume that there will be errors and confusion on the site and add a contingency to their price for absorbing the risk of poor productivity. This contingency will not be included in the price with the owner because it is assumed that the model will accurately reflect what will happen.

The owner and the construction manager are closely involved in the process to be a resource for the trade contractors as they detail the work in a finely planned and efficient manner. The IPD is more conducive to this level of collaboration in the design process. An extremely high level of trust in other trades and the owner is needed because the accuracy of the final model is dependent on the skill of each of the contributors.

Raymond and the design team on the IPD are modeling the project through five dimensions. Because time and cost functions are included in the model, each of the team members can have greater confidence in the constructability of the model and the business plan of the project venture. The risk of the design is born by the designers, including Raymond, but the cost of doing this work early before the construction starts is borne by the owner, such that the owner is poised to receive the benefits of clash detection and appropriate design strategies through reduction of change orders. The owner anticipates spending 3-4 percent more using detailed BIM than by typical 2-D plans, but expects to virtually eliminate change orders due to inadequate plans. The owner is very sophisticated and knows that changes on this type of project usually amount to 10 percent of the total project costs. By spending the additional money at the beginning of the project on planning, the owner anticipates a net 6 to 7 percent savings on the project costs. Furthermore, they anticipate schedule reduction and a more streamlined, less painful, construction process. There are very few projects which are detailed to this level and in this manner with the builders actually modeling the work they will perform. All members look forward to the learning to be gained concerning project productivity of field labor.

5.8.2 Observed Consequences of Using BIM

The exact productivity rate increase, and thus savings due to BIM usage, is not known internally to Raymond. Therefore, they do not know for sure what the return on modeling a project is. They are looking at the information available from various projects to evaluate when it is appropriate to BIM. Ashish Peters, the BIM director for Raymond and Kim Lorch agree that projects that are modeled go better than those that are not. They see the following benefits:

- When Raymond is involved in the BIM coordination, the RFI in the field are greatly reduced and usually eliminated. The RFIs that do occur happen earlier and informally, during the design phase. The requests for clarification are issued before field personnel are situated in the field attempting to install work based on an imperfect plan.
- Re-work is reduced on projects that employ BIM. Raymond keeps records concerning the amount of time wasted in the field due to rework and plan conflict, but only when the delay or extra work results in a change order. If loss of productivity does not appear to be billable, the time spent standing around, waiting for direction, or trying to figure out what to do due to poor planning is not recorded by the field labor management.
- Although Raymond does not know precisely how much time is spent in non-productive activity as a result of a lack of proper coordination or scheduling, they do know that the number is significant and preliminary experiences indicate that BIM usage decreases the non-productive field time.

The greatest benefits to field productivity are realized in complex projects such as hospitals, casinos, and high-level finish jobs. This is due to the coordination with other trades more than the detailed planning of their own work.

5.8.3 Challenges of Using BIM

Raymond does not feel comfortable with their understanding of the exact costs and benefits of BIM due to lack of sufficient data on comparable projects. They know how much they spend but do not know exactly how it affects their field productivity. There are various factors besides BIM usage and they are not sure which ones have the greater impact. BIM projects have tended to be more complex so they can only compare to other complex projects that tend to suffer from productivity problems. Not knowing the cost savings keeps Raymond from feeling confident in their decisions on when and how much to model on a project by project case.

The limited number of BIM-capable employees and engineers make modeling each job impractical at this time so they need to feel confident that they are spending their BIM dollars wisely. Until they are afforded more opportunities sponsored by the owners in which they can gain better understanding of their modeling costs and resultant effects on their productivity and profitability, they will be hesitant to make more commitments to BIM without outside pressure.

5.8.4 Conclusions

The cost of modeling can be more than the perceived savings when the project is very typical and when coordination with other trades is not performed. Mr. Lorch thinks that the benefits gained from planning their own work is not enough to warrant the modeling effort because they have an effective planning system and understand their work very well through years of successful work in the trade and legacy systems understood by operations. The benefits of BIM are realized when their models are coordinated with others, specifically, MEP. Most of their re-work and non-productive time is a result of MEP conflicts in the field. They feel that the bigger benefit may be for others, but even reducing the MEP's conflicts helps Raymond to be more efficient because they do not have to tear out installed work nor do they have to move from one area to another in a less than optimal way due to field conflicts. Any coordination work done prior to field work reduces RFIs, re-work and change orders.

5.9 Qualitative Summary of Case Study Findings

Benefits of BIM usage in the design and construction process vary based on the perspective of the stakeholder. Each member of the construction process claims that BIM is advantageous to differing degrees, but each finds savings in different ways. Any one member "bimming" may find advantage for their own operations, but only limited results are generally reported if each member does not contribute to the process. The ability to rely on the entire team to perform its planning and coordination functions is crucial for the success of the process. BIM is very dependent on synergistic relations and is a process where the whole is greater than the sum of the parts.

Benefits common to BIM users included in the case studies include:

- RFIs on BIM projects were decreased from 50% to 100%. Owners and general contractors observe this to be a huge savings in process time and administrative savings. Trade contractors tend to cite the field labor advantages when their laborers do not have to wait for instructions or spend time solving conflicts or re-mobilizing to different areas.
- Re-work is reduced dramatically on BIM projects. Owners notice that this reduces their change order time and speeds construction. Contractors see labor savings with less re-work.

- Change order frequency and costs are significantly lower on BIM projects – generally eliminated in the terms of plan conflicts. All parties attribute this to coordinated plans that eliminate confusion in the field.

Stakeholders who claim to have success in their BIM practices report the following:

- Earlier involvement of the contractors in the design process,
- Owner involvement and support of BIM expenditures as an integral part of the design process.
- Regular, structured coordination meetings with the architect present.

Stakeholders that held reservations concerning the value of BIM usage, either conditionally or entirely, indicate the following:

- Competitive bid contracts for the general contractor made BIM usage unprofitable. Competitive bid contracts for trade contractors reduced the amount of savings to the owner in terms of BIM.
- Complex existing conditions made modeling impractical because of the difficulty of obtaining reliable information on existing situations.
- Securing personnel that can operate BIM programs, understand field work and manage the BIM process is difficult. More so than software training, the weakness is in process understanding.
- The owner and/or architect will not give models or support for contractors to model the work.

- Because of differing factors, exact productivity rate changes and profitability rates are elusive. Firms that track their costs tend to be more interested in using BIM more aggressively.
- Reliance on other parties for correct information on the model is worrisome. In cases where they have had to rework because another party did not model correctly, there is lack of trust in the system as well as team members.

Stakeholder's interests varied:

- Owners observe that the reduction in change orders and a more reliable schedule are valuable to them. The owners who are keeping their buildings for their own use are interested in getting accurate models, but more interested in the proper design BIM fosters.
- General contractors that are doing DB or CM work are more interested in the coordination of trades so that conflicts are reduced. As RFI decrease, their management time can be spent on proper quality assurance. Rework avoided means that there are fewer complaints from the trade contractors and increased owner satisfaction. Increased ability to control schedule due to confidence in the plans is another important factor as evidenced by the increasing use of 4-D by general contractors. Contractors in the competitive bid market do not see a great need for BIM because they are not paid to prevent problems – just to build the plans.
- Trade contractors are interested in reducing idle time for their labor and minimizing rework. They are at risk for labor productivity and will expend resources to model their work for clash detection. This is the single biggest

benefit of BIM for contractors – reduction of conflicts so that they can build more efficiently. Prefabrication is another advantage made available through BIM. It helps reduce accidents, increases efficiency, and reduces labor time in the field where it is more likely to be less controlled.

Each case study participant experienced challenges in implementing BIM. Success of the project was determined by the way that the project team dealt with those problems. The early BIM adopters tend to report less of a problem with learning the system but also tend to indicate that the learning curve is longer. Later adopters tend to be concerned about the steep learning curve but also report that it is shorter. The contractors that evaluate their own operations and make adjustments to meet BIM management processes found much more success with BIM in their projects. Contractors that have gone through the BIM learning curve do not bemoan the process but those who have not experienced successful BIM implementations cite the learning curve as a stumbling block. Those project teams that focus on the BIM process more than on the BIM software reported greater savings due to BIM usage.

A significant finding is that nearly all participants in the case studies and surveys would not or could not share specific productivity change values. A few participants shared numbers on a specific job with narrowly defined criteria, typical responses are “an improvement,” “better,” or given as a range up to 30%, and with a caveat such as “when we have a good team.” Many say only that there is a reduction in conflict. Several contractors and owners said that they would not share the information even when confidentiality agreements were offered. However, the most common response to what the productivity change is was that they are not sure as to what the productivity difference is. Most BIM projects have been completed on challenging buildings so that contractors are hesitant to compare them directly, but the fact that most contractors do not even know their rates on normal projects indicates that the problem does not originate with the implementation of BIM, but it is rather a question of understanding their own operations.

5.10 Quantitative Summary of Case Studies and Interviews

Data collected during the interviews and case studies showed positive results based on BIM usage, but because the various cultural and operational differences of the firms and interviewees, a consistent numerical reporting system was challenging. Nearly all firms were apprehensive to give exact numbers or did not know them. The approach of this study was to discover the perspective of managers who understood the construction, rather than design side of the process. Input from one owner and three executive level managers were included to illustrate varied views of how BIM affects the construction process. The persons and firms interviewed and studied are listed in Appendix A. Because a majority of contractors requested anonymity, their information will be included only in the appendix and the data that has been compiled and included in this section and in the discussion of findings will be arranged randomly rather than by alphabetical or other systematic method.

5.10.1 Evaluation at the Project Level

Eleven projects were studied in order to determine how the KPI results varied based on various project management criteria. The criteria evaluated were:

- Project type – the projects are grouped into one of four types of buildings: educational (one high school and three university), office (including medical offices), hospitals, and medical process (research laboratories).
- Project size – in millions of dollars, ranged from eight to 231 millions.
- BIM experience – on how many prior projects the team had utilized BIM. This can include institutional learning.
- Experience in project type – the number of projects the team has completed which are similar in nature to the studied project, regardless of the use of BIM.
- PDM – projects were classified as either a DB, CM (either at-risk or design-assist) or DBB. The sole DBB project here was operated like a CM at-risk project for all intents and purposes, however.
- BIM expenditures – amount of money spent by the contractor reporting the project information. This figure is converted to a percentage of contract value.

These variables were compared to the number of RFI and change orders experienced on the project after converting the number to RFI per $10 million of contract value for ease of comparison. The results are shown on Table 1 and they are discussed in the next chapter.

	Project Type	Size ($M)	BIM Exp	Type Exp	PDM	BIM cost ($1K)	BIM cost (cont %)	# RFI	RFI/ $10M	CO	CO/ $10M
1	Educational	15	1	2	CM	42	0.3%	52	35	7	4.7
2	Office	32	1	5	DB	100	0.3%	28	9	2	0.6
3	Hospital	107	2	5	DB	440	0.4%	300	28		
4	Hospital	231	3	8	CM	1000	0.4%	291	13	9	0.4
5	Office	120	2	5	CM	650	0.5%	32	3	1	0.1
6	Med. Proc.	145	1	4	DB	800	0.6%	137	9	2	0.1
7	Educational	61	2	4	CM	500	0.8%	21	3	3	0.5
8	Hospital	8	1	3	CM	75	0.9%	25	31	1	1.3
9	Educational	78	3	2	DB	800	1.0%	17	2	3	0.4
10	Educational	42	3	3	DBB	550	1.3%	11	3	2	0.5
11	Hospital	96	5	4	DB	500	0.5%	4	0.4	0	0.0

Table 1- Results of eleven projects completed using BIM for coordination to varying extents.

5.10.2 Numerical Evaluation of Case Studies and Interviews

The survey attempted did not produce significant enough quantities of data for evaluation but the questionnaire format was used as a basis for conducting interviews with practitioners of BIM. Rather than a project level approach, these interviews and case studies focused on the impressions and experiences of the users of BIM. Of the 17 parties included in the findings, one is an owner, eight are GCs or construction managers, five are trade contractors and three are GCs but were evaluated from their perspectives as either concrete or framing trade contractors. The results of the eight case studies and of the nine interviews are shown in Table 2.

The interviewees were generally apprehensive to, or unable to provide numbers to evaluate BIM performance. A scale of 1-5 associated with their perception of how strongly BIM affected certain results was difficult because those interviewed were unsure of how to respond or hesitant to quantify results. The results of the eight case studies and nine of the interviews were reviewed and a numerical rating to each of the following statement was interpolated from the response of the interviewee:

- BIM usage brings about significant reduction in the number of RFI on projects.
- BIM usage causes a reduction in the amount of change orders on projects.
- BIM usage reduces the amount of rework and field personnel idle time.
- BIM has a positive effect on the schedule accuracy and speed.
- The BIM process increases field productivity rates.
- The shop drawing process is shortened and simplified by BIM usage.
- BIM enables greater levels of prefabrication such that overall project costs are diminished.
- Quality of the finish product is enhanced through the use of BIM by contractors.

Each of these Likert items was assigned a numeric value based on:

1. Little or no positive impact
2. Some impact noticeable but not necessarily important
3. Apparent impact but not certain of net outcome
4. Very noticeable impact and a positive effect on the project
5. Very significant impact and important to project success

Assigning a number to each question for each firm was not possible due to a lack of response by the interviewee or because conflicting information. In these cases, a response was not recorded so that the results would not be biased. The Likert score is given for each respondent. This number is a statement of how strongly BIM affects productivity indicators.

DEGREE TO WHICH BIM IMPACTS PERFORMANCE

(Likert Items: 1=no effect, 5= great effect)

	Stake-holder	RFI	CO	Re-work	Cont Cost	Sched ule	Pro-ductivity	Shop Draw	Pre fab	Qual -ity	Reported Scale	RFI %
1	Owner	5	5	3		4				4	4.20	90+
2	GC	5	5	5	5	4	4			5	4.71	90+
3	GC	4	5	5	4	3	4		4	4	4.13	50+
4	GC/Conc.	3	3	2	2		2		2		2.33	50
5	Elect	4		4	4	2	2	4	4	4	3.50	
6	Mech.	5	4	5	5	3	5	5	5	5	4.67	90+
7	Mech.	2			1	1	1	2			1.40	
8	Frame	5	3	4	3	3	4			4	3.71	
9	Plumb	5		5			4	5	4	4	4.50	
10	GC	5	4	4		4	5	5	4	5	4.50	80+
11	GC/Frame	5	5	4	4	4	5	5		5	4.63	90+
12	GC	4	3	4		3		5			3.80	
13	GC	5	4	3	3	4		4		4	3.86	85
14	GC	4	3	4		4	4	4		4	3.86	
15	GC	4		4	4	4				4	4.00	-
16	GC/Conc.	5	4	5	5	4				5	4.67	-
17	GC	5	5	4	4	5	4				4.50	-
	Average	4.4	4.1	4.1	3.7	3.5	3.7	4.3	3.8	4.4	3.9	

Table 2 - Likert item evaluation of the effects of BIM on productivity KPI.

Eight of the 17 participants were able to provide a numeric value of the reduction of RFI. These were compared against the Likert item response for RFI but no strong correlation was found. The principle type of contracts performed by the participant and the method whereby they manage the coordination process with BIM were also included in order to determine which method produced higher values of influence.

Chapter 6: DISCUSSION OF FINDINGS

6.1 Introduction

The purpose of this research is to determine how much effect the use of BIM has on field productivity so that expected productivity rates can be estimated or BIM projects. Owners and contractors collectively do not appear to know the extent of the savings at the project level once BIM is implemented. The uniqueness of construction projects makes it difficult to evaluate precise quantitative variations as a result of specific actions and conditions of specific projects. Due to the newness of BIM, little historical data is available. Consequently, cause-effect relations of specific management choices concerning BIM usage are not known. Another significant problem in calculating construction productivity changes is that many contractors cannot identify their productivity rates on typical jobs, let alone BIM projects. Following is an evaluation of the data obtained:

Initial Surveys and Research: From the initial surveys and research, it was apparent that nearly all contracting firms were not open to publishing their productivity rates. Therefore, factors that were anticipated to indicate overall project productivity were sought. The contractors were reserved in supplying much of that information as well, but sufficient data was collected that would allow interpretation and comparison based on industry standard research. Nearly as revealing as the data gathered, was the data that was not able to be collected.

Case Studies and General Survey: Evaluation of the case studies and general survey of BIM usage performed on 47 firms has revealed factors concerning the state of affairs concerning trends and results of BIM practices. Each case study is used to show best practices and individual lessons learned. These serve to illustrate industry trends revealed by the larger sampling of industry members.

6.2 Target Data Collected

The research, both interview surveys and case studies, focused on data needed to calculate productivity increases. Because the vast majority of contractors in the pilot study showed extreme reluctance to sharing actual project productivity numbers or overall savings to their project costs, the research was directed toward the leading indicators of field efficiency: RFI, rework, change orders and schedule compliance.

6.2.1 RFI Reduction

The number of RFI on BIM projects was drastically reduced by over 90% from what would be expected on a similar project without the aid of BIM. This marked improvement is due to the reduction in clashes in the field between the various trades' work. Normal planning using overlays of 2-D drawings does not communicate the numerous instances of interference. Three contractors in the case studies claimed that there were probably more RFIs on BIM projects but that they occurred informally during the coordination phase rather than in the field. This had the effect of reducing RFIs encountered in the field. Mechanical contractors cite the greatest advantages to the reduction in conflict, followed by plumbing and electrical. The RFI reduction numbers are based on field RFI but the general contractors that had performed at least three major BIM projects reported that RFI in general decreased because the planning not only reduced field conflict but revealed design issues that would impact the facility user.

