The Impact of the Systematic Incorporation of Tolerances on Gypsum Board Installation

---

A Dissertation

Presented to

The College of Graduate and Professional Studies

College of Technology

Indiana State University

Terre Haute, Indiana

In Partial Fulfillment of the

Requirements for the Degree

Doctor of Philosophy

By

Curtis W. Bradford

May 2017

Keywords: tolerances, technology management, construction quality, lean construction

VITA

Curtis W. Bradford

EDUCATION

2017 Indiana State University- Terre Haute, Indiana
PhD. Technology Management- Construction Management
Dissertation: The Impact of the Systematic Incorporation of ASTM C 840 Standards on Gypsum Board Installation

2003 Central Missouri State University – Warrensburg, Missouri
MS Industrial Technology, Construction Management

2002 Central Missouri State University – Warrensburg, Missouri
BS Construction Management

1984 Manhattan Area Vocational Technical School- Manhattan, Kansas
AS Applied Building Trades

PROFESSIONAL CERTIFICATION

Certified Professional Constructor, American Institute of Constructors
Certified Technology Manager, the Association of Technology, Management, Applied Eng.
Concrete Field Testing Technician Grade 1, American Concrete Institute
Construction Quality Management, US Army Corps of Engineers

PROFESSIONAL EXPERIENCE

2011 - Present	Assistant Professor, Construction Mgmt.	University Central Missouri
2007 - 2011	Senior Project Manager	STRUCTURAL-Pullman
2004 - 2007	Project Manager	Hoffman Cortes Inc.
1998 - 2004	Construction Manager	AECOM-DMJM H&N
1997 - 1998	Quality Control Manager	Roxco, Ltd
1993 - 1997	Superintendent	Ferrell Construction, Inc.
1984 – 1993	Construction Trades Foreman	US Construction Companies

PUBLICATIONS

Bradford, C., Sauer, A., (2016), The impact of systematic incorporation of ASTM C 840 standards on gypsum board installation, *abstract in progress research*, 52nd ASC Annual International Conference Proceedings.

Bradford, C., Bruce, R., McCandless, D., (2014), Challenges in the identification and implementation of reference standards in gypsum board installation; a study of 20 projects, 50th ASC Annual International Conference Proceedings.

COMMITTEE MEMBERS

Committee Chair: Ronald C. Woolsey, Ph.D.

Graduate Coordinator, School of Technology

University of Central Missouri

Committee Member: A. Mehran Shahhosseini Ph.D.

Director, Ph.D. in Technology Management Consortium

Indiana State University

Committee Member: David McCandless Ed.D.

Professor of Construction Management

University of Central Missouri

ABSTRACT

To meet the challenges of productivity in construction new technologies and management techniques have been introduced. Building Information Modeling (BIM) has shown signs of increased efficiency on projects. Lean Construction is founded in the principles of Lean manufacturing and is focused on reducing waste at all steps in the construction process. Construction robotics has emerged as a viable solution to skilled labor shortages. Each of these solutions are based on consistency of product installation and tolerance use will be vital to success. Although each of these initiatives shows progress they have failed to meet the expectations of the customer or increased worker production rates. The latest innovations in the industry rely on the increased use of precise tolerances. Moving from a craft based worker model to tolerance model driven merits study.

This research sought to study the impact of systematically deploying a construction industry reference standard at the trade worker level to measure impact it had on production and quality. In addition, the research sought to measure the change in perception of quality when these standards are actively used by inspection. As a surrogate the researcher investigated the impact on quality and production for gypsum board installation when tolerances of ASTM C 840 are actively incorporated. This study has shown use of a reference standard with established tolerances can be used to reduce waste and improve productivity. Lean construction is based on the reduction of waste in all resources and it may prove fruitful to investigate the Industry Standards in other phases of the construction process.

ACKNOWLEDGMENTS

I would like to acknowledge the members of my committee, Ronald Woolsey, David McCandless and Mehran Shahhosseini for their guidance and support during this research.

I would also like to express a deep appreciation for the other members of the UCM construction management faculty, David McCandless, Jerry Penland, Aaron Sauer, Kyle Larson, Steve Bloess, and Joe Kupersmith, for their help during the design and execution of the research. A big thank you to all of the UCM students that participated in the study without you this research would not have been possible.