These were addressed during the detail design phase so that the owner did not need to wait until the building was taking shape before being able to visualize the physical space and then see the need to change the building plans.

Section 2.7.1.5 showed that the cost of an RFI averages $425 for administration of the process for the construction team. It was also determined that the average CM project experiences 155 RFI per $10 million, or 0.65% of total project costs. The findings from this research indicate an arithmetic average of only 10 RFI/$10 million (M) on projects that utilized BIM to any degree. The range was from 0.4 to 35 RFI/$10M on projects that ranged from $8 to $231 million with an average of $85 million. As discussed before, the RFIs still occur on BIM projects – they just take place earlier and quicker, as part of the design process, and cost very little. RFI reduction represents approximately a 0.65% savings in the administration of the project. Field productivity savings are much more significant and will be discussed later.

The type of PDM made a difference in the amount of RFI on the project. DB projects average 10 RFI/$10M while CM projects average 17, as shown in Table 3. Only one DBB project reported enough numbers to be evaluated and it had the lowest rate of all types at 3 RFI/$10M. This number is representative of only a portion (structural concrete work) of the project and is suspected to be incomplete because the MEP RFI and processes were not included. The author was

	RFI per $10 M	
	Design-Build	**Const. Mngmt.**
Educational		34.7
Educational	8.8	
Educational	28.2	
Educational		12.6
Hospital		2.7
Hospital	9.4	
Hospital		3.4
Hospital		31.3
Office	2.2	
Office		
Med. Proc.	0.4	
RFI by PDM	49	85
RFI/$10M	**10**	**17**

Table 3 - The number of RFI is significantly fewer on DB projects than on CM projects. Data from Table 1 in 5.9.1.

not able to contact the person who represented those numbers on follow up due to the interviewee's change of employment.

The relationship between the amounts of money spent on BIM as a percent of project costs was not significant. The trend is that the more money is spent on BIM, the lower the number of RFI are produced, but there were several exceptions and the best fit equation, y = (-10.1)ln(x)+6.782, has an R-squared value of only 0.154 which is insignificant, as show in Chart 1. The average expenditure is approximately 0.5% and decreases slightly with repeated use. The outlier in Chart 1 is 31 RFI/\$10M. If it is removed, there is a greater correlation between the data, but I found no reason to discount that data point.

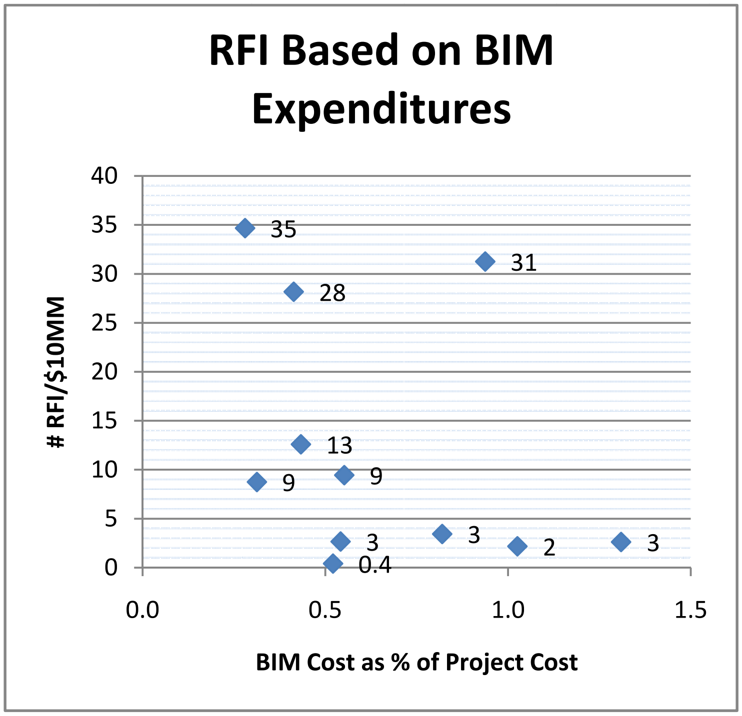

Chart 1- Number of RFI as a function of expenditures of BIM in terms of percentage of project contract value.

The case studies revealed that there are several instances where the owner invests 4-5% of the project costs on BIM. Sutter HealthCare in California is a leader in this process. They assemble the construction team early to model in great detail so that realistic construction targets may be set and contracts awarded based on the ultra-accurate information available to the constructors. The constructors in these situations are ideally the same entities that participated in the design but there are some cases where there was a switch part way through the design-construction process. These projects are not completed yet so that the outcomes are not included in this study.

The number of BIM projects completed by the key members of the project team appears to have the strongest correlation to the number of RFI on the project. The R-squared value is .614 on the best fit equation of $y = (-0.71)\ln(x)+3.503$. As can be seen in Chart 2, the numbers of RFIs diminish as the manager's experience with BIM increases from 1 to 3 projects. This supports the observations made in four of the case studies that the learning curve for using BIM is between one to five projects, depending on type and technical skills of the operators.

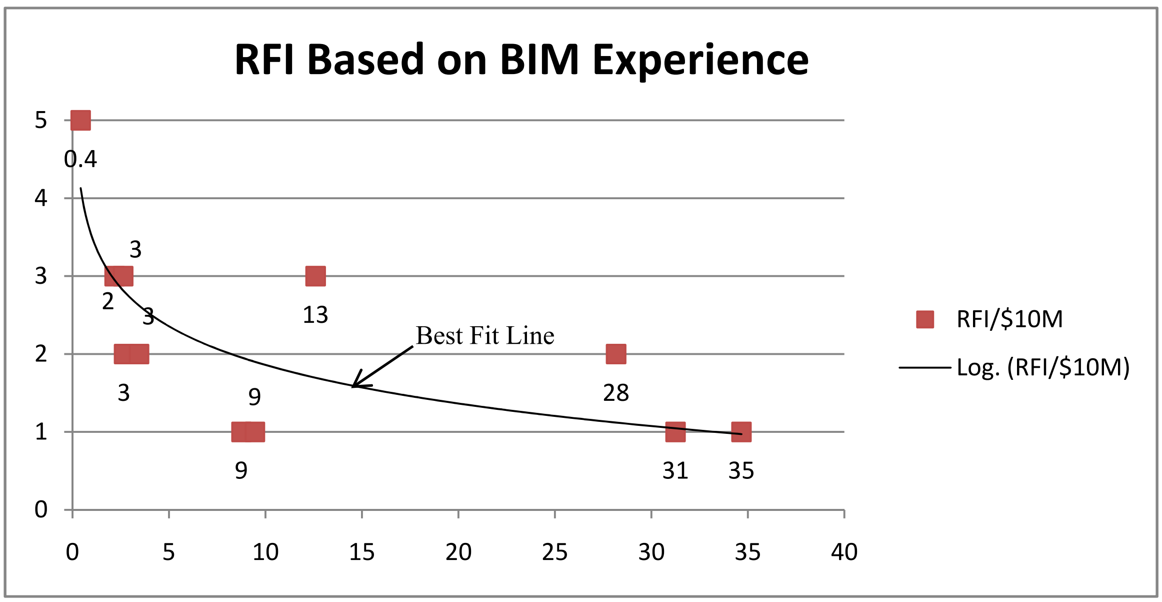

Chart 2- RFI as a function of project team BIM experience.

The last relationship measured on RFI was that of the team's experience on that *type* of project, independent of the number of BIM projects completed. As shown in Chart 3, there is little correlation on this data set but it is interesting to note that two of the projects were being done by teams with only one prior project of the type they were building and they had the highest (35) and second to the lowest (2) numbers of RFI on their project. It is suspected that team members with more experience running a project may decrease time spent on planning because they personally know the construction process.

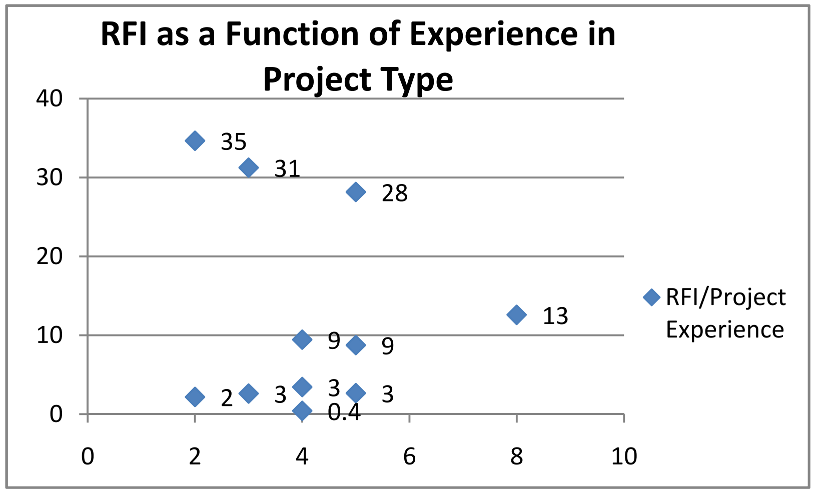

Chart 3 - Number of RFI based on the number of projects completed by the team of the same project type. No correlation observed.

6.2.2 Rework Due to Field Conflict

Rework was nearly eliminated on projects as reported by MEP and Framing/Drywall contractors. Every general contractor studied observed that the amount of rework, as well as the time that field labor spent standing idle, either waiting for instructions or attempting to figure out field logistic problems, was dramatically lower for the trade contractors. According to the majority of trade contractors, rework is reduced to just a few percent of labor costs or lower.

During this study it was found that 79% (37 of 47) said there was "very little rework and standing around time" when BIM was used for coordination. Thirteen percent (6 of 47) said that there was improvement but were not sure of the amount. The remainder said they did not know or could not say. None of the respondents returned an hour or percentage savings, so in order to more closely define "little rework," ten projects were investigated more closely concerning rework. The results, illustrated in Figure 11, ranged from 43 hours on a 25,000 man-hour project (less than 0.2%) to about 500 hours on a 13,000 man-hour project (3.8%) with an average rework rate of nearly 1.56% of project costs. Four of the responses were reports based on time reports from the field while 6 were estimates generated by the managers on the project. The four contractors who knew and reported the *actual* number of hours of rework performed gave rework percentage rates of 0.6% with an average deviation of 0.4% (350 hours of rework on 58,000 hours of work). Respondents who gave *estimated* amounts of rework averaged 1.9% rework with an average deviation of 0.7% (1560 hours of rework for 79,000 hours of project work). Figure 12 illustrates that the firms that used estimates gave a higher rework rate than those that monitored their labor costs on rework. It is unlikely that the contractors with lower rework rates were desirous to overstate their numbers given the tendency for contractors to protect their productivity data. Greater accuracy in

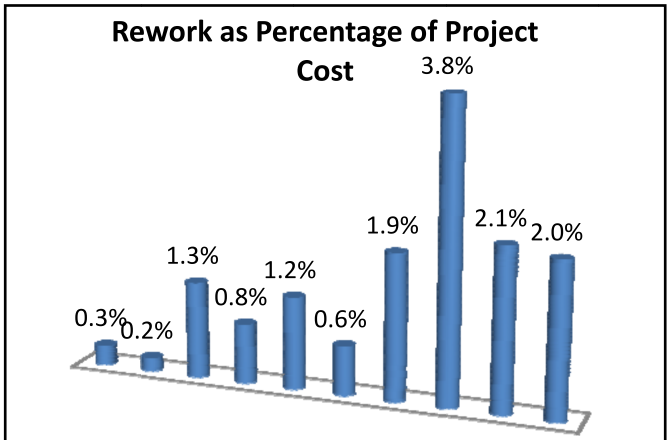

Figure 11- Rework performed by contractors on ten projects. This is a representation only.

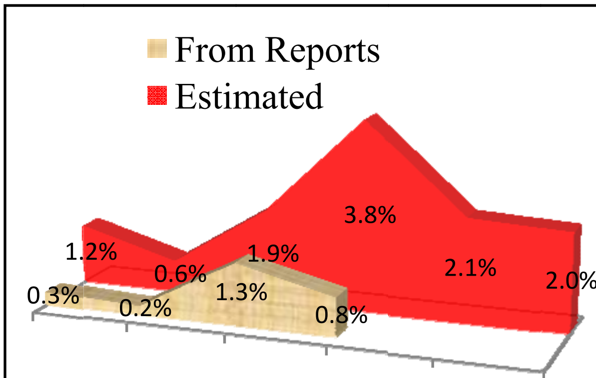

Figure 12 - Participants that estimated rework costs rather than obtaining them from field reports reported higher costs on average. This comparison is illustrative only and does represent relationships between projects.

reporting is an indication that the firm is monitoring their activity more closely in order to understand and improve their internal operations (Deming, 1986; Young, 2008). Section 3.3 discusses the finding that firms that measure ROI tend to report higher ROIs. The material costs on the rework on BIM projects were, in all cases, considered negligible by the reporting companies. The amount of improved rates was greatest for the mechanical contractors, followed by electrical, plumbing, framing, and structural. Compared to the industry standard of 12% of contract price being spent on rework (direct and indirect costs), as reported by Irani (2003), this represents a 10% reduction in time spent repairing problems. *Based on these findings, 10% fewer hours would be spent completing the contract work.* This number corresponds to the amount of money that many of the contractors add to their lump sum bid to account for discrepancies in plans and lack of coordination.

6.2.3 Change Orders

Change orders due to errors and omissions and to field conflict based on incomplete plans were reduced dramatically. Owners claimed that change orders on BIM projects are reduced to virtually nothing for field coordination issues. In one case, an owner faced a 16% increase in contract price but did not dispute the extra charges because BIM was used to show that the costs were scope changes required by the hospital rather than poor planning or coordination between the MEP trades and structural/framing contractors. In cases of higher owner involvement, the change orders for conflicts are less than 1%, but generally close to zero dollars. For the two cases in which the contract type was lump-sum based on a competitive bid, the change orders were "a few percent" rather than the typical 12% for this type of project for a school district (Sacramento Bee, 2009).

The 12% refers to the total amount of changes, not just due to plan conflict so that it does not follow that 10% of project costs were saved due to BIM. However, considering that the typical project has 2-5% of change costs due to plan conflict, there is still a noticeable savings of 5 to 8%.

In addition to the changes saved by reducing the design conflicts, the contractors and owners claimed that change orders were drastically reduced because the owner's intent was better represented in three dimensions so that the owners (users) and builders communicated more efficiently and thus created models that represented what was needed. Owners in the survey believed they saved 4-7% of project costs because of the non-issuance of change orders. Sophisticated owners of projects researched in this study are becoming more involved in the design process and investing money into the BIM process because they feel the investment will save them money because of better design and also because of the elimination of changes due to design issues. Two experienced owners (Sutter Health Care referenced in the Hunt case and Disney discussed in the Southland Industries and Raymond cases) were spending 4-5% of the project budget on BIM, expecting to eliminate the changes orders that would typically amount to 10% on those types of projects. This is a net savings of 5-6% on change orders alone.

6.2.4 Schedule Compliance

Schedules were reported shortened and followed more accurately when BIM was utilized. The Layton case (5.2) discussed two similar healthcare projects – one utilizing BIM and the other, not. The BIM project was 11% ahead of schedule while the non-BIM project was 8% behind schedule. Another general contractor, Hunt, reported in their case study (5.3) that the hospital they had just completed ran 6 months over original schedule due to additional work required by the owner, but the CM/GC felt the project was successful in terms of schedule. By using 4-D modeling they were able to reduce errors in the field that would require rework, prepare materials and layout better with the models, and prefabricate more components in order to reduce field construction time requirements. Target reported (5.1) that schedules were more accurate and shorter but just started measuring exact results. As is common when discussing BIM savings, the owners and contractors tend to measure savings in terms of what was avoided rather than what was saved.

In addition to forward scheduling, BIM can be used to justify actions and show logic in site set-up. One general contractor (Hunt case 5.2) used the 4-D schedule to determine the best way to stage its own work with consideration of public access constraints and events scheduling at a stadium. They also showed the owner that delays in the schedule after the owner changed some work requirements in a hospital project were justified and needed. This appears contrary to the teachings of the teamwork and quicker schedules made possible by BIM. It does, however, follow the mindset of the general contractor who makes money by the traditional contracting methods by controlling productivity factors as much as possible and then charging for work strictly outside the contract documents. Even though the hospital project ran six months long, the contractor and owner both felt that 4-D scheduling was a benefit to the project.

The greatest schedule advantage of BIM usage, based on the Southland Industries case study, is the ability to more accurately predict how long the parts will take to be assembled in the field because trade contractors do not need to add excessive “fudge factors” to compensate for unknowns. The ability for the GC to control the construction process with tight schedules is enhanced by BIM, as two of the GCs (Layton and Hunt) related in the case studies. The Southland Industries case further supports this by praising Hensel Phelps' detailed scheduling practices as an advantage to the trade contractors' field personnel productivity rates. Six of the eight case studies in this thesis indicate that 4-D BIM usage is increasing in popularity with GCs and owners and is treated less suspiciously by the trade contractors as they observe the benefits of tighter schedules. Several trade contractors in the interviews and case studies expressed disdain for the tight scheduling because they felt constrained to produce per the aggressive schedules, but the majority found the tight scheduling beneficial when based on the models that the trade contractors helped to develop (Southland Industries case study). BIM was reported to be an effective tool for scheduling because the durations and relations are created from the models made by the trades. Therefore the trade subcontractors feel more comfortable committing to schedule durations.

Three of the contractors in the case studies mention that pull construction techniques were used so that rather than merely reducing the task duration, the reliability of the scheduled task duration increased. This was accomplished by breaking the tasks and material packages to smaller segments so that there is less variation in achieving tasks. More detailed schedules based on accurate models make the process smoother. Smaller work packages mean that there is less material sitting on the project so that there is more room to work and there is generally less anxiety about who will have what space at the site. This makes work for the trade contractor laborers easier because they can focus on installation work more than on site and material management logistics. Each trade contractor in the case studies cited this tighter schedule ability as an advantage of

BIM but Dr. Sanvido in the Southland Industries case indicated that the detailed schedule that was accurate (not just faster) was absolutely required to gain the increases in field productivity available through BIM usage. Four contractors who participated in the interviews and case studies used Last Planner to some extent and three more indicated that they used pull flow or JIT to manage schedule. Two of the firms using Last Planner and one of the firms doing pull flow reported using 4-D to model to varying degrees. No significant difference was observed between the firms that used BIM *and* some variety of pull flow and those firms that used BIM but not use pull flow methods. The varying levels of experience at 4-D and the small sample size do not support conclusions as to the amount of impact 4-D scheduling has when used as part of pull flow, but in each case where pull flow and 4-D were used, favorable results were reported.

An exact number for schedule acceleration or reliability was not discovered, but 6 of the seven contractors and the owner included in the case studies said that the projects went faster with BIM. Eight of the nine interviewed contractors also indicated that the schedule improved as a result of BIM. The reasons given for time savings were the increase in productivity due to reductions in clashes between trades, more precise scheduling made possible and prefabrication of components. The results of BIM benefits to schedule are related to other factors such as general contractors implementing a productivity improvement method such as Lean Construction, Last Planner or “pull construction.” This study did not separate the effects of 4-D modeling from these other planning techniques. The principle schedule benefits gained by using the BIM process are less rework, quicker layout, increased prefabrication and detail scheduling capabilities.

Contractors that would comment on the amount of schedule change felt that there were savings of 5% to 10% based on the advantages listed above.

6.2.5 Productivity Gains

Productivity rate increases could not be obtained directly due to reasons discussed earlier in this thesis, but KPI indicative of overall project productivity rates evidence that there is a marked improvement in productivity rates. The Likert scale approach explained in section 5.10.2 (see Table 2) is used to quantify the level of agreement that interview and case study participants had in regards to KPI and productivity rates. As can be seen from Table 2 and as summarized in Table 4, the average agreement that RFI are greatly reduced by BIM usage is 4.4 on a 1-5 scale. The average Likert scale, or average of each Likert item, is 3.9 which indicates that users give BIM an significant impact on operations.

DEGREE TO WHICH BIM IMPACTS PERFORMANCE
(Likert Items: 1=no effect, 5= great effect)

Stake-holder	RFI	CO	Re-work	Const Cost	Schedule	Productivity	Shop Draw	Pre fab	Quality	Reported Scale
Average	4.4	4.1	4.1	3.7	3.5	3.7	4.3	3.8	4.4	3.9

Table 4 - Average score on productivity KPI for each Likert item.

As shown earlier in this thesis, the first three KPI – RFI, change orders, and rework/idle time – are the most measurable and indicative of field productivity rates. These three were evaluated and compared to the respondents' perception of BIM's effect on productivity rate improvement. As can be seen in Table 5, the perception of improvement based on the three leading KPI, averaged at 4.12 out of 5, is higher than the perceived effect on productivity, average of 3.67. The difference of 0.44 on the 5 point scale represents a 13% variation. A difference between the two figures is expected given that AEC members are hesitant to publicize productivity rates and that the majority of

Likert Evaluation of Leading Productivity KPI and Productivity Rate Comparison

BIM usage effects on:
1 = no or little effect, 5= significant and meaningful effect

`	Stake-holder	RFI	CO	Rework	KPI Scale	Productivity	KPI-Prod Diff	% Lower than KPI
1	Owner	5	5	3	4.33	-	--	-
2	GC	5	5	5	5.00	4	1.00	20%
3	GC	4	5	5	4.67	4	0.67	14%
4	GC/Concrete	3	3	2	2.67	2	0.67	25%
5	Electrical	4	-	4	4.00	2	2.00	50%
6	Mechanical	5	4	5	4.67	5	-0.33	-7%
7	Mechanical	2	-	-	2.00	1	1.00	50%
8	Framing	5	3	4	4.00	4	0.00	0%
9	Plumbing	5	-	5	5.00	4	1.00	20%
10	GC	5	4	4	4.33	5	-0.67	-15%
11	GC/Frame	5	5	4	4.67	5	-0.33	-7%
12	GC	4	3	4	3.67	-	-	-
13	GC	5	4	3	4.00	-	-	-
14	GC	4	3	4	3.67	4	-0.33	-9%
15	GC	4	-	4	4.00	-	-	-
16	GC/Concrete	5	4	5	4.67	-	-	-
17	GC	5	5	4	4.67	4	0.67	14%
				Average	4.12	3.67	0.44	13%

Table 5 - Likert item scores are higher for three indicators than for productivity rate item. This result is expected due to the tendency to understate or not understand true productivity levels.

contractors do not know their actual rates. These numbers to not translate directly to productivity rate improvement but do give an indication of what contractors are experiencing. The responses are gauges of how significant an impact that BIM usage is having on construction and management processes. The overall project productivity is improved significantly according to these findings. The results of the Likert evaluation are fairly consistent with the exception of two of the participants. Table 6 shows the stakeholder type and the total Likert score indicate their view of how significant an effect that BIM has on productivity related indicators. The recorded 1.40 value on Table 6 is from a superintendent in charge of small, fast track projects in which BIM is not able to be used to the same extent as the larger projects. Interviews with members of the same firm, but that work on larger projects that are modeled, give a much higher evaluation of BIMs impact because the types of projects they work on are the types that benefit more from BIM usage. The next lowest value, 2.33, is from a contractor which had a BIM manager, but recently discontinued their in-house BIM management because their contracts are competitive bid, adversarial based delivery methods. They found it counterproductive to voluntarily spend resources to reduce conflicts virtually without pay when they would be paid extra to solve the conflicts in the field. This firm indicated that there were increases in productivity, but that unless the project was DB, there was little incentive to seek the savings available through using BIM. Removing these two contractors from the table increases the average score from 3.0 to 4.2. Additionally, their removal from the pool increases all Likert item scores, with the exception of schedule impact, to above a 4. This fact indicates that serious users of BIM

SIGNIFICANCE OF EFFECT OF BIM ON PRODUCTIVITY INDICATORS

Stake-holder	Reported Scale
Owner	4.20
GC	4.71
GC	4.13
GC/Concrete	2.33
Electrical	3.50
Mechanical	4.67
Mechanical	1.40
Framing & Drywall	3.71
Plumbing	4.50
GC	4.50
GC/Framing & Drywall	4.63
GC	3.80
GC	3.86
GC	3.86
GC	4.00
GC/Concrete	4.67
GC	4.50
Average	3.9

Table 6 - Significance of BIM on productivity indicators is generally perceived to be above 4 out of 5. The few outliers were not using BIM actively or were working competitive bid work for the government.

perceive it to be a greater effect on productivity related measures than those that only use BIM when required or are merely dabbling or experimenting with some of the BIM functionalities.

6.3 Target Data Not Obtained

The results from the "Questionnaire to determine BIM user survey," shown in Appendix B did not reveal the actual productivity rates. Some participants said that the information was not made public. Those contractors performing DB work exclusively were far more likely to provide numbers on savings than those that were involved in other types of contracting systems. Virtual elimination of rework was claimed by 16 of the 17 participants in the interviews and case studies (Diffenbaugh gave a low Likert item score because they felt that it was only a great advantage to the MEP contractors), but exact numbers were not known. In these cases it appeared that the contractors did not identify the rates because they only track rework when a differing condition or change directive caused them to record the amount of time that was spent tearing out and replacing materials as well as time spent performing additional coordination or solving conflicts in the field (see Raymond case). Since a large amount of time is spent trying to figure out how to piece parts together in the field, contactors add money in their bids to account for this – generally about 10% for trade contractors.

Sutter Health Care (Sutter), a large healthcare owner parted ways with the design assist CM manager and most of the team they had assembled to construct a hospital (from the Hunt case). The key issue was that the owner wanted more services provided without additional compensation. As Sutter completes more projects and financially supports BIM usage through the design phase, it has become more aware of the savings that are available due to the increases in productivity, especially at the field level. Contractors, especially the early adopters of BIM who have already invested in the technology and expect to make some profit by using it, are becoming even more wary of reporting productivity rates because they are the thing that contractors typically controlled to make profit. The general contractors and construction managers included in the interviews and case studies who do little or no self-performed work are less concerned about the rates because they make their money on managing the process rather than the construction, which is under the direct purview of the trade contractors. Both contractors and owners (see Target case) guard profitability numbers and BIM advantages because they consider it a competitive edge.

General contractors in this study were quick to point out that their subcontractors were seeing field productivity savings due to less idle time of the labor, but they were less enthusiastic about sharing their own field productivity increases due to better coordination even though they have direct control over the labor and should have access to the numbers.

6.4 Discussion of Management Choices

The project team cannot choose a productivity rate or other result, but they can choose to do specific tasks that increase the probability of the desired productivity rate. There are a few key management choices concerning BIM protocol; the combination of these decisions influences the success of BIM implementation. As with scheduling, some of these factors are more critical than others. Just as increased production on critical path activities shorten the project length, so do the most critical BIM factors have the greatest effect on the productivity of a project. The factors that were studied for their impact on productivity are: Project Delivery Method (PDM), project team selection, level of owner and architect participation in coordination process, coordination meeting format and frequency, type of BIM software, which entity models details, level of detail modeled, and whether models are included as a contract document.

6.4.1 Project Delivery Method & Team Selection

6.4.1.1 Effects of PDM on BIM Value

Much literature is devoted to the topic of team building and collaboration as part of the BIM process (see Kymmell, 2009). The focus of this research was not the study team dynamics, but it was observed that contractors on CM/GC and DBB projects reported that the "team" worked to solve problems. When the architect and owner become more involved in the coordination process, production is increased. In all the case studies and interviews, on DB projects contractors refer to architects as an integral member of the team. On IPD projects, the contractors viewed the owners and designers as members of the team. On DBB projects, however, the contractors did not include architects, engineers or owners as part of the construction team. The contract type seems to impact the spirit of teamwork. Team collaboration should not just be the contractors who design and coordinate their work but include designers and owners so that constructability and design coordination are not just a method by constructors to "fix" design errors. The importance of this idea does not appear to be realized by a majority of decision makers. There are great savings realized now from the conflict reduction and these savings are realized by the contractors in terms of productivity and reduced change orders to the owners. For further improvement in the efficiency of the design and construction process, BIM usage in an integrated team will be required from the owner as part of the program.

Whereas BIM conflict coordination is not typically done on competitive bid projects, one educational facility was bid and awarded to the contractor modeling the project in order to produce a more accurate bid. The contractor spent 10 times what normally would have been spent on a bid but gained enough confidence in the construction aspect of the building that they could price the project without as much of a waste factor for their operations. They were $10 million lower than the next bidder on their $103.5 million bid. This contractor wanted the project badly enough to invest time and money into the bid process, but still deemed that the project could be successfully managed and built more effectively than by using 2-D drawings.

This research indicates that if the owner of a prospective project were willing to pay contractors to model the building, they would they get lower bids. Findings from this research, as shown in Table 2, reveal that 0.5% to 1.0% of project costs are being spent by contractors on modeling. If the owner in the educational facility project mentioned above would have paid three bidders to model the project, they would have paid between $1.5MM to $3MM to the contractors performing the modeling. The contract price from the contractor that estimated based on a model was over 10% lower than the non-modeling companies. If competitive pressures force the contractors to reduce even more, the price could descend even lower. Even if the price were only 10% less, the overall savings would still be 7%-8.5% depending on the level of modeling required of the contractors. Owner can invests money up front in BIM processes by providing bidders with models, paying for bidders to model or requiring bidders to model prior to bid. This investment increases contractor's knowledge of the project processes, thus their contingencies or "waste factors" can be decreased.

The issue of who gets the money saved from productivity gains is raised here. The party which takes the risk of making the model should be rewarded with the savings. On the DBB education facility project mentioned above, the GC that got the job did the investment of BIM. They were awarded the project and attributed the cost to marketing. Their ability to bid at 10% lower than their competitors was based on the large reduction in waste – in terms of rework and lower productivity - to the order of 20% to 30% which would lower their overall costs by 10% or more. This case is one of the few DBB projects that the GC was willing to model a project without a reasonable assurance that they would likely be awarded the contract. A majority of contractors indicated they did not model extensively until they had a project in the competitive bid market. Most DB contractors indicated that they modeled projects to some extent in order to be awarded the project. Impressing the owner with their technical ability and them gaining confidence in their own ability to build the structure were both factors in the decision to model prior to award of contract.

One general contractor, Diffenbaugh, in the case studies (Section 5.4) said that they had discontinued the practice of modeling every project. They indicated the market had said they needed to BIM, but after putting forth a good faith effort, this same contractor indicated that the market dictated that they needed to BIM only when requested by the owner. Diffenbaugh found that spending money on modeling would reduce the change orders but that was the architect's job, not theirs. They said they were supposed to build, not design. With more owners desiring DB and BIM, they are using

BIM on those projects and have even looked at integrated systems. However, this contractor still performs these projects as CM design assist or DB with the architect in the role of BIM coordinator. The main reason BIM did not work for them was the fact that the architect did not work with them on the modeling and coordination process. This contractor believed that a DB contract would resolve many of the issues since the architect works with the construction team. Hunt and Turner are much larger contractors than Diffenbaugh, but their usage of BIM as a tool to fulfill owner requirements more than directly to improve productivity is similar. This study indicates that proper BIM usage involves open collaboration with the entire design/construction team and DBB does not appear to support that notion as it is contrary to the business model for contractors in that PDM. The IPD, on the other hand requires members to collaborate, trust and use BIM. This switch is difficult because it is cultural more than contractual. Dr. Sanvido observed that “contract jockeys” may be able to manipulate BIM into the contract, but if the process is contract driven rather than collaboration driven, the open relations of trust and confidence will not allow the savings that are available.

In DBB projects the building team is selected based on low apparent price. This type of selection criteria does not generally attract the contractors that are willing to invest in new technologies and processes. Based on the case studies and interviews, a vast majority of the contractors that have adopted BIM processes have done so in CM or DB PDMs because they are based on trust and qualification more than on beginning sales price. Companies that are focused on price competition have been less able to invest in new technologies or cost-reducing methods outside of an awarded contract in which money for the initial investment is included. In each of the case studies, BIM “failure” occurred when contractors had no support or incentive to model.

On IPD or DB projects, the owner is more likely to be more heavily involved in the coordination process. This involvement with the owner, architect and GC is more likely to produce a plan that is more effective for overall project productivity. In the CM PDM the MEP contractors are generally not brought into the process until the building design is done. At this point, the contractors become more interested in reducing conflict in order to increase their own profitability more so than a desire to increase productivity at the project level. The DBB PDM offers little incentive to a contractor to spend effort to reduce conflict in the field because they are paying to solve another party’s problems. Very few contractors have used BIM to some degree on a project and have said that it was not important or valuable to them. Only three of 18 parties interviewed in this study said they will not BIM again unless required by the owner. Five of the contractors said they would like to use BIM on future projects but will only use BIM when paid for by the owner. The interesting thing about this result is that those contractors who are less satisfied with BIM are all working in the DBB segment, with 4 of the 5 doing government work.

6.4.1.2 How and When to Choose Project Team

For most projects discussed during this research, the contractors assembled as a team after 2-D contract drawings were prepared. However, indications from the case studies are that the best time to begin modeling with the trade contractors is early. This stage of the design process has different names given by different contractors, but comes at the time when the schematic drawings are taking shape and the consideration to details of system design and components are being considered. In this ideal situation each of the trade contractors will know how they can best create their part of the building and can now design this in conjunction with the other team members. This is the ideal in the IPD arrangement. Very few have been done but seem to have been a success for the owners. Realistically, contractors are not in the business of design, but in the business of building. They are better suited to determine the means and methods, e.g. connection details, rather than system designs.

According to Dr. Sanvido in case study #6 (5.6), 50% of the cost structure is determined by the end of the conceptual design, and 75% by design development and the last 25% in the detail stage. The results of this research are that most successful teams start designing during the design development phase. In five of the eight case studies it was thought that at about 50% to 75% complete was the best time to bring the trade contractors in. One of the eight thought that bringing the team together prior to 50% was important and the other two stated that it depended on the case. Three reasons for this based on the case studies are:

1. The majority of contractors feel that their job is to build – not design. If there is not enough definition and planning done before contractors are brought into the design picture, the trades must wait for answers on big picture design elements. Most trade contractors are better at reading plans than at project outcome descriptions as a means of determining what to build. Allowing them to join the process when they can visualize their work is more efficient for them. Contractors performing more DBB work than DB type projects are more likely to want to become involved in BIM later in the design process – typically with permit ready plans. Contractors who do

primarily DB work want to become involved at the 50% or earlier stage so that they can have a greater say in the way their components are placed and coordinated.