Thanks to Aaron Sauer for the guidance in navigating the administrative aspects of the ISU consortium program and to Kyle Larson for the emotional support during the writing phase.

Thanks to my son Gregory Bradford and daughter Rachael Bradford for the numerous weekend hours of labor preparing and keeping the research area ready for the experiment. And I would like to express my sincere appreciation to my wife, Jennifer Bradford for her help with preparing this dissertation and putting up with me in general.

This research was supported by a grant from University of Central Missouri Faculty Senate, Performance Enhancement Committee.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE

INTRODUCTION

The New York Times reported in 1911 the work of Frank B. Gilbreth in the article "*Bricklaying Yields to Science for the First Time"* (New York Times, 1911). The article focuses on Mr. Gilbreth's study and utilization of efficiency of movement and products to improve the brick installation process. Each step a mason took in the installation of a brick was mapped with all unnecessary steps eliminated from the process. Based on the improved process, tools were then designed to enhance the production of his tradesman. While controversial at the time, his motion study increased worker productivity, reduced fatigue, and enhanced the quality of the finished product (New York Times). Mr. Gilbreth's manufacturing approach to the construction process improved speed and efficiency was groundbreaking at the time and he is often referred to as the "father of industrial engineering" (Forbes, 2011, p. 52).

The construction industry is one of the largest industries in the United States contributing significantly to the national economy and accounting for an estimated 10 percent of the gross national product (Bentil, 1989). Construction defects are costly and at times deadly. Contractors must balance issues of quality while being faced with pressure from owners, regulators and sureties for higher standards all while facing skilled labor shortages (Fiori, 2003; McGrath-Champ, 2011).

The construction industry struggles to implement uniform standards and the adoption of improvement systems that have been successful in other industries. Quality standards and tolerances once identified by design professionals in project documents have been replaced by verbiage of incorporation of applicable reference standards whether or not they are pertinent to the project (Frank, 2012). In his text, Construction Quality, Do it Right or Pay the Price, author George C. Frank states, “Frequently, the architect listing the standard doesn’t even have copies of the standard and has never seen nor read the whole standard; yet the contractor must ostensibly discover and know what the standard requires” (Frank, p. 83). The burden of meeting quality expectations is thus passed down to supervisors that may be the least able to interpret the standard. The number of agencies and standards is staggering; the American National Standard Institute, (ANSI), the American Society for Testing and Materials, (ASTM), American Concrete Institute, (ACI), and American Institute of Steel Construction (AISC) represent a few of the hundreds of standards published regularly and incorporated by reference into a construction contract. As a result, construction is one of the least efficient industries and one of the most hazardous occupations (Bentil, 1989).

Productivity and New Technologies

In 2004, Dr. Paul Teicholz, Emeritus Professor, of the Department of Civil and Environmental Engineering at Stanford University released data comparing Construction and Non-Farm Labor Productivity from 1964 through 2003 (Teicholz, Labor Productivity Declines in the Construction Industry: Causes and Remedies, 2004). These data showed the construction sector in a dramatic decline of productivity as compared to other industries. Dr. Teicholz’s follow up study in 2013 was done to see how new technologies have impacted worker productivity. He concluded that though there may be minor improvements, linear decline of 0.32

percent per year remains versus Non-Farm industries which have a positive 3.06 percent per year (Teicholz, 2013).

To meet the challenges of productivity in construction new technologies and management techniques have been introduced. Building Information Modeling (BIM) has shown signs of increased efficiency on projects. Lean Construction is founded in the principles of lean manufacturing and has focused on reducing waste at all steps in the construction process by fostering collaborative efforts between members of a team focused singularly on the success of the project. Construction robotics has also emerged as a viable solution to skilled labor shortages. These solutions are based on consistency of product installation without focus on the development of the processes and standards required for the successful execution of installation by the workforce. Although each of these initiatives shows progress to streamlining the construction process, they have failed to meet the expectations of the customer or increased worker production rates.