2. "Too many cooks spoil the stew." The process becomes more democratic or discussion based so that it loses the efficiency of a select group of designers creating the building space and conditions. Without very strong leadership, the design of the building will be influenced by contractors who are looking at means and methods. If the building process becomes more important than the building product, it may be more efficient to build, but not so effective for the user. The design themes in a building may also be compromised if the team designing the building is too big. Those contractors that are brought in prior to complete drawings from the architect all agree that strong owner or architect involvement is needed.
3. Hunt, in case study #3 (5.3), observed that perhaps working with others on the design made the architects and engineers uncomfortable because they were asked to be involved in the means and methods part of construction. Architects do appear to be wary of becoming too involved in trade design because it is traditionally done by the trades. Each specialist has a way of working and detailing and the architect is not concerned with how a bolt is installed, rather what the finished product looks like and how it works. Architects need to be involved in the process of trade coordination, but more as a set of eyes ensuring that the design of the trades complies with the big picture requirements.

It was found that after three projects using BIM, the contractors were adept at the process (see Target, Layton, Hunt, Diffenbaugh and Raymond cases). Choosing a project team using contractors with at least this much BIM experience increases the likelihood of success. Experience in a project type does not have the same impact on project success as does BIM experience. As shown in Charts 2 and 3 (see page 212 and 213), the number of project RFIs did not strongly correlate to the number of projects a contractor had completed of that type, but did correlate with the amount of BIM experience the contractor had. Contractors want to plan the project and complete their work quickly and safely in order to make a profit, and they will cooperate with each other to accomplish this. Bringing a group of designers together and building a relationship of trust between them is the most effective way to start the teamwork. The details of these meetings were not discussed in the research but most contractors indicated that after a day or two, the teams knew each other well enough to 'put a name with a face' and work together properly (see Layton, Hunt and Southland Industries case studies).

Requiring the principle subcontractors to model their work and coordinate as a team was impractical in almost every project in which the construction team was selected primarily by low cost consideration. Due to the competitive scenario, general contractors or construction managers are typically constrained to use the low bid contractors, including MEP contractors and thus may not have the ability to do BIM coordination. In cases where modeling was done for clash detection RFIs, rework and change orders decreased. Even when the teams do not coordinate until after the plans are complete, there is still advantage to be gained. The response of the general contractors having been awarded projects is to require by contract that trade contractors model their work as a team just as on non-BIM projects they coordinated through a series of meetings, plan overlay sessions and re-design in the field. This scenario is most common in the CM projects because it reduces field work (as required by the GM/GC contract with the owner) and forces the trade contractors to be involved in a more meaningful and structured coordination procedure.

6.4.2 Owner and Architect Involvement

Owner support of the BIM process formalizes and validates the work of the design team. In all cases in this study, when the owners support and pay for BIM up front, the overall cost of the project decrease in terms of total expenditures by the owner. A majority of general contractors in this research claim to be driving the BIM usage on the projects - only four of the contractors interviewed said they did not BIM if they were not asked to do so by the owner. This contradicts the findings of the SmartMarket report which reported that the architects and owners lead the industry in BIM usage. The contractors surveyed in this study overwhelmingly (14 out of 16) wished that more owners would pay for BIM usage but would likely do BIM even if there were no mandate from the owner. The resistance from contractors to adopt BIM as reported by other findings is most likely based on public owners who are using competitive bidding as the principle contractor selection criteria. This DBB arrangement is, in many regards, antithetical to profitability for contractors.

Three cases were studied in which the project team was assembled early in the design stage and co-located so that they could facilitate a complete model which would be accurate. The owner had representatives that understood the process and the architect was there to answer questions regarding trade specific requirements. In each case the owner anticipated saving 4% to 6% on the project by investing in BIM upfront. Spending money up front and having the architect involved in the process is the most effective way the owner can encourage BIM usage.

Depending on the owner's needs, other decisions can have an effect on the productivity outcome: if minimizing changes is a priority, an owner can require BIM coordination and make contractors responsible for the design. Incentives were given in two cases to encourage contractors to reduce changes in the field and decrease time required for the project.

Results of this study indicate that contractors want more involvement from the architects. Reasons varied from "they are the ones that messed up the plans" to a more cordial "they are better qualified to ensure design intent is met." At any rate, the contractors agreed with an architect who acts as a BIM coordinator on IPD projects: "Designers should lead constructors through the design process as the design is developed, especially when trades have begun their detailing efforts. Done right … design administration reaps benefits during construction. Ensuring a positive outcome can be achieved with an IPD agreement employing hourly compensation and a liability waiver for all participating stakeholders" (Ruber, 2009). There are indications that removal of liability would be welcomed by contractors, but the approach by most contractors is that the person closest to the work models what they feel is needed and they are responsible for what they did or did not model.

6.4.3 Planning and Coordination Meetings

6.4.3.1 The "Big Room" for Collaboration

The "Big Room" is a popular method used to coordinate trades, but it is not required for project success. Indeed a majority of contractors found co-location to be cumbersome and expensive. Many of the design employees doing the modeling for these firms do not like being taken from their office and placed in a big room with others because of the following reasons:

- The inconvenience of switching offices takes time and money.
- Most employees become accustomed to the environment they create in their own office and have all the tools they use. It is disruptive to be put in a less comfortable environment so that efficiency suffers at the beginning of the process. Beyond this issue of efficiency, several of the employees stated that they just like their real office better. This study did not evaluate as to whether or not this ‘morale’ issue was a productivity factor.
- Alteration of commute to work including increased travel time to the jobsite is a negative for the employee. In all but one case, the employees reported traveling a greater distance to ‘work’ or a less convenient commute. A majority of the construction firms have offices that are outside the central core of the city so that parking and access is easier. Parking was more difficult in some of the jobsites because they were at airports, by busy hospitals or other congested area. The one employee who did not travel further or suffer commuting problems did not like the switch because it disrupted his life pattern. Many people establish childcare arrangements and other business based on their drive to and from work. Commute distance and ease are a factor in home location based on their office location. A moving office makes home selection difficult.

Layton (case study #2) starts out the design coordination process with face to face meetings and then has periodic (every three months, or so) meetings where all participants come together. This supports the idea of trust and friendship within the team as discussed in the Southland Industries case (Section 5.6) but avoids some of the problems associated with co-location.

A more significant concern to general contractors than to MEP contractors is the loss of control of the coordination process. The trust relations and continual casual communication causes informality and a decrease in documentation and can reduce the formal planning that is needed so that all modeling efforts are done and communicated correctly. There is a concern with the general contractors that this loss of formality may actually decrease the effectiveness of the open collaboration as it becomes too unstructured. The important thing is that all members of the design team have met and know how to work with each other and trust each other – usually at a kick-off meeting where everyone becomes acquainted and understands the procedures and rules. There they plan what each will model and to what extent it will be modeled. The plan is extremely important or there will be duplication of effort in some cases and not enough effort in other cases.

The option favored by the majority of contractors is GoToMeeting®. These are very effective if the team members have a working relationship with each other. Most contractors report that the productivity of the design process increases with these GoTo Meetings. In three of the case studies, the interviewed person mentioned that the correspondents can work on their own work when others are working out their own conflicts or planning. Having witnessed many of these meetings as part of this study, there is a great deal of time spent idle waiting for relevant material to be covered. It could be argued that if you don't spend all your time in meetings, you could have a better model.

The big room concept is practiced by a third of the contractors on larger, more complex projects. As indicated in the Southland Industries case, the big room is good for putting people close to streamline the design process but the biggest advantage is in the collaboration that occurs openly because of the trust relationship developed as they work closely. In the three IPD projects discussed with seven contractors, a big room was used early in the project. Each was paid for directly by the owner as part of the design stage. These were appropriate for the type of project because the complexity of the design required short duration iterations to reduce the amount of rework in terms of designing elements that would need to be changed.

6.4.3.2 Collaboration Meeting Format

Coordination meetings are usually held weekly during design coordination. The few firms that held meetings more frequently did not report lower frequency of field RFI or rework. The few firms that meet twice monthly had no more field RFI or rework than those that met weekly. The advantage indicated was attributed to regular meetings appropriate for the stage of design coordination. There was less satisfaction in the design process when the meetings were less than weekly. This research did not discover if there was a difference in design costs based on the frequency of meetings but the modelers said they spent more time modeling if they had meetings less frequently than once a week. This supports the iterative cycle and the collaboration as written by Kymmell and Onuma. The shorter iterations mean less re-work in the design stage and more consistent work conditions for designers who will not spend money producing designs that will not work. The saved money can be spent managing quality later in the project.

At these weekly meetings, clash detection on the big items should be discussed, avoiding minutia involving only one or two trade contractors. Layton, Southland Industries and Turner (Sections 5.2, 5.6 and 5.5, respectively) speak specifically to this issue. GoToMeeting® is used for many of these coordination meetings so that all participants can be present while in their home office. This allows designers to continue working on their models while still participating as needed in the coordination process. Remote meetings enabled with a SMART Board™ also increase efficiency of the process because the users are able to communicate more effectively. All contractors agree that the architect should be present or available at each one of these meetings. In every case this was indicated as very important so that contractors are not wasting their time obtaining answers for what they need. The architect needs to have knowledge of the models and be an active participant in the meetings.

Each meeting observed during the research proceeded well and no incidences were reported in which conflicts became arguments. Of all the cases studied and interviews performed, only three contractors had required all members to be present at all coordination meetings. A mechanical contractor stated that these meetings were not productive for all members. Indeed, many contractors at these meetings sat for hours contributing or gaining nothing. A general contractor stated that they received many complaints about these meetings. They realized that having people sitting around at the meetings did not increase the amount of model produced and coordinated, yet took more time. These meetings were actually negatively impacting productivity since more resources than needed were being spent on the design coordination. Of course, this had no impact on field productivity, but overall project productivity, output/ input, suffered.

The purpose of these meetings is to facilitate communication between team members. Two dimensional drawings on paper required 2-D meetings with all members present because the visual aspect of pointing and drawing sketches was important. With 3-D designing, the visual representation and communication decreases the need for the participants to physically be in the same room. This research indicates that the meetings increase productivity rates if members can participate remotely. However, 80% of the responses in this research indicated that “knowing who you are dealing with” was an important part of the meetings. Follow up on this point revealed that with only one exception, coordination meetings can be effectively run remotely if the members have already put a face to the name at the other end of the phone.

Three basic methods of managing the BIM process were discovered during the research. 1) The general contractor actively manages BIM usage. 2) The general contractor requires BIM usage and observes and monitors usage. 3) The architect manages BIM process.

The most commonly observed method in managing BIM usage for construction coordination is for the general contractor to assign protocol in the contract with each major trade contractor and assign the responsibility for doing clash detection to the mechanical contractor. Mechanical contractors have been doing modeling longer than most other contractors because they design their ductwork in 3-D in order to produce fabrication drawings for their metal. Because they tend to be more comfortable with the technical aspect of models, they were better able to incorporate the models from others subs and run the clash detection function more handily than other subs. The three mechanical contractors in the survey who discussed this question felt that this was a major reason that they ran the detection for the project – ‘because we know how,’ Additionally, the mechanical contractors traditionally get first run at space because their work is the largest and most difficult to route. The standard thought is that the other trades will design around their work. Mechanical contractors suffer from productivity loss more than most other contractors due to the difficulty of reconfiguring their work. Since the coordination phase for the MEP has largely been dominated by ductwork in traditional construction practices, it feels natural for the mechanical contractor to assume the role as coordinator. Nine of the 11 trade contractors included in the survey process felt that mechanical was in a good position to perform coordination for one or more of these reasons. However, two felt that these may be valid points but not good enough reasons for them to manage the process. They felt that the general contractor should control it more so that “mechanical did not always get their way.”

In the Layton (5.2) and Diffenbaugh (5.3) case studies it was discussed that the preferred management method of GCs was to let the MEP contractors work out their design conflicts rather than having the GC get involved. In fact, six out of 10 general contractors preferred to not make the general contractor or architect the process leader. Over 70% of the GCs surveyed have some concern with being coordinators because of the implications relating to being a designer and thus held liable for constructability. In traditional contract arrangements between GCs and MEP contractors, the GC mandates that the MEP contractors perform coordination planning with the other trades to ensure that their own procedures do not conflict with others. This practice is practical since each specialty contractor knows their trade better than the GCs. Most of the MEP contractors work with each other regularly and develop good relationships that enable them to work with each other. Whereas the mechanical subcontractor is commonly assigned the role to do the clash detections, they are generally not formally called the BIM coordinator. The Southland Industries case (5.6) discusses the apprehension of mechanical (or any other one) contractor to be labeled the leader. It may give them control of the space but it also makes them responsible for the errors in the model and design and increases their time spent on the process.

Advantages of mechanical contractor managing the clash detection process	**Disadvantages** of mechanical contractor managing the clash detection process
1. They have more at stake in terms of productivity. 2. More experience at modeling and coordination. 3. GC is apprehensive to assume liability of planning and coordination responsibility of trade contractors. 4. Architects apprehensive to assume role of means and methods designer.	1. Added responsibility may not be welcome. 2. GC does not control process of methods coordination which is under its purview. 3. The most effective project level solution may not be arrived at without 'big-picture' view of GC or architect.

6.4.4 Selection of BIM Software

Revit is the most common modeler in the market but the type of modeler does not have an impact on field productivity. Most firms choose Revit because it's accepted and there is a large object library available to them. Few contractors indicated using Revit because of compatibility issues, but would use any modeler that was required by the owner. This would increase costs because many would model in the software they are familiar with and then convert it to the required type. Trade contractors tend to use trade specific software. Overall, there was no relationship between the type of software used to the number of RFI, cohesiveness of the design team or productivity so long as every member of the team uses NavisWorks. The only case in which it matters which software is utilized is if the owner requires the model to be delivered at the end of the project.

Some firms such as DPR, Layton and R & S require/encourage everyone to use Autodesk (Revit) which contains a whole suite of software for trade contractors. This does streamline the design process because information-rich models can be shared more readily. However, many of the trade contractors don't like it and would rather model in their specialty modeling tool. In a few cases they have reported that they will model in their own software and then convert that to the Revit model that is required by the owner. This is not because they don't understand or like Revit, but because their software works better for their trade or is integrated to their operational infrastructure. It is not a learning curve issue, it's a usability issue. From this study, the trade off point was not able to be determined. At a certain point, double entry does not make sense anymore. The person doing the modeling should be able to use any software they like if their work is only for clash detection because models are converted to NavisWorks such that compatibility is not a major issue

As recently as two years ago, one of the major concerns among users and potential users of BIM was that of compatibility of the different software platforms. The concern was that work modeled in one program would not be usable in a team member's platform so that modeling work would need to be replicated. This has become a non-issue to the users interviewed.

The use of NavisWorks as a model integrator and clash detector is practically universal. Every company interviewed has used NavisWorks and all but two use it as their primary detector. Contractors who have managed a BIM job have learned that each trade's model is to be converted to and combined in a NavisWorks file and then a clash detection run. It is true that most of the data on the BIM is not included on this model, but the surfaces of the model components are integrated such that conflicts are evident. Repairs must be made on the intelligent models of each team member, but they only include work pertinent to them in their models. Compatibility between the platforms is only needed during clash detection and for full integration of all project information. When a model contains too much information much of it must be turned off by hiding unneeded layers or erasing data that is not needed. Eliminating excess data is common among trade contractors who have been given a model for the base of their modeling efforts. The concept of all information in one location is lucrative, but operating such a piece generally proves to be unwieldy and hard to use because of the massive amounts of data to look through.

Many owners are beginning to want a model with all data embedded in it. They will probably settle on several models with the data pertinent to that trade on them for simplicity's sake and ease of their internal operations. None of the firms interviewed mentioned the use of Construction Operations Building Information Exchange (COBie), a recently developed system for integration of project information for inclusion in a cohesive and user-friendly format for the owner's use. But those firms that produce a unified model will be better able to meet those requirements when owners require them.

6.4.5 Who Models and When to Start

The selection of a good BIM team needs to be done as early in the process as practicable but this can be done only in DB or, to a limited degree, CM-design assist projects. The full advantage of better design will not be realized in the DBB market because the coordinating team is not brought into the design process early enough to resolve plan conflicts prior to pricing. However, if only field productivity concerns are evaluated, the modeling can start after construction has begun. In fact, modeling should be done as late as possible on projects where conditions or design is likely to change. Details modeled too early on a project which suffers from major design change may need to be redone after major changes have been made.

There is a relationship between who models and the field productivity based on rework and number of RFI. Three companies hired their modeling out to third parties which had modeling technical ability, but did not understand the way the contractors perform their work. Persons that are not familiar with the field work do not understand the components they are modeling virtually. These modelers were found in two case studies to find conflicts that were not actually conflicts in the field. Spending time on components that are insignificant to field personnel is a waste of time to the modelers because they have to spend extra time working through conflicts. Experienced modelers become irritated at excessive modeling because it wastes their time. In the Hunt case (5.3), inexperienced modelers were found to slow the coordination process. To help rectify this problem, they are pairing experienced MEP coordinators with modelers as mentors so that the latter can learn the reality of what they are modeling.

Bringing the design team together earlier is important for the design process, but for the field coordination, it can be done later with no real impact. In fact, if done too early, the tenet of Lean Construction concerning the avoidance of wasted effort may be violated. Design time spent on models that will be changed or re-designed later in the design phase is time ill spent. Layton (5.2), on its CM projects, brings in trade contractors for design at the 50% stage such that they are missing the opportunity to create a building with better value based on shared design done by builders but are able to still complete field work coordination. The later the trades are brought into the design process, the more re-design will need to be done in order to ‘value engineer’.

Each case study supports the idea that the team member closest to the work should model it. Because the models are representations of how the project will occur in the real world, the contractor with the knowledge of and responsibility for constructing the actual objects should model these features. As discussed earlier, the person modeling for the contractor must be familiar with the field work so that they can model properly. If the architect models to the detail needed to perform field operations, the model would produce plans that are buildable, but the architect is not in the field of means and methods. The contracting company who models its own work also acts as a double check to make sure that the architect’s model is correct and constructable. Contractors in this study (see especially Layton, Hunt, Helix and Southland Industries) found that the best method to make the modeler effective was to have the BIM operator go into the field and become trained in this aspect of the work so they can visualize how the images actually fit together in real life. The architects’ and engineers’ modeling appearance or schema may suffice without detailed knowledge of connection methods, but the process cannot be finalized until the individual who knows precisely how the work will be assembled has represented that the detail fits within the parameters designed by those who do not share the intimate knowledge of construction.

Different contractors handle the assignment of at what point in the building process the modeling starts and who gets what areas to model in different ways. DPR likes to become involved early to model their parts because they feel they can control what conditions they get. Southland Industries likes to be the first in a space so they can model more easily and optimize their duct runs. This modeling philosophy is comparable to Kinetics TI division who wants to rush in before others are able to get to the site and "get the prime working conditions." Layton's approach is to let the trades decide who gets what areas in which to model their work, but they will assign zones if contractors cannot decide amongst themselves. This research showed no clear relationship between how the areas were delineated and when the modelers began their work to the amount of RFI, rework or change orders in the field.

6.4.6 What to Model

6.4.6.1 Level of Detail

It would seem that having all the information available in a model when doing detail design would help ensure that there are no conflicts in the virtual rendering, but in reality complex lines and data obscure what the trade modelers are viewing. This supports the observations of Brown and Duguid (2000) that 6-D is "not necessarily twice as good as … 3-D". On the other hand, not modeling enough objects means that field conflicts will not be discovered prior to construction.

One of the biggest errors made by coordination teams is in the amount of material they choose to model. Academics may say that nobody can model too much, but this is not the case according to this study. The most common complaints about what was modeled were that too little was modeled. This shortage does have an impact on field productivity. In the Helix Electric case, one complaint about BIM was that another trade did not model properly such Helix Electric's work suffered. This turned out to be a result of the framing contractor not modeling some of its supports. Too little modeling caused the field conflict in this case. This is not an isolated case. Many contractors had similar incidences to report.

As discussed earlier, modeling too much can waste time in coordination meetings by working on details that will not benefit other trades, but this error does not negatively affect the field productivity. There are a few cases where modeling to great detail is not practical. The Hunt, Layton and Southland Industries cases showed that modeling existing conditions was very time consumptive and they found that it was generally less expensive to let the laborers in the field make measurements and then make field adjustments as needed. Target and two of the contractors in the case studies each had experience in using PointCloud3D but found that it was cumbersome and did not feel that modeling existing conditions to such a level of detail was practical considering the limited benefits compared to the costs of modeling. Not modeling the existing conditions did decrease field productivity but the increased costs were less than the costs incurred making the accurate model. Another time when modeling does not pay is when there is very little time from receiving plans to having the work completed. Kinetics is one such case. Whereas they have a robust modeling department, they do not model smaller projects in existing spaces because they believe it is better to be the first into the site so that they can do their work before other trades show up and get in the way. This is common in construction but can cause problems if the later trades have conflicts which require the first contractors in to do rework.

The level of detail to be modeled does not conform to a number but appears from the research to be a value determination based on experience. Approaches vary from defining sizes of objects to be modeled to “what you think is necessary.” The latter approach by Layton follows the assumption that the trade contractor will only take time to model items that it does not want to have to pay to alter if it does not fit in the field. This gives latitude to the trade contractor and, based on their experience, may save considerable time and money modeling. Common approaches by owners or general contractors require anything larger than 1” to be modeled (40%) to anything larger than 2” or in racks (30%). The remaining 30% varies widely. Some responses were based on complexity and some seemed arbitrary but about 1/3 of these left the decision to the specialty contractors. The research results indicate no significant relationship between RFI, CO, schedule performance or other measures and the amount of modeling specified. The author attributes this to the fact that the modelers have enough experience to know what should be modeled.

Getting trades to model to the proper level is done in several ways. The most effective seems to be to make the trades responsible for following the approved model. Southland Industries gets the other trades and the GC on the team to sign off on the model as resolved in the coordination/clash meetings. If one of the trades does not build what the model says then that contractor is financially responsible to fix it. Layton’s approach is to make subcontractors financially responsible for anything that is not modeled and becomes a conflict in the field requiring rework. They do not define what to model in terms of LOD but rather use past experience to base the decision concerning which details should be modeled for each project. If a MEP contractor opts not to model a rack of ½" pipes going through an area and there is conflict with another object that was modeled, the contractor that did not model their component will be required to pay for the rework or fix. This appears to be a good solution because the decision of what to model is incumbent on the trade contractor rather than based on an arbitrary process or on an experience from a different, dissimilar project.

According to the case studies some contractors will model even other trades components because they feel it is a benefit to them. Southland Industries models most objects – even to the point of modeling other trades' work if needed – so that they can order their material and plan work more accurately. It also aids in prefabrication which will be discussed later. Raymond will also do detail design for other trades – even if they don't get prime conditions – because they do not have to do re-work or experience idle time while the framers are figuring out how to solve a problem in the field. They will model every kicker or brace in a small area to determine the space they will need, and then block out areas where others should not model in order to keep the space open for the kickers they know will be there. This way the whole area represents space taken on regular intervals, but not continuously. In some applications, this does not work because there are too many components that need to be included in a small space.

Owners that are involved through an IPD arrangement helped define what was modeled. In most cases, anything 1" or larger or anything in a rack were modeled. The determination as to exactly what is modeled is a matter of experience gained after several projects and the author could discover no rules as to what should be done that correlated with differences in field productivity indicators. Contractors in the DBB market claim that owners are requiring that BIM be used on some of their projects but that a clear description on the desired level of detail or what to model is not clear. This survey did not investigate how these owners are specifying BIM usage, but the contractors in that market feel unsure of how they are expected to use the tool.

Southland Industries is taking the idea of detailed modeling further than other contractors in this study, both virtually and physically, by bringing other trades into very detailed designs and then inviting them into their shop to prefabricate entire assemblies based on the models. By modeling and controlling work in their environment, they are assured prime conditions and all avoid having to work in less favorable conditions in the field.

6.4.6.2 Schedule

Layton, Hunt and HP perform 4-D modeling on some of their complex projects in order to do schedule validation or assuring that the sequence of the tasks are feasible based on order of assembly. Southland Industries and Raymond will model work of other trades who do not model as do several of the general contractors. They have found that they will get a better schedule due to not having to rework or spend idle time in the field due to conflicts or confusion. The schedule is just as important as the model. According to Dr. Sanvido, a model you can rely on is important, but a schedule that is accurate is needed so that labor and production can be planned properly Southland Industries was able to trust schedules produced by HP better because they were based on models, and this improved their ability to perform work efficiently. General contractors who modeled schedule reported shortened construction times but were not able to separate the effects of 3-D from 4-D modeling on the project. Both Hunt and Layton used Syncro to aid in their scheduling, but other contractors studied used different products such as Vico with lines of balance scheduling functions. The construction scheduling was important, but the interaction of construction activities with public traffic patterns was considered a key reason to 4-D model.

Hunt hires out their schedule building to a third party because they think it is more cost effective than paying to have a person on staff to share between projects. Their project engineers maintain the schedule and the schedule consultant reviews their input and updates. Part of the reason for hiring this function is a result of wanting to have a 3rd party look at the schedule so that in the event of conflict with the owner or in the event of litigation there is an outside source for documentation. This strategy might not solve problems because the 3rd party was an agent of the contractor. GCs that hire out this task most likely do not view scheduling of the project as a core competency. Any sound business model indicates that a firm will self-perform core competencies and hire other special tasks to qualified groups.

6.4.6.3 Cost & Maintenance Data

Target, a progressive company with BIM experience, was the only owner included in the case studies. They indicated that they had a strong interest in the 6-D, or cost and maintenance information, as part of the final model. They have a large inventory of existing buildings and are trying to work out the means of a consistent method of information management concerning their buildings. None of the contractors mentioned specific requirements in turning over models to owners but mentioned that the owners are beginning to request the building information models at the completion of the project. COBie may become more popular with owners as a consistent method of providing building data to the operators. None of the contractors had been required to use COBie.

The subject of this research was field productivity and did not attempt to determine what the effects of modeling in solid surface had on later intelligent models turned over to the owner. The intelligent functions of BIM require that all data be incorporated into a single source. This makes conflict coordination difficult with given software and procedures. If owners are to receive a unified, data-rich model, they will need to specify a software type so that the models are done on one platform or combined into one.

6.4.7 Models as Contract Documents

There are mixed signals from contractors as to whether or not the architects or owners should supply a working model to contractors for their use. Hunt (5.3) and Diffenbaugh (5.4) wanted a better model from the architect that they could use as a base for their modeling efforts. Most of the trade contractors did not indicate irritation at the need to create their own 3-D models based on 2-D drawings and, in fact, some preferred it because there were fewer things for them to decipher and model around.

Some contractors provide a shared model to the trade contractors so that they can reference the model or build from it. DPR has found this to be successful in their teams and have not observed any liability issues. This approach is similar to the idea of open source software in that no one person is entirely responsible for the content, but that the various team members will 'keep others honest' and provide a more useful base. R&S also keep an active model on file so that team members may have access to the information on it through an FTP site. The GC's role in these situations is to monitor the model and attempt to keep it current for the use of others.

Contractors who have more BIM experience were less likely to state that the owner/architect should provide better models. They are used to creating models from plans and understand some of the benefits of doing it that way. Those that have modeled projects from models and from 2-D drawings say that they prefer to have a 3-D model so that they can at least check the designer's intent by viewing the model. The research showed no correlation between the number of RFI, amount of rework or change orders based on the availability a working model from the architect. The design process, however, was easier and/or faster if one was available.

One argument heard during the research was that since the architects are using BIM to create their designs, they might as well provide them as contract documents. The architects produce 2-D drawings from the 3-D models in many cases, but still do not issue the 3-D as an official design document. The liability concern associated with this was discussed in the literature review. Theoretically, the project would be well coordinated if done in BIM by the architect, but this was not found to be the case in this study. Most architects did use BIM, but there was a slightly negative, but insignificant correlation between RFIs and if the architect used 3-D as a design basis rather than 2-D. The field coordination effort appears to be independent of the original method of design. Despite this, a majority of contractors want, at a minimum, a working model as a reference and feel that it should be a contract document. This is, of course, a non-issue on DB and IPD projects.

6.4.8 How Much to Spend on BIM

Contractors with several projects of BIM experience claim to spend between 0.5% and 1% of the contract on modeling. This research discovered no strong correlation between BIM expenditures and the number of field RFI. From the owner's perspective, BIM expenditures are generally included as part of the contractor's fee. For IPD or near-IPD agreements, the owners tend to pay for the BIM work upfront. In two cases, the general contractors who had been modeling the project were 'fired' from the project by the owner. The completed modeling work was owned by the owner so that information was not lost to the owner. In most cases, contractors will not model work that they are not under contract for and for which the costs of modeling are included in their fees. Therefore, the contractors invoice the owners for that work as a preconstruction service. Hunt took over one of these projects and has assumed the use of some of the models produced by the previous contracting team.

Raymond is involved in a DB integrated project where they are being paid a certain amount of money to be involved in the design process. Once the model is completed and agreed upon, they will be locked into a lump sum price based on the model-generated quantities and agreed upon productivity rates based on past experience. In this case the owner pays the contractors for the initial design work but also holds each contractor accountable for the model which it helped to create. The owner is spending about 4-5 percent of the projected construction costs on the model itself. Sutter Health is similarly engaged in several projects in which they anticipate spending 4-5 percent of the project up front in order to reap the anticipated savings of nearly 10% of reduced change orders due to better planning.

6.5 Learning Curve Effects of BIM

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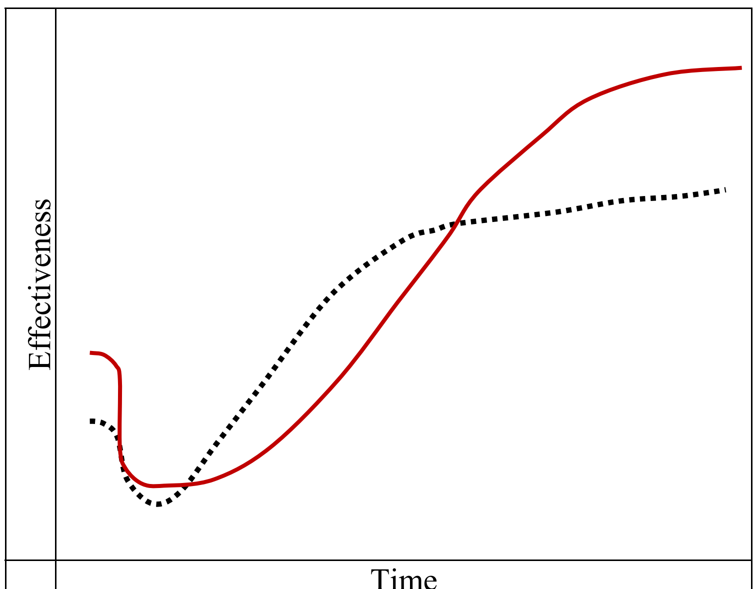
This study shows overwhelmingly that individuals who have experience with BIM do not want to go back to traditional coordination methods. This is similar to the DB approach of contracting, but with BIM, over 90% of users indicated that they would not want to do another project without BIM. A study done for Minnesota found that the major hurdle in getting DOT engineers to consider that DB is superior to traditional PDMs is to have them do a project with DB. States that did not have DB found that DBB was better while states with DB found that DB was much better (Strong, 2006). This obvious finding shows that people resist things they are not used to. In order to get more contractors to try BIM, owners need to pay for it. In order for more owners to use BIM, the contractors will have to pay for it. Most contractors began using BIM upon the request of an owner and found that the learning curve is short as indicated by the Strong report on DB and supported by this research.

Persons who have CAD experience were found to become proficient in BIM usage after 3-4 projects.



Persons with CAD experience (red line) initially suffer through an adjustment period where they have lower productivity than a person without CAD experience (black dashed line).

Figure 13 - Formal training on software is needed to gain the full advantage of BIM but the initial learning curve effect is more noticeable to experienced CAD users.

People who did not have such experience were found to “catch on” after 2-3 projects. Although this result seems counterintuitive, it is thought that those with CAD experience go through a transition phase where they initially have to mentally change their operating habits (see Figure l3).

However, once this adjustment has been made, the CAD experience proves to be an asset because they are able to understand the shortcuts and nuances of the modeling process better that those without CAD experience. Proficiency at BIM is more than knowing keystrokes. The technical ability to run software is not the most significant learning curve, but the understanding of what to model. As discussed above, modeling too much is a waste of time and modeling too little increases field conflicts. Many teams said they wanted to model more but did not have the time.

Learning to model is difficult for field personnel because many are not comfortable with computers and images. The younger, new hires that can operate BIM software are not experienced in the field. The time it takes them to learn the reality of construction means and methods is the limiting aspect of the learning curve for BIM. A solution to this was given by three contractors in the case studies: have the new modeler observe experienced people solve problems and then model the conflict and solutions. Showing the model to the experienced person will teach the latter to use models better and it will also show if the new person understands both the problem and how the work is to be done. Secondly, the company will have a record of the solution and a model that can be used for future projects in solving similar problems. The library will make future modeling efforts faster and allow more time for modelers to identify further problems.

The learning curve is important in that as contractors become more comfortable with the process, they will be able to lower their prices. This has occurred on a few recent projects mentioned in this research. Three contractors who all use BIM were vying for a hospital project. One of the contractors was able to lower their prices because they felt they would be exposed to less risk because of their building model. The lower price was attractive to the owner, but the confidence in their model that the contractor demonstrated by lowering their bid price was an important indication of the contractor's ability. In another case, a contractor was able to feel enough comfort with a lower project bid because the model removed confusion and some of the waste factors in its labor cost.

6.6 Special Considerations in the Decision to BIM

Based on the case studies, three issues other than productivity or change order reduction should be considered when deciding on modeling a project. Lean Construction principles are better achieved by the use of BIM. Some contracts may require applying specified TQM or ISO standards to the construction process. BIM is integral in the Last Planner system so that it will help to achieve these goals. LEED projects can benefit from BIM because of the increased design capabilities but also in terms of field work. Keeping a site clean and orderly, reducing waste, and integrated planning are all ways to earn LEED points and are achieved easier with the use of BIM. Special needs of the owner can be a factor as well. One worth mentioning is that TI work performed after the building is completed is much simpler if there is a working model of the base building and improvements to it. Requiring each TI project to be modeled and combined with the master building model would keep the building model current so future planning efforts were more efficient.