Building Information Modeling (BIM)

The use of BIM by contractors has increased dramatically in recent years with an estimated adoption by 74% of respondents to a 2012 survey. (Jones, 2012) The survey indicates the greater use in large vs. medium firms (90% vs. 49% respectively). Contractors point to increased profits, maintaining repeat business and greater constructability analysis as reasons to expand their use of BIM. BIM has started to move from an exclusively office based tool to successful jobsite implementation. Contractors are using BIM guided tools to precisely locate penetration, hangers, embeds and other site elements leading to the increases in opportunities for off-site fabrication. Validation of as built conditions can now be accomplished with true dimensions from laser integration allowing for adjustment of the model during the construction process. Utilization and implementation of increasingly sophisticated technology on remote job sites has increased including the use of computers and mobile devices. Wireless integration and cloud type storage have been cited as revolutionary advances instrumental in overcoming previous limitations with BIM implementation in the field (Jones).

Robotics

At the 16th International Symposium on Automation and Robotics in Construction in 1999, the Swiss Federal Institute of Technology in Zurich presented results on a fully automatic shot-crete robot which can spray concrete on a surface independently (Kochan, 2000). At the Technology Conference 2012, electrical contractor and inventor, Sam Stathis, introduced a construction robot that interprets a designer’s BIM model. The robot then transfers the wall layout to the physical building, eliminating the on-site drawing interpretation by workers (Healey, 2012). Though U.S. sales and use of robots lags behind Europe, Asia and Australia, modest growth is expected through 2016 (Healey).

Lean Construction

Lean Construction is a combination of operational research and practical development in design and construction with an adoption of Lean manufacturing principles and practices to the end-to-end design and construction process. Unlike manufacturing, construction is a project based-production process. The term "Lean Construction" was coined by the International Group for Lean Construction in its first meeting in 1993 (Gleeson et al. 2007). The Construction in "Lean Construction" refers to the entire industry and not the phase during which construction takes place. Reduction of buffers and waste are key to the Lean Construction principles and can easily fold in sustainable construction techniques. Lean production in construction is described as the difference between craft productivity and mass production (Forbes, 2011, p. 46). The project centric nature of a Lean project enables designers and contractors to reduce waste and incorporate solutions that are in the best interest of the project. The Lean Construction movement is focused process improvement; however the statistical analysis for improvement is limited to meeting obligations of the downstream customers in completing assigned tasks.

The three major innovations in the United States construction industry have produced remarkable results, though consumer studies indicate the industry is still falling short of meeting expectations.

Construction Quality

A Zurich study points to a project owner trend to select only contractors having formal quality management protocols. (Andrews, 2013). This has its basis in the recognition that the costs associated with poor quality work compounded with that of rework and those accompanying time delays are passed to owners. The challenge exists for owners to engage contractors with formal quality programs in place. However, it is estimated that only 5 to 10 percent of United States contractors have a formal quality program (Whiteman, 2004).

In 2003, California Senate Bill 800 or SB 800, commonly known as the "Right of Repair Bill", extended the time from 4 to 10 years for latent defects by developers, contractors and subcontractors for all but a few items in a residential building. (Construction Web Links, 2003) Interestingly, a contractor is also required to provide a "fit-and-finish" warranty for a minimum of one year. The interpretation of "fit-and–finish" tolerances is left to the judgment of each party resulting in ambiguity and allowing "fit-and-finish" builders set their own tolerance for proper fit in the warrantee documents. (Construction Web Links). This bill specifically codifies the relationship between the builder and the customer in a way not previously seen in the construction industry.

Traditional principles of a successful construction project are based on three elements. The project was delivered safely, on time, within budget and of high quality thus meeting or exceeding the overall specifications of the project. Contractors define the quality of a project as meeting tolerances set forth in the plans and specifications. As the industry has advanced, drawings and specifications have become less precise. Designers have deferred to government standards, codes and regulations for tolerances leaving interpretation of quality to the individual contractor (Frank, 2012). The result of this practice is the "drift" in the implementation of standards not only between contractors but also between projects.

This ambiguity has caused contractors adhere to the traditional idea that each project is unique and therefore quality is defined in real time. Each step of the construction process is adjusted to the fit the last stage or parts are made and modified to fit (CMHC, 2014). Construction tolerances vary by supplier, subcontractor, trade and division of work. Reliance on experienced skilled tradesman has been essential to the overall integration of the building or project. The variability in tolerances also results in the need for "as-built" or "record drawings" showing how the building was modified during construction from the original design. The completeness of these drawings again is subject to the interpretation of the contractor.

These construction tolerances define the allowable deviation from values provided in the contract documents. The inherent imperfections in measurements require the interpretation of work in degrees of accuracy resulting in the definition of allowable tolerances by industry standards and guidelines (Ballast, 2011). A TQM (Total Quality Management) implementation survey demonstrated that the top reason not to implement TQM was the burden of documentation and paperwork. (Whiteman, 2004). Also cited was the difficulty in the measurement and interpretation results with regard to the unique nature of each project.

Although tolerances are sometimes difficult to define, there are two components of quality in construction: conforming to requirements of the contract and achieving customer satisfaction. (Torbica, 2000) Traditionally, the industry prefers conformance requirements set in construction documents, building codes and zoning. This approach relies heavily on design and specifications to establish quality standards of measurement. Quality control is generally limited to retrospective inspection as a measure of compliance to standards. The customer satisfaction approach to quality is very complex and difficult to measure. “Quality is a perception. Because consumers do not always possess complete information about a product’s attributes, they must frequently rely on indirect measures when comparing brands.” (Aft, 1998, p. 5) Each customer’s perspective of tolerance and quality makes this extremely challenging.

Designers incorporate in the specifications, a section containing a listing of “applicable standards”, regardless of the project being constructed (Frank, 2012). There is a universal responsibility for compliance with industry standards but unfortunately, this does not guarantee understanding on the part of the contractor. In a United Kingdom study utilizing Weber’s Law (the just-noticeable difference between two stimuli is proportional to the magnitude of the stimuli, (and the subject's sensitivity), consumers rated the quality of the installation of floor tile. It was discovered that joint width in tile could vary by up to 70% before crossing the threshold of consumer acceptance. (Forsythe, 2006) In this case, no uniform standard existed for “fit and finish” making interpretation of quality a subjective measure.

Since quality is often very subjective, contractors have relied on the contract documents to set forth the design specifications in measuring quality standards. A young tradesman or construction manager will describe the role of specifications as identifying the products, processes and quality of installation required for a project. According to Fisk, specifications are a detailed description of requirements, dimensions and materials intended to complement the drawings by defining the workmanship and procedures to be followed in constructing the project (Fisk, 2010).

Craft workers

The current shortage of skilled workers creates a gap in continuity and a knowledge void. Skilled trade workers rank first and fourth for the most difficult jobs to fill in respectively globally and in the United States (Manpower Group, 2012). The average age of a skilled construction worker has increased from 37.9 years to 41.5 years between 2000 and 2010 (Richey, 2013). Labor costs on a construction project often are 30 to 40 percent of the projects total projected costs. The industry trains workers in a craft-based education system. Workers enter the industry as formal or informal apprentices and gain experience to attain a journeyman status. Years of training are required for the worker to understand and recognize parameters of quality workmanship.

Traditionally, contractors have relied on the contract documents to set forth the design specifications in measuring quality standards. In the absence of design specifications, construction tolerances were based on past experiences and professional judgment; complemented by an intimate knowledge of the materials and construction process.

In addition, craftwork training resources may also hinder production and increase costs when compared to industry reference standards. When a comparison was made between three training resources, ASTM C 840, GS 216 and McGraw Hill's Carpentry and Building Construction textbook, on the installation of single ply gypsum board to wood framing without adhesive, a difference in the number and location of fasteners was noted. In this example, McGraw Hill's text book recommends installing 10-22 percent more fasteners than required by either ASTM C 840 or GS 216. This example illustrates how a craft worker resource does not align with industry reference standards. Use of the standard tolerance found in ASTM C 840 in this case could produce savings in materials and labor.

Conclusion

The latest innovations in the industry, BIM, robotics, Lean, all rely on precise tolerances. Incorporation of prefabricated construction units has encouraged Lean Construction management to increase the speed of construction. These trends match the desires of customers that a building be constructed as designed to meet long-term expectations they have for a substantial investment. How these changes will impact production at a micro level and to what extent is yet to be determined.

Statement of the Problem

The construction industry struggles to adopt systems of improvement used in other industries, and as a result remains one of the least productive and challenged with poor quality. A 2014 study demonstrated an inconsistent application of specifications between designers and contractors in the installation of drywall. The most commonly referenced standard was, the American Society for Testing and Materials guideline C 840 (ASTM C 840) followed by the Gypsum Association's Application and Finishing of Gypsum Panel Products (GA 216) and thirdly, the manufactures written instructions (Bradford, 2014). This study demonstrated that while there is a lack of consistency of specifications between designers, contractors could use the ASTM C 840 reference standard as a baseline for quality and construction tolerances (Bradford).