6.7 RFI, Rework and Change Order Effects on Project Productivity

Most contractors indicate that there are probably more RFI when using BIM, but` that they happen in the design phase and are answered in the weekly design meetings where they cost nothing or very little. Whether coordination meetings are integral with the project design process or only as field coordination exercises, they yield high returns. When BIM is performed as indicated in this thesis, the projects have an average reduction in RFI's of 90%. Several firms claim that *field generated conflict* RFIs are reduced to virtually none. Several firms claim that RFIs are reduced to a very small amount. The least successful project in terms of RFI reduction was an estimated "50% of what they would have been." This project experienced 2,200 RFI due to the large amount of owner changes to scope but the project manager expects that without the BIM process there would be been twice as many. Most of these RFI where not conflict related and there was no clear number of how many were due to conflict. Considering the cost of RFI, this is a significant cost reduction. As indicated in 2.7.1.5, the average cost of an RFI on hospital and complex office/educational projects is $425. Based on that amount, this project with an estimated reduction of 2,200 RFI experienced an estimated savings of $935,000 on the project. Because the reduction in RFI is an assumption based on what "could have" been, the dollar amount of savings cannot be deemed as accurate, but the fact that the savings are approximately $935,000 on a project that only reduced RFI by one half shows how important the coordination effort is. Considering that the GC spent $140,000 on BIM on that project, the ROI on BIM for RFI savings alone is 6.7 times. The average number of RFI estimated to have not occurred on the projects in this study that provided such numbers was 111RFI/$10MM. Thus, *the average savings on the projects in this study* *was $47,175 per $10MM in contract price*. This is, of course, an anticipated reduction in expenditures required to administer the project.

As RFI decrease, the amount of rework similarly drops. The fishbone diagram shown in Figure 14 below shows the contributors to rework. When done properly, BIM decreases the effects of most of the elements in each of the main categories, especially the errors and omissions, constructability problems and instructions to workers.

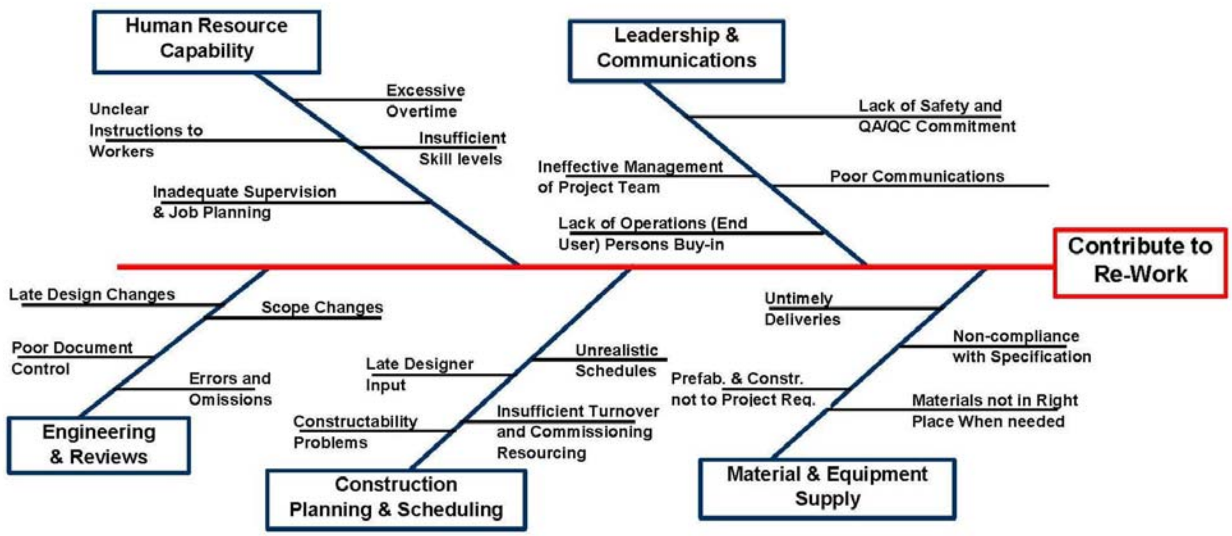


Figure 14 - Fishbone Rework Cause Classification from COAA. (Source: Fayek, 2003).

Section 2.7.1.7 reviewed rework costs on projects. The range was large but averaged around 12% of total project costs. In the middle of the range was a study that found that 79% of rework was done due to poor coordination and that 12.4% was the average amount of rework. Using these figures, the cost of rework on the average project due to poor coordination is 9%. During this research, only two contractors (both mechanical) would give rework rates and they were ranges from 10% to 20% from one contractor and 1% to 50% from another. Several contractors in the case studies estimated that rework was about 10 or 20 percent, but did not know for sure. Based on this information, the 9% figure will be used as a basis for calculating the savings in rework based on poor coordination. BIM would be expected to save $7.6MM of the average project size of $85MM in this study. When discussing these savings with a contractor in this study, they were told that, on their $61MM project they would expect a savings of $5.5MM due to reduction of rework. The contractor initially denied spending that much on rework, saying that they did not spend more than 10 to 15 percent on rework. After examining some math principles the contractor agreed that $5.5MM might be a reasonable figure. Some of the rework costs are associated with idle time and confusion due to coordination, but the cost to contractors is high, nonetheless and all rework reduces productivity based on product/effort.

6.8 Productivity Changes due to BIM usage

Productivity rate changes were not known by contractors or not made public such that these increases could not be discovered. Most contractors are realizing savings or else they would not continue to use BIM. Only a few contractors indicated that they did not BIM their projects if the owner would not pay for it. As the contractors perform more BIM projects, it is anticipated that their productivity rates will change. Three contractors, when asked if their company-wide productivity rates or unit prices were changing due to BIM projects, indicated that their estimators kept separate numbers for BIM projects and knew how to estimate them. Apparently the new pricing structure is not being shared with the owners, but it is apparent that contractors are realizing a productivity increase. A significant part of the increase is the reduction in rework and idle time due to confusion, but the ability to pre-fabricate, layout with full stations programmed from models, and reducing RFI contribute to this overall increase as well. The discussion in 2.1.2

concerning PAR covered standard processes, but has been observed in at least one contractor's operations. After utilizing BIM, Helix Electric made production projections on the project that seemed faster than normal to the superintendent. However, the field personnel were producing near the rates projected by the estimators who used information from past BIM projects to determine the productivity rate projections.

6.8.1 Owner Savings

The owners forfeit a great amount of money for waste as can be seen from a few of the following research highlights:

- 38-51% of projects are above budget by more than 5% (Konchar, 1997).
- Deviation costs of defects are 12.4% of installed project cost (Burati, 1992).
- Value-adding work is 31.9% (Levy, 1990).
- Bids by trade contractors are increased by up to 10% based on expectation of poor general contractor performance on site (O'Briend, 1998).
- HVAC interference or conflicts increase costs 5-10% (Gunnarsson, 1994).

Each of these examples shows various aspects of the construction process that can be improved by the use of BIM. Owners have not been realizing savings as indicated above, but they have been encouraged by BIM such that many are requiring modeling of their contractors. Sophisticated owners like Target have determined that BIM improves the process of facility construction and management. Though they were not willing to share numbers, their experience with BIM caused them to increase BIM expenditures and usage on future projects.

As mention earlier, several owners in the case studies were willing to spend 4-5 percent of project costs in the design stage in order to save an anticipated 10% in change orders. This savings in change orders appears to be the biggest cost advantage to owners. Research has shown change orders to average 5% to 12% for an average project, depending on which research project is used. Most of this research focused on hospitals or other complex commercial or education structures. These tend to average about 10% cost increases over base contracts. Most of the contractors and owners indicated that there were very few change orders due to conflicts and that the owner saved 5% to 7% on project costs considering these 'non change-orders.'

Owners who require the use of BIM on their projects can hope to achieve not only a savings in the cost of construction, but also in the proper design of the building. One owner required a virtual mock-up of the exterior skin for the project from the contractor and invested the money required to perform this. After seeing the results of that mock-up, the owner decided to spend an additional $150,000 for a third party consultant to use BIM to show problems with the building system and correct them. This owner later estimated a savings of $1,387,500 on issues relating to that mock-up. This is an example of saving on change orders due to BIM.

Some owners are beginning to see savings due to increased productivity. As mentioned earlier, two projects in this study had lowered prices to the owner because BIM enabled them to see that productivity would be improved and that their charge to the owner could be reduced. As more contractors learn how to use BIM, market pressures will likely cause prices to drop further – not because contractors are giving up money, but because waste is being eliminated and the savings are shared. As owners invest more actively in BIM, they will be able to reap more of the savings because they will be owners of the information and be in a better position to expect better productivity rates from contractors.

6.8.2 Contractor Savings

This research did not discover any cases of the owner feeling that BIM did not save them money but there were three cases in which the contractors felt that there was no appreciable savings to them. Indeed, one contractor discontinued the practice of modeling all its work. The savings noted by the owner seem to be a result of eliminating change orders rather than directly due to productivity improvement. *Contractors do not save money by eliminating change orders but by increasing productivity*. In most cases, decreased conflict lowers change orders and increases productivity, but there are rare cases where there is no appreciable productivity gain seen. This phenomenon was observed in case studies where repetitive work by experienced field crews is the profit center for the contractor. One contractor in the case studies modeled their concrete work prior to the field performing their work. The amount of clashes they detected indicated that there should have been savings, but there was no corresponding field productivity increase measured. The types of conflicts that were detected by the modelers were generally dealt with easily by field crew. Therefore, earlier detection in the office saved little time in the field.

The 2009 SmartMarket report indicated that trade contractors get the smallest values of BIM benefit. This research, however, found that trade contractors (with mechanical being the highest) reap the highest increases in productivity gains. The amount of time spent idle or waiting for instructions is generally assumed to be about

35%, as shown earlier in section 1.1.3. Rework time and other conflicts lowers productivity rates further. The trade contractors all reported an increase in productivity or at least a very noticeable decline in rework and idle time due to field conflicts. There were very few complaints from MEP contractors about modeling because they viewed it to be such a benefit to their field operations. General contractors and non-MEP contractors saw an advantage to field productivity, but not as marked the MEP trades.

Another savings due to BIM is improved safety brought about by the ability to prefabricate pieces that are safer to install and reduce work in hard to access places. Southland Industries reports that it is fabricating material at waist height in the shop and installing bigger pieces that cannot be picked up by one person. Therefore, proper equipment is planned for and used to hoist up the bigger pieces and the final connections are made in a safer way. Since they started doing this, their EMR has improved 34% from 0.68 to 0.45. Material waste is generally decreased with BIM planning so that material and garbage around the jobsite is reduced, lessening obstructions to operations. Accidents were reported to be lower by three of the contractors in this study on projects that utilized BIM for material planning and coordination. This in turn lowered their EMR as well as increased worker morale and productivity.

Prefabrication not only increases safety, but allows work to be done in a more productive and controlled environment. Hester (1991) found that productivity in elevated areas is 20% higher than for work at floor level because foremen plan and prepare those areas more closely. Planning, more than location, is essential to higher productivity. Southland Industries pre-assembles large components in their shop in conjunction with other trade contractors so that installation is faster and easier for all. This process combines higher efficiencies of shop work and planning. Helix Electric reported that they ordered larger and more complete busways and cable trays due to the increased accuracy of the models. This decreases their time in the field bending and assembling these components. Southland Industries reports placing wheels on their prefabricated components and Turner has required all contractors to place all their materials on carts at the project site for easy transport. On one Turner jobsite, it was estimated that every dollar spent modeling and planning the project saved $17 dollars in construction field costs. Much of this is attributable to BIM related activities such as limiting the amount of material on the project and requiring all materials to be on movable carts so that material handling is reduced, but the majority is due to savings in rework, idle time reduction and increased efficiencies afforded by prefabrication.

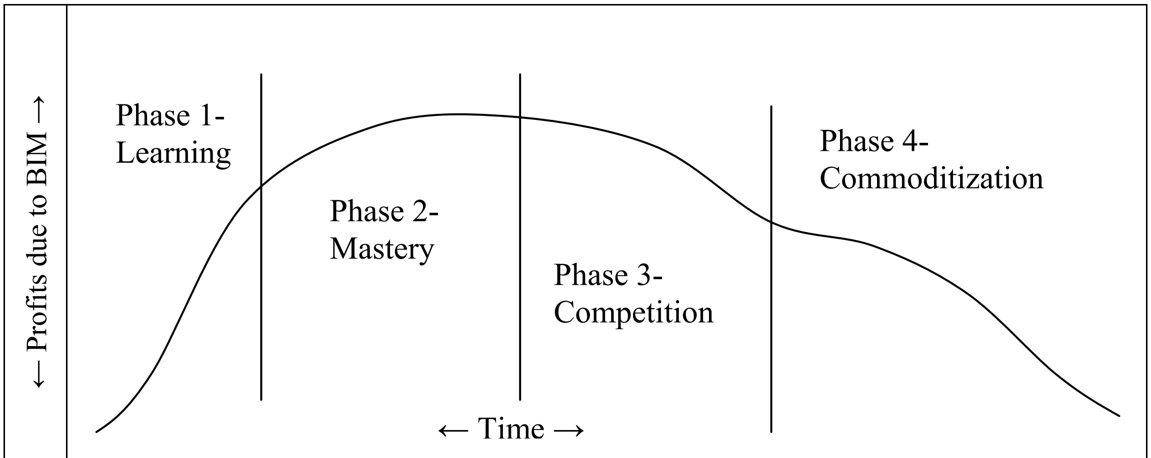
Chapter 7: CONCLUSIONS

7.1 Findings – Recommendations

Stakeholder's Gains by BIM Usage:

The fact that productivity rates increase is acknowledged widely by contractors who utilize BIM, but the amount of these gains is aggressively guarded as a great treasure. Indeed, contractors bid projects using non-BIM, historic productivity rates and are finding the savings in productivity alone bring profits. There are few exceptions to this rule and these are generally from contractors in the competitive bid market. As a result of the research process, it became apparent that contractors realize that as long as they can keep their increased productivity rates due to BIM implementation a secret, the longer that they can hold on to their increased profits. Some contractors are comfortable indicating there is profit, but do not elaborate on the specific ways to manage the process that creates the greatest returns. In some cases, the productivity rates are not known or calculated. In these cases the contractors tended to model only if requested and paid for by the owner or general contractor. In no cases were specific productivity rates or rate changes disclosed by a contractor or owner.

Following the typical cycle of innovation, early adopters of BIM processes have been able to learn BIM technology and management skills while owners have been satisfied with investing into BIM for time savings and reduction of change orders. Most contractors in this study indicated that initial BIM usage was funded, at least in part, by the owner of a project. Figure 15 illustrates the profit pattern over time which is typical of new means and methods technologies adopted by construction firms. Generally, if a



Phase 1 – Contractor invests resources into BIM processes and begins to make profits due to productivity increase based on reduction of waste.
Phase 2 – Contractor becomes more skilled at BIM management. Owners expect more of the savings due to the "value adding" process and reduction of waste but contractors can still profit because few other contractors are using BIM.
Phase 3 – More of the contractor's competitors are using BIM and owners expect savings passed on to them. Prices decline as owners become more sophisticated.
Phase 4 – Most contractors now becoming proficient enough at BIM that market pressures make BIM a needed commodity rather than a profitable "value added" feature for contractor.

Figure 15 – Profits available to the developer of new value-adding technology change over time as market pressures and competition makes the technologies common and become more of a commodity rather than a service.

contractor discovers a way to lower productivity costs, that contractor is able to keep most of the savings to the project as added profit. Over time, other contractors and architects begin to learn of the method of decreasing costs and it is adopted by designers and/or contractors on other projects until the method is no longer a competitive advantage, but a necessary service. In the case of BIM, many owners have funded much of the learning curve for the contractors such that the methods are being demanded more frequently by them so that the contractors more quickly need to adopt the innovation in order to be competitive in the market. In order to delay the inevitable loss of competitive edge attributed to their ability to lower productivity rates and increase profits by the use of BIM, contractors are very apprehensive to provide their production numbers.

Key Performance Indicators that Reveal Productivity Rate Increases:

When BIM is performed, projects have an average reduction in RFI's of greater than 90% and several firms claim that field generated conflict RFIs are reduced to virtually none. Although it a curious measurement, the positive productivity gains of BIM are gauged by what doesn't happen rather than what does. The reduction of field generated RFI is an indicator of plan coordination and constructability improvement through the use of BIM. The average number of RFI *estimated to have not occurred* on projects was 111RFI per $10MM. Thus, *the average savings on these projects was $47,175 per $10MM* (0.5%) *in contract price*. This saving is based on general contractors' cost to manage the RFI process. This small percentage may seem insignificant, but it must be remembered that the cost to manage projects is general about 5% of total contract costs. The RFI savings are a portion of that management process so that the savings to the management process is about 9%.