To investigate the viability of using reference standards as a guide for contractors this study is necessary to quantify the impact on worker production. Changes in the perception of quality will be studied by the use of reference standards as a guide for allowable tolerances. This research seeks to investigate the impact on construction production and quality measures in a controlled study on the installation of a product with and without adherence to and the ASTM Standards.

Statement of the Purpose

The goal of any quality program in an organization is to continue to reduce the variability around the target and improve consistency. Ultimately this will achieve the goal of increasing productivity (Aft, 1998). Establishing tolerances is key to measuring improvement. Statistical Process Control (SPS) is the ongoing process to improve quality by reducing the variability with regards to the ultimate target. Setting quality targets is generally a straight forward process though it remains a challenge in the building industry as defining quality perceptions.

Manufacturing has shown that improvement in quality leads to increased productivity (Belay, 2012). Belay's study of labor-intensive manufacturing indicated a positive correlation between adoption of quality management tools and the revenue generated per employee. Though each construction project is unique in many ways, the standards specified by designers are consistent. When trained for adherence to reference standards workers quality may improve and result in increased productivity. Use of objective reference standards as opposed to more subjective measures may aid the performance of the lesser skilled worker and lead to less rework. The purpose of this study is to measure the impact on worker productivity and quality when measurable and quantifiable parameters are used.

Statement of the Need

The construction industry is adopting new technologies and management methods focused on performance improvement and to fill the void in skilled labor resulting from a shrinking work force. As the industry moves from a craft based process to a production model the role of the worker is changing. Process improvement has been studied at the macro-level with the implementation of BIM, Lean processes and robotics have been studied at a macro level but there remains a disconnect at the worker level between labor productivity and requirements for high quality. There is a need to study the standardization of methods and their implementation at the production or worker level and objectively report the impact on productivity and quality.

Statement of the Assumptions

The construction tolerance reference standards are widely accepted by the industry as a whole. Any changes in production or quality can be measured in the application of the standard. This study will utilize reference standards in the controlled installation of gypsum board as a surrogate for wider spread implementation in the field. It is assumed that the results of this study can be incorporated into other phases of the construction process.

Statement of the Limitations

The study is limited in scope to the installation of gypsum board with a sample group of less than 100 participants. Tolerance measurements will be based on ASTM C 840 Standards of Gypsum Board Installation.

Statement of Terminology

The following terms are used throughout the study. When appropriate, operational definitions have been provided along with the associated reference information.

Building Information Modeling (BIM) is the process of generating and managing building data during its life cycle. It is a model based technology linked with a database of project information. A BIM carries all information related to a facility, including its physical and functional characteristics and project life cycle information, in a series of smart objects (Forbes, 2011, p. 457)

Lean Construction is a set of ideas, practiced by individuals in the construction industry, based in the holistic pursuit of continuous improvements aimed at minimizing costs and maximizing value to clients in all dimensions of the built and natural environment: planning, design, construction, activation, operations, maintenance, salvaging, and recycling (Abdelhamid, 2011, pp. R-2).

Construction Tolerance is defined by the National Engineering Handbook Part 645 as the permissible range of variation in a dimension of an object, permissible variation of an object in some characteristic such as hardness, density or size or permissible deviation from plan alignment, location or grade (USDA, 2011).

CHAPTER TWO

REVIEW OF REVIEW OF RELATED LITERATURE

Technology

Merriam-Webster's definition of technology is; 1) technical language, 2) an applied science or a scientific method of achieving a practical purpose, 3) the totality of the means to provide objects necessary for human sustenance and comfort (Merriam-Webster, 1988). Few would contest the link between technological innovation and societal values throughout history as innovation is inherently linked with positive societal changes. In Robert W. King's article *Technology and Social Progress,* published in the Political Science Quarterly in 1961 he stated, "Technological man, so firmly seated in the saddle and virtually certain to guide social developments for years to come, what can be said of the world's probable spiritual gain or loss since the driver's chief concern will be for material gain?" (King, 1961). Rudi Volti defined technology in *Society and Technological Change*, as a "system based on application of knowledge, manifested in physical objects and organizational forms, for the attainment of specific goals" (Volti, 1995, p. 23).