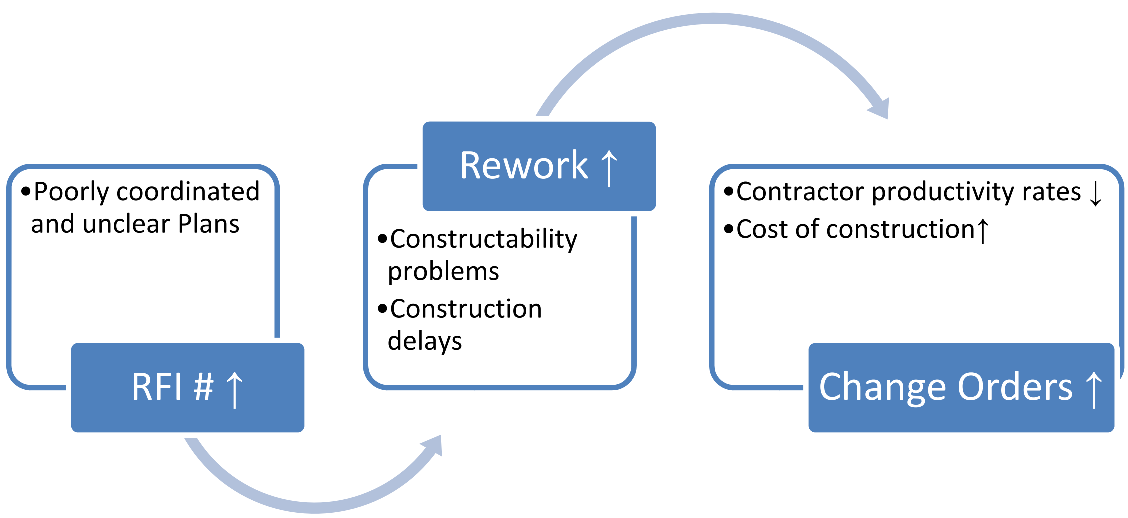


Figure 16 – RFIs are an indication of confusion about the plans such that higher numbers of RFIs means increased field conflicts which cause re-work and idle time. Much this cost is passed to the owner as change orders and some are absorbed by the contractor.

Owners realize a significant savings by the drastic reduction of change orders due to their inability to understand drawings and the elimination of most constructability conflicts in poorly coordinated plans (see Figure 14). As owner involvement and support increases, the amount of money they save by these 'non-change orders' (money gained by not spending on changes) represents from 4-7% of contract costs. This is remarkable considering that typical projects of the type studied (hospital & complex commercial) usually suffer from contract increase on the order of 10% or more. In addition to time savings and change order reduction, some projects were found in which contractors lowered their prices to the owner because BIM enabled (or required) them to recognize that productivity would be improved. This amount in one case was nearly 10% - the amount that many contractors typically add to their labor estimates to cover the anticipated inefficiencies on the project. Some of these anticipated savings were passed on to the owner in order to be more competitive. This is generally experienced when the owner supports detailed modeling up front as in an integrated project as a profit sharing technique, but it is also seen in more competitively bid projects.

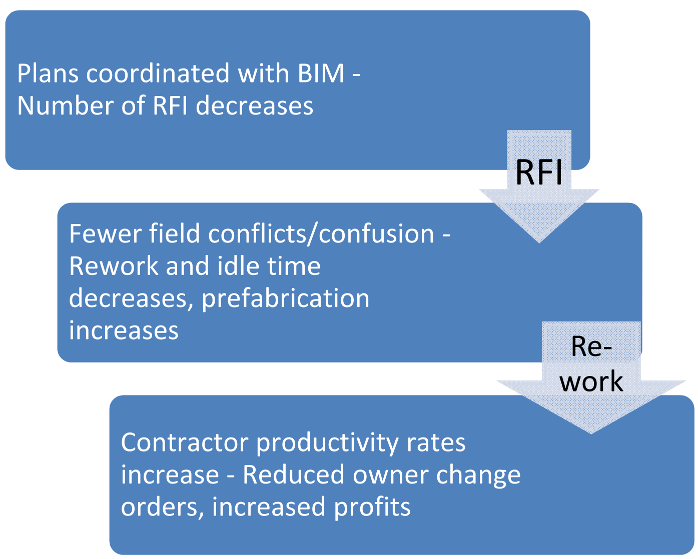


Figure 17 – BIM coordination reduce RFI, rework, idle time and change orders while increasing prefabrication. Contractors keep profits they realized by their modeling efforts. If the owner was the sponsor of BIM, then they are able to gain productivity savings as well.

As a direct consequence of using BIM, *trade contractors see a significant reduction in rework and idle time for their labor to the order of 9% of their project cost and also gain substantial benefits due to the ability to prefabricate materials.* Safety is also reportedly enhanced because of the ability to prefabricate more accurately. The MEP trades gain the greatest savings when the work is coordinated using BIM, but concrete, framing and glazing trades also see significant advantages to modeling.

Losers in the BIM process:

It has been shown that money is being saved because of efficiencies gained through BIM. Owners may spend 4-10% less for a building due to BIM. Where does this money come from? Who is losing this money? Generally, when there is change there are winners and losers. For example, insulated concrete forms (ICF) increase the energy efficiency of a house. Overall ownership costs to the owner decrease, concrete companies increase sales, and the ICF manufacturers and installers increase revenues. However, because the houses are more energy efficient, HVAC suppliers produce smaller or units for the house and thus experience decrease in sales and the framers who are used to using wood to frame walls must learn to form and pour ICF or lose business. The biggest losers, however are the lumber suppliers and retailers. It can also be argued that the environment loses in the short term because wood, as a building material is renewable and more environmentally friendly that foam which is produced from oil and then concrete which is produced at a high energy cost.

BIM usage increases productivity but the savings are beneficial to contractors with fixed cost contracts because they are paid for work that contributes to the building and not to wasted effort. The losers in BIM are minor and none would complain vocally because they would be deemed backwards to fight for inefficiency and waste. Fewer materials are wasted so there is less material sold on each project. However, because money is being saved by productivity increase, buildings may increase in size or quality of finish so that materials are merely being spent on other, more efficient buildings. The money that is saved is not coming from any group as a loss, but rather is merely not being thrown away. Wasted material and labor are thrown away on typical project. In the case of BIM, there really are no losers that are justified in expecting to keep things status quo because the existing system is notoriously inefficient.

Key BIM Management Choices that Optimize Productivity Increases:

Although BIM usage almost always has a positive increase in productivity in the field, some key BIM decision will optimize these productivity increases. The following section will summarize these decisions and their effect on productivity.

Effects of Project Delivery Methods on BIM effectiveness:

The design-bid-build (DBB) project delivery method (PDM) will not likely attain the full amount of value that can be gained by using BIM with other delivery methods. The value adding function of BIM is error elimination, and the competitive bid contract culture rewards contractors who manage field conflict by identifying conflicts and issuing claims for extra work and/or managing productivity despite plan confusion. Merely modifying DBB contracts will not rectify the problem because the BIM process is only marginally effective without an open collaborative environment. Value can still be gained if owners define BIM requirements and reward contractors to follow them by sharing savings or at least paying for modeling efforts directly. There are a few cases where the owner has modeled the project and provided that model to contractors prior to bid to gain more favorable pricing. Increasing information and confidence in the plans is a very successful way of reducing construction costs by about 10%. This research did not discover any cases of the owner feeling that BIM did not save them money but there were three cases in which the contractors felt that there was no appreciable savings to them. Each of these cases was experienced in a DBB PDM.

Cost savings are evident for both contractor and owner on CM and DB projects. DB projects had nearly half of the RFI that comparable CM project experienced. Two factors which are likely to have caused this difference are that on the DB projects there was typically more owner support and involvement and the trade contractors were involved earlier (at least by the 50% plans completion point) in the design process. The trade contractors were selected primarily by qualifications for the DB projects but by low bid on the CM projects. These factors point toward more collaborative team members when DB is the IPD used. Few projects are truly integrated projects (IPD) but the projects that were claimed to be such each had an owner who was actively involved in bringing the entire team together early and contractually tying team member profitability to the work as based on the model. In terms of satisfaction and apparent savings to the owner, the greatest savings follow the subsequent order, from least to greatest savings: DBB, CM, CM design assist, DB, IPD.

When to Select Design Team:

It was found that contractors should be involved at the 50% or earlier design stage. By so doing they can have a greater say in the way their components are placed and coordinated such that the need for constructability reviews are not needed. Whereas this improves the design process, the plan coordination or clash detection is the process that most affects field productivity directly. Brought in too early, however, before clear project definition by the architect, they will not be as effective. This research showed a weak positive relationship between the modelers beginning their work by the 50% mark to the number of RFI and rework. *However, clash detection was the BIM process that caused the great reduction in RFI.*

Coordination Meetings Management:

Design coordination meetings for the purpose of clash detection should be held weekly. Most contractors favor the GoToMeeting® because they allow attendees to work from their more efficient home office and can work when they are not involved in the conversation at hand. Discussing only major or important conflicts at these meetings is important lest they become a waste of time for contractors. The productivity level of the meeting does not have a significant impact on field productivity, but it does affect overall project costs. Co-location is not critical to project success and unless the project is particularly large and complex, the "big room" may be detrimental in terms of designer satisfaction. Field productivity increases due to rework elimination and prefabrication cooperation between trade contractors were evident when the modelers knew and trusted their counterparts from other trades. Mechanical contractors are frequently called upon to perform coordination between the models from all the contractors but it was found to be more effective for the general contractor or architect to *manage* the meetings. *There was little effect on field productivity based on who managed the process, but the design process effectiveness was dependent on the management methods.*

BIM Software and Modeler's Experience:

There was no relationship discovered between the brand of software used and field productivity. All models were converted to NavisWorks for coordination so that the software type did not matter. Many contractors urge the use of Revit and it is the most common, but the quality of the coordination based on the number of field RFI and rework did not appear to be dependent on all contractors using the same modeling software. Design operations efficiencies were noted in some cases where all members used the same software. Another occasion to use specific software is when the owner requires a comprehensive model at the end of the project.

There is a relationship between the skill level of the individual who does the actual modeling and field productivity based on rework and number of RFI. If the modeler does not understand field operations for the trade they are modeling, their model may not include components that should have been included or depict these components improperly. Inexperienced modelers were cited as a significant cause of BIM failure causing rework in the field. The learning curve for the technical aspect of BIM is approximately 3-4 projects. The learning curve for managing the modeling (knowing what to model, e.g.) is 2 to 3 projects. If the modeler does not understand field operations the learning curve is as long as it takes to learn field operations. At the contractor level, the firm that will perform the physical work should be the one that models virtually. Similarly, there is a strong correlation between the competency of the contractor modeling its work and the rework performed associated with it. This has the effect of reducing field productivity. Contractors in this study found that the best method to make the BIM modeler effective was to have the BIM operator go into the field and become trained in this aspect of the work so they can visualize how the images actually fit together in real life.

Level of Detail:

The level of detail to be modeled is determined by experience. Some contractors specify minimum sizes of components to model while others let the trade contractors decide what to model but hold them responsible if their components clash with another trade's work that was modeled. Too little modeling can be a cause for lower field productivity, but too much modeling does not negatively affect field operations. The most common complaint about what was modeled was that *too little* was being modeled, thus increasing waste and decreasing productivity.

When BIM Usage is NOT Warranted:

Certain circumstances negate the net value of productivity typically gained by using BIM. Modeling existing conditions does not generally increase field productivity rates enough to compensate for the increased costs associated with creating the model. Another instance when modeling does not create a net value increase would be a situation where there is very little time between receiving the work directive and the required completion of the project. The general consensus is that all pipes and connections do not need to be modeled but a firm rule of what sizes do need to be modeled was not determined. The decision of level of detail to model is based on experience gained after several projects.

The research indicates no strongly significant relationship between RFI, CO, schedule performance or other measures and the amount of modeling specified for the project. However, there is evidence indicating that the most effective method to determine what is modeled is to make the trade contractor responsible for any components that they should model. If they fail to model something that later conflicts in the field with a modeled component, they become responsible for the cost to repair it.

Correlation between Amount Expended on BIM and Productivity Increase: Most projects have BIM expenditures of less than 1%. Many contractors begin modeling only basic components in order to learn the BIM process. As they perceive conflicts, they determine that they should model the areas of conflict on the next project. Thus, as their efficiency increases, the amount they model increases, but their costs do not necessarily rise proportionately. Owners of more integrated projects will expend up to 5% of project costs on early modeling in order to reduce change orders and reduce unknowns about the project so that contractors can feel more confident and lower their prices. On these integrated projects the agreed upon model becomes the basis for contract price. *Incredibly, no strong correlation between the amount spent on BIM and the number of RFI was found except for integrated projects in which the owner paid up front to model to great detail. In these cases RFI and rework were low and the owner anticipated contract savings based on lower project waste.*

Correlation between a Working Model from the Architect and Productivity: *No strong correlation was found between the number of RFI and amount of rework and the availability of a working model from the architect*. The design process, however, was easier and/or faster if one was available. Many think that the plans should be well-coordinated if done in BIM by the architect, but this was not found to be the case in this study. Most architects did use BIM, but there was a slight negative correlation between the number of RFIs and the architect using 3-D as a design basis rather than 2-D.

This study suggests that contractors desire more involvement from architects. A model that can be used either as a reference or a base for detailed modeling would be a benefit to them because it would reduce their model construction labor time. Most contractors are becoming used to not having a contract model, but the more integrated projects define model requirements and include models as part of the contract since they are the basis for pricing and schedule.

Other Factors:

When BIM is used in conjunction with proper time planning procedures, time reduction of up to 10% are experienced. General contractors who modeled schedules reported shortened construction times but were not able to separate the effects of 3-D from 4-D modeling on the project. Other arguably non-pecuniary reasons to use BIM are increased safety levels, LEED credits, and better facility life-cycle evaluation.

7.2 Limitations of Research

This research focused on field productivity at the contractor's level. Most of the existing research is based on design productivity or project level effectiveness based on the owner's needs. Due to the relatively limited amount of projects which have been completed using BIM there is little quantitative study results. Contractors were in almost all cases unwilling to share their productivity numbers or key indicators of their productivity on their projects with the exception of a few who were eager to market their abilities. Other contractors did not know their productivity levels because they do not have the metrics in place in their firm to obtain data. The data and information for this study was gathered from 37 firms that had enough BIM experience to respond to some of the issues being researched. Due to the small sample size, this is essentially a qualitative rather than quantitative report. Strong correlations with high R-squared values were not found because of the varied responses and the small sample size.

Toward the end of this research, the author started to obtain some information unavailable the year before. More contractors are beginning to understand the BIM process well enough to have some data on the number of RFI and their causes relative to BIM and others are gathering data on their productivity levels. The lack of reliable data, either because of proprietary concerns or because of lack of knowledge, limits the view of this research.

7.3 Future Research Needs

Finding true productivity rates for contractors: BIM is used to produce parts for assembly on site. These parts can be tagged and tracked to determine how long it takes to install the part. It would be informative to find firms that have data related to the installation of the parts modeled and compare the productivity rates to the projected model and also compare it to a typical project in which BIM coordination is not performed.

Cost of rework due to using multiple BIM software: The amount of time spent in the design process on double entry in terms of model design appears to be high. When multiple platforms are used, contractors produce their own model from 2-D representations or, in some cases, a surface model. The working solid model of each contractor is transformed to a NavisWorks file as a surface model. Clashes discovered are made in each trade contractor's model rather than on one common model. There are advantages of double checking and ease of individual modeling, but there is also additional time spent on repetition. Additionally, if a comprehensive model is needed by the owner, all the information would have to be combined eventually. This would represent more double entry by contractors who did not model on the platform desired by the owner. The research need is to find the trade-off point where time savings of avoiding double entry and being able to coordinate using intelligent models are greater than the cost of using unfamiliar software or software that is not suited for that trade's work.

Contract growth in DB – BIM projects due to owner changes: Perkins (2007) indicates that DB owner changes are higher than DBB projects while design error changes are lower than DBB. He attributes this to the fact that the owner discovers problems in the design and pays to fix them rather than go without the changes as would likely be done in a DBB project. BIM brings design forward. Would the faster and more accurate representation of the project in a model make a difference in the amount of contract cost growth for DB or CM projects?

Value of prefabrication: Trade contractors indicated that the ability to prefabricate bigger complex components for final assembly at the site or the ability to order fabricated components directly from the supplier was a significant advantage. However, the author was not able to determine how much of a productivity gain this facet is in terms of dollars or percentage. Considering the significance the trade contractors placed on this aspect, knowing quantitatively the effect would be valuable.

7.4 Conclusions

It was estimated that every dollar spent modeling and planning the project saved $17 dollars in construction field costs. Much of this is attributable to BIM related activities such as limiting the amount of material on the project and requiring all materials to be on movable carts so that material handling is reduced, but the majority is due to savings in rework, idle time reduction and increased efficiencies afforded by prefabrication. These savings are interdependent and cannot be evaluated in a vacuum. BIM practices vary from one company to the next but even similar practices wrought differing results when performed by companies with different cultures. Business management theory discusses culture of a firm and how it affects the way it accomplishes its core competencies.

The BIM software is a tool that is used in diverse methods by individual firms. The owner and architect can use it to evaluate needs and design and for life-cycle costing. General contractors use it to coordinate trade activities and the flow of information as well as scheduling activities on the project. Trade contractors use it to plan their means and methods and coordinate between other trades in order to perform their labor most effectively on the project. Each of these tasks is performed to differing degrees of effectiveness based on the firm's willingness to cooperate and openly collaborate with others. BIM is not a contract driven system as much as it depends on a culture of collaboration and trust. Only firms that have been able to shed the adversarial thinking endemic in the competitive bid market will be able to assume an appropriate role as part of a more interrelated team. The clash detection is the most common function, but information sharing, estimating, scheduling, project loading, maintenance information, and future work considerations can all be included in the BIM process so that it functions as an entire design and construct process. Many firms have used BIM on several projects and claim to have evolved into a system that is successful for their team.

Unfortunately, this author sees that the BIM process that most contractors, architects and owners are following only accomplish a small portion of what BIM has to offer. The new technology is being used for a few point solutions and the rest of the opportunities are being ignored. If the construction teams do not cooperate, BIM is likely to become another part of the contract that will be manipulated by team members that do not have the cultural savvy to use BIM properly. Aggressive members who seek for a larger “share of the pie” on each project have not been included in future projects in the DB and CM markets and are likely to drive the BIM market to commodity pricing because the regulation of the process will be reduced to contract rather than collaboration. BIM works best with trust and, as of now, tends to attract persons and firms who favor more collaborative team settings. BIM, without the culture to run it, becomes a tool that will increase the ability of unscrupulous persons to step on others to get ahead. The IPD that ties teams together should succeed if the players truly adopt the proper cultural shift, but any PDM can be effective at realizing team savings so long as the members view project effectiveness as the goal rather than cost-reduction only as a way of making profits.

Each team member should be able to maintain profits. Whoever is the principle driver and coordinator of the BIM process should be rewarded for their risk taking in that regard. Whoever does the modeling of the work they will be performing should receive compensation for knowledge of their trade and accurate modeling. Architects who participate in the clash detection process without fear of means and methods should be rewarded for their team work. Owners that pay for modeling in detail before the project starts should be afforded the benefits of increased productivity and receive lower bids for their risk in bringing a modeling team together. As shown in the graphs in Figure 18, each group benefits from BIM in a particular manner and seeks to gain profits based on these advantages. For the BIM process to continue to increase profits, all users will have to receive a share of the profit. Combined, the advantages are skewed in favor of the trade contractor, general contractor, architects and owners, in that order. Savings are gained by those groups, yet owners are beginning to gain greater rewards when they assemble BIM teams early in the process. Otherwise, much of the savings shown are being gained by the contractors as indicated on the graphs.

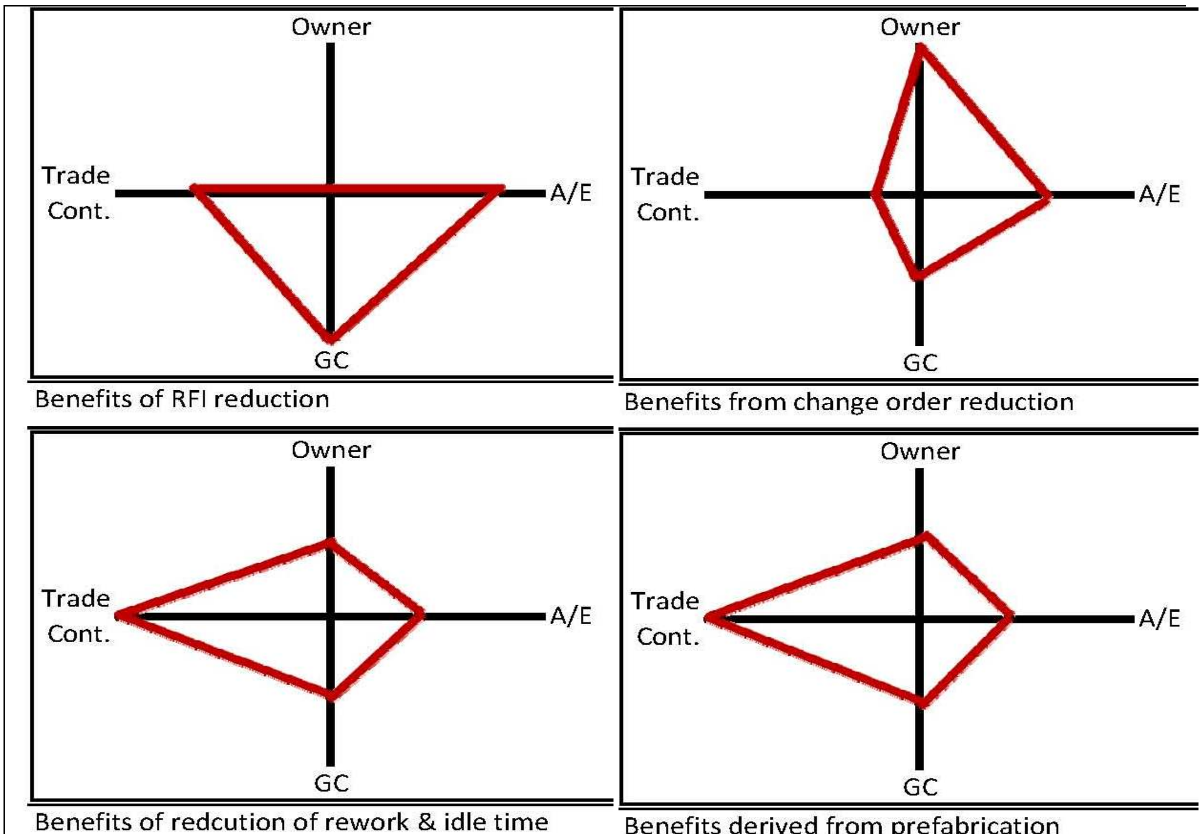


Figure 18 – Benefits gained from BIM work for each of the stakeholders. The greatest benefits in terms of increased productivity due to BIM usage is skewed toward the contactors. The closer the stakeholder is to the work, the more benefit they derive from the improved planning and coordination of BIM.

Figure 18 shows a distribution paradigm similar to that seen in theoretical integrated project agreements where the cost savings accomplished through BIM usage are shared synergistically. In cases of IPD, the owners attempt to establish a profit sharing program whereby they reap half of the productivity gains and the rest of the team shares the other half. The trade contractors are closest to the greatest savings in field productivity, but the owner is attaining more of the savings as competitive pressures and owner organization of the team increases.

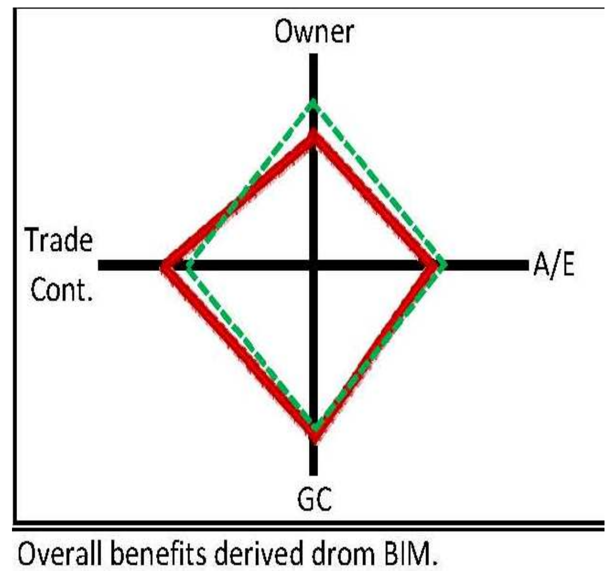


Figure 19 - The red solid line represents the composite savings gained most directly by each stakeholder, the green dashed line represents a more equitable distribution.

The newness of BIM allows contractors the opportunity to increase profits by improving productivity while using pre-BIM productivity rates. This productivity is gained by clear visualization of the component assembly and elimination of conflicts in the field. Labor does not stand idle waiting to figure out how to install material because it was coordinated in the model. There is little rework done because of conflicts. Bigger, prefabricated parts make it easier to perform more work in the shop where conditions are more favorable to high production. These causes contribute to the reduction in amount of time that is spent to produce the structure. Until more contractors are able to manage the coordination process and realize lower costs, there will continue to be an opportunity to gain early adopters’ profits. As more contractors learn how to increase their productivity, the amount of money that can be charged will begin to decrease.

Perhaps the most telling component of this survey is the common attitudes of all stake holders towards the future implementation of BIM. After completing BIM projects, over 90% of those surveyed claimed to not want to do another project without the use of BIM. BIM's evolution is not yet complete and has not reached its potential. This advancement of BIM from a construction tool to a culture can be seen as the gradual construction of a new intellectual and cooperative attitude. Productivity gains in the field will only be one symptom of the successful implementation of the BIM Cultural Revolution but is one of the first that has been realized.

Appendix A:

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Section 1.5 case study information:

Loudoun County Hospital MOB Addition,

Leesburg, VA (September 2003 – March 2005).

- Douglas Chelson was project manager for the general contractor, Foulger-Pratt Construction, Inc of Rockville, MD, and represented the developer's interest since the developer was part of the same umbrella corporation. Jim Foulger was the developer for the projector. The owner was Loudoun County Hospital.
- Architect: Digiorgio Associates Inc., Boston, MA; Team leader: Jason Beshore

The building was designed using traditional CAD methods and the modeling was only to represent the finish appearance to the owner rather than for design or construction coordination.

Appendix B:

The following survey was intended to be used as an on-line data collecting tool. It was effective as an interview basis rather than a direct answer tool. Most persons felt comfortable talking about their experiences using BIM, but were hesitant to answer with exact numbers. Most answers given were qualified by the respondent in an attempt to explain their results. Because of this, it was determined that open responses to these questions were preferred to a 'numbers only' approach.

Building Information Modeling (BIM) is a process and software that aids in design and construction by communicating design intent through the use of 3-D models.

1. What type project delivery method was used (contract type)?
   a. Design-Bid-Build
   b. CM at Risk
   c. CM Design-Assist
   d. Design-Build
   e. Integrated Project Delivery
   f. Other
2. What type of project was this?
   a. Healthcare
   b. Commercial
   c. Industrial
   d. Educational
   e. Other
3. What type of owner?
   a. Government
   b. Private
   c. Other
4. Was LEED certification sought on this project? Y/N
5. How long did the design process take (months)? ______
6. How long did construction take (months)? ______
7. Was there overlap in the design and construction phase (fast track)? Y/N
8. How many RFIs were developed on this project? ______

9. How long was the average response time for RFIs (days)? ______

10. What was total contract dollar amount of the project? $_______

11. What was the total amount of change orders due to inadequate plans, planning conflicts, missing information or phasing of work? $_________.

12. How close did the project come to its original budget? $ +/- _____

13. How many delays were experienced on the project due to plan conflicts or unclear direction concerning design? ____

14. How close was the duration of the project to the original schedule? +/- ____weeks

15. Was this project a success? Y/N

16. Did your project utilize any BIM tools or processes at any point in its duration? Y/N

If you answered no to #16, skip to #29, otherwise answer #17-28.

17. Who was the driving force behind BIM usage on this project?
    a. Owner
    b. Architect
    c. GC / Construction Manager
    d. Trade Contractor

18. Did the owner explicitly pay for BIM usage on this project? Y/N

19. If the owner did not pay directly for BIM would your firm use BIM anyway? Y/N

20. What software was used on this project? _______________________________

21. How are trade contractor models produced?
    a. From 2-D schematics from architect
    b. From 2-D construction documents from architect
    c. From 3-D model from architect

22. Who conducted BIM coordination meetings?

23. How often where BIM coordination meetings held?
    a. Monthly
    b. Every two weeks
    c. Weekly
    d. Twice a week or more

24. Who performed the file coordination and clash detection for the coordination meetings?

a. Architect

b. General contractor

c. Mechanical contractor

d. Other

25. What were the primary reasons BIM was used? (1 = most important)

a. Clash detection

b. System design

c. Scheduling

d. Sales/Preconstruction

e. Other

26. Was more prefabrication performed due to BIM planning on this project? 1 2 3 4 5 (1= none, 5 = big increase in prefabrication).

27. How much money was spent on BIM on this project? $________, or project cost %______

28. After completing the project did you want to use BIM again on the next one? Y/N

Non BIM users:

29. Was there discussion of using BIM for the design or construction phases of the project?

30. Why was BIM not used on the project?

Appendix C:

Data Tables from Interviews and Case Studies:

The following charts represent results from the interviews and surveys. Table number 2 in section 5.10.2 contains the numerical value of the participants' indications of the strength and importance of the relationship between KPI and BIM usage. Chart C-1 shows which firms' responses are associated with the Likert item responses. Chart C-2 lists comments that were deemed important for each participant by the investigator.

Chart C-1 showing relationship between respondent firm and the results of their evaluation of the effects of BIM practices on KPI as indicated in Table 2 in section 5.10.2. Table 2 does not indicate the name of the firm due to confidentiality concerns by the respondents. In order to respect the privacy wishes of some of the firms, all names are withheld when attributing specific data. The principle type of project delivery method or contract type is shown here along with who manages the model coordination process.

		Stake-holder	Principle Contract	Model Manager	RFI % Change
Target	1	Owner	CM-DA	GC office	90+
Layton Construction	2	GC	CM-DA/DB	GC	90+
Hunt Construction Group	3	GC	CM	GC/Mech	50+
Diffenbaugh	4	GC/Conc.	DBB/CM	Arch/Mech	50
Helix Electric, Inc.	5	Elect	CM	Mech	
Southland Industries, Inc.	6	Mech	DB/CM	Mech/GC	90+
Kinetics	7	Mech	CM/DBB		
Raymond	8	Frame	CM/DB	Owner/GC	
AECO Engineered Systems	9	Plumb	CM	Mech	
Turner Construction Co.	10	GC	CM/DB	Mech/Arch	80+
DPR Construction Inc.	11	GC/Frame	DB/CM	GC	90+
Clark Construction – CA	12	GC	CM/DB	Mech	
Sundt	13	GC	CM/DB	Mech/GC	85
Hensel Phelps Construction Co.	14	GC	CM/DB	GC/Mech	
Suffolk Construction	15	GC	CM/DB	GC/Mech	
M. A. Mortenson Construction	16	GC/Conc.	CM/DB	GC	
Rudolph and Sletten	17	GC	CM/DB	GC/Mech	

See Appendix A for company and respondent information.

Chart C-2. Noteworthy observations attributed to the participants included in the Likert evaluation process shown in Table 2 in section 5.10.2.	
1	Just starting to measure schedule
2	Lower bid prices due to BIM
3	Lower bids due to BIM
4	Architect should control - used for MEP coordination
5	Production rates met more consistently
6	BIM needs strong GC to drive schedule
7	BIM is communication tool
8	MEP coordination is biggest advantage for framer/DW
9	Can coordinate plumbing on light table - but that does not communicate to others trades
10	MEP coordination
11	Sharing model used in some offices
12	MEP coordination is principle value
13	Trades talk and find plan problems
14	Use closely with schedule
15	Most jobs are BIM but they hire out modeling to 3rd party
16	It is the way we do business
17	All projects are BIM projects (field is not always aware of this)

Glossary

AEC: Architectural, engineering and construction. This refers to the industry members that design, plan and perform the creation of the built environment.

BIM: Building information modeling can reference a process of using the planning and software tools to coordinate the design and construction process; the software that enable the relational designs; or the model that is produced by the process and software tools. It does not refer solely to software, but to the process of designing collaboratively and iteratively.

CM: Construction Management. A project delivery method in which the owner contracts with the architect and builder, but the builder is selected based on qualifications during the design phase so that it can perform constructability reviews. The builder has a fiscal contractual responsibility to the owner to ensure design constructability, thus reducing later errors and changes. This PDM also allows for fast-track construction that generally saves months of total project duration. Most research indicates that CM saves on total construction costs, but the bigger motivation is the time savings.

DB: Design-Build. A project delivery method in which the owner contracts with a firm that supplies and/or coordinates the design and construction functions. This one-stop-shopping approach requires a greater level of trust between the parties because there is less outside verification that the price is right. The contractor is picked based upon proposal package rather than price alone. This process saves time and money according to research, but the parties must have a clearly defined protocol and trust in each other.

DBB: Design-Bid-Build. A project delivery method in which the architect/engineers produces complete construction prior to involvement by the builder. Builders bid on the documents and the lowest responsible bid is typically awarded the project. The owner contracts with the builder to complete the work as specified on the bid documents which become contract documents. The architect monitors the construction process to ensure adherence to the plans and specifications. The three-way relationship is sometimes called an adversarial relationship (Rogers, 1990). This is because the contract pits the parties against each other with the construction documents as the battleground.

ERP: Enterprise Resource Planner. This is the software system that manages information for a firm's operations and operates based on a central database that enables data sharing and process interoperability.

IPD: Integrated Project Delivery. A recent development in construction that ties project outcomes to all parties such that design and construction responsibilities are shared in a more collaborative process. This form is akin to joint-ventures used in business where all teams are tied to the outcome. BIM is used as a basic premise in this arrangement because of its power as a collaborative and visualization tool.

LEED: Leadership in Energy and Environmental Design is a system developed by the US Green Building Council to evaluate and certify a building to be built in an environmentally responsible manner.

Means and methods: The contractor is responsible for the way a project is completed. The architect and engineer determine *what* is to be built, but the contractor determines *how* it is built.

MEP: Mechanical, Electrical & Plumbing are the three principle trades involved most heavily in clash detection processes. Fire protection is generally included here under plumbing.

PAR: Performance Ability Ratio takes the exemplary performance of a crew and uses it as the basis for performance. Average productivity may improve while the basis remains the same. Rather than increasing isolated instances in high productivity, management tries to reduce the variations to raise average work performance.

RFI: Request for information is the principle tool used during the construction process to gain clarity about the meaning of the construction documents. Plans that are not coordinated or that are unclear as to their meaning cause field personnel to stop construction processes and ask for direction.

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