Productivity and New Technology

Technological advances though history has moved the world from local artisans crafting essential items to collaboration of multinational corporations working in concert to deliver products to the market place. The manufacturing and construction industries are linked through most of modern history in the advances obtained by technology. Both industries are product-based, that is providing finished products to consumers (Halpin, 2011). As the industries have matured the link between manufacturing and the construction has remained strong though stark differences have emerged.

In manufacturing products are designed, developed, built, and marketed to an unknown purchaser. Products are mass produced based on speculation that the items will be purchased as a product; a drill, a ball bearing, or a bolt (Halpin, 2011, Chase, 2006, Hillis, 2012). Manfuacturers offer their products for sale as an end-product to a consumer or wholesaler or parts used to assemble other end use products (Halpin). The North American Industry Classification System (NAICS), was created in 1997 to provide a taxonomy of manufacturing as a guide to classification due to the complexity of the industry (Hillis). NAICS identifies manufacturing companies that are involved in the mechnical, physical, or chemical transformation of materials, substances, or components. Of the 21 major product groups for manufacturing, construction industry actvities are not included, highlighting a fundamental difference between manufacturing and construction (Hillis, p. 39).

Figure 1. Customer interaction in the manufacturing industry process.

In contrast to the manufacturing industry, the construction industry's "product" is focused on the production of a single unique end product (Halpin, 2011, Forbes, 2011, Ballast, 2011). The process begins when a client approachs a design professional to define the nature of the end product which will meet the client's needs. The conceptual product is described in a set of building plans and specifications that fulfill the need of the client. The drawings are then provided to a contractor who will "manufacture" the product. Due to the uniqueness of each project the client approachs a set of potential contractors to select the builder. In this age of mass production, the process remains similar to a 16th century customer approaching a craftsman to build a piece of furniture for his home. (Halpin).

Figure 2. Customer interaction the construction industry process.

The construction industry is made up of several product specific sectors similarly to manufacturing. Based on the end product, the industry can be broadly classified as building construction, engineered construction, and industrial construction. The building sector generally includes facilities used for habitation, educational, commercial, or recreational use. Engineered construction, also referred to as civil construction, involves projects that provide a public function and are engineering focused. In contrast, building construction is architecturally focused. Engineering construction projects are generally infrastructure, highways, dams, or utilities. Industrial construction projects are usually found in manufacturing facilities, processing plants and are highly technical (Halpin, 2011).

The United States construction industry is often credited as "the engine that keeps the economy moving" as it represents one of the largest economic sectors (Soares, 2013, Ballast, 2011, Teicholz, 2004, Borcherding, 2004, Construction Web Links, 2003). The United States Census Bureau estimated the value of buisness in the construction sector (NAICS 23) in 2012 at $1,366.427 billion, down 22.1% from 2007 level still representing 8% of the gross domestic product (GDP). Despite the recent economic downturn the Census Bureau estimated the construction industry employed 5.669 million people in 2012 (US Census Bureau, 2016). The indusry consists of large and small firms with the largest exceeding $20 billion per year in gross income and employing thousands (Halpin, 2011). In contrast with the large companies, 444,211 small contractors employee four or less employees (US Census Bureau).

Organizational Management

The manufacturing and construction industries transform materials to a finished product or structure. In the manufacturing sector operations can account for 60 to 80 percent of the cost of a product (Chase, Operations management for competivie advantages 11 ed., 2006). The construction industry is also heavily dependent on labor with a cost of 40 to 60 percent of a project (Forbes, 2011). Operation management is defined by Chase as the, "design, operation, and improvement of the systems that create and deliver the firm's primary products and services," (Chase, Operations management for competivie advantages 11 ed., p. 9). With the majority of costs of a product/project being attributed to employee payroll, productivity is key to a successful business. Productivity is generally measured as the amount of outputs divided by the inputs, (P = Outputs/Inputs). So to increase productivity output must be increased. Both industries use measures of labor as an input in determining productivity as the number of units produced per man-hour (Chase, Operations management for competivie advantages 11 ed.).

The timeline found in figure 5 represents the historical perspective of changes within the industries to improve productivity and rise of operational management in industry. This foundation of theory and practical application translates into very high worker output when comparing the United States to other industrialized nations. Most of the improvements in construction productivity have been the result of research and development work in the manufacturing industry related to construction machinery (Forbes, 2011). In spite of the improvements the construction sector lags behind its productive cousin (Teicholz, 2004).

Year	Concept	Tool	Originator
1910s	Principles of scientific management Industrial psychology Moving assembly line	Time-study and work-study concepts. Motion study Activity scheduling	Frederick Taylor Frank & Lillian Gilbreth Henry Ford and Henry L. Gantt
1930s	Quality Control Hawthorne studies of worker motivation	Sampling inspection and statistical tables for quality control. Activity sampling for work analysis	Walter Shewhart, H.F. Dodge and H.G. Romig Elton Mayo
1940s	Multidisciplinary team to approaches complex system problem	Simplex method of linear programming	Operations research groups in England and George B. Dantzig
1950s-60s	Development of operations research tools	Simulation, waiting-line theory, decision theory, mathematical programming, project scheduling techniques of PERT and CPM	Many researchers in the United States and Western Europe
1970's	Widespread use of computers in business	Shop scheduling, inventory control, forecasting, project management, MPR	Led by manufactures, IBM, Joseph Orlicky and Oliver Wight
1980's	Manufacturing strategy paradigm JIT, TQC, and factory automation Synchronous manufacturing	Manufacturing as a competitive weapon Kanban, Poka-yokes, CIM, FMS, CAD/CAM, robots. Bottleneck analysis, OPT theory of constraints	Harvard Business School faculty TAI-Ichi Ohno, W.E. Deming, J.M. Juran and engineering disciplines Eliyahu Goldratt
1990's	Total Quality Mgmt. Business process reengineering Supply chain mgt.	Baldrige quality award, ISO 9000, quality function development, value and Radical change paradigm. SAP/R3, Client/server software	National Institute of Standards and Technology, American Society of Quality Control, and ISO Michael Hammer SAP, Oracle

Figure 3. Historical summary of operations management (Chase, Operations management for competivie advantages 11 ed., 2006, p. 17)

Management in the construction industry is generally broken into four hiearchical levels; organizational, project, operation or process and tasks (figure 6). At the organizaional level, the focus is on the legal and buisness structure of the firm and interaction of the field managers. The project level is focused on time and cost control. Resources are defined by a related activity or other descriptive attribute of an activity for the purpose of maintaining a schedule. Operation and/or process is focused on the use of resourses such as time, material, labor, and equipment and the details of how the work is performed. Due to the complexity of the construction operation most are broken down further to tasks. The task level is focused on the identification and assignment of elemental portions of the work to field units and work crews (Halpin, 2011).

This tradtional concept of division of work and actions by allocation into specialized departments has come under attack. Critics point to the lack of effective communication, fragmented teams, segregated knowledge, individuality, and lack of trust as reasons to restructure the industry (Soares, 2013 vol 4). An article titled “Construction and the Internet-New Wiring” in the The Economist, dated January 15, 2000, noted that up to 30 percent of construction costs are due to inefficiencies, mistakes, delays and poor communication (Construction and the internet - new wiring, 2000) . The Construction Industry Institute (CII) estimates that in the United States, losses incurrred by errors in information when translating designs to actual construction and inter-operability between communications in the design and supply chain account for $17 to 36 billion per year (Soares, 2013 vol 4, Forbes, 2011, p. 3).

Construction Productivity

Construction productivity is lower than other industries, when comparing construction labor productivity from 1964 to 2012. A negative linear trend line shows a -0.32 percent decline with nonfarm industries during the same time period show a positive 3.06 percent per year (US

Census Bureau, 2016). The industry has justified the loss in productivity to increased regulation of the environment, climatic effects, cost of energy, loss of craft workers, and other factors (Soares, 2013 vol 4, Teicholz, 2004, 2013, Ibbs, 2012, Forbes, 2011). The cost of regulation on overall construction projects is estimated to be 3.7 percent but only contributes to a productivity loss of 0.1 percent a year according to a recent paper by the U.S. Bureau of Labor Statistics (Sveikauskas, 2014).

Productivity in the industry has been difficult to measure due to the fractured nature of the industry with two-thirds of the companies employeeing 1-4 employees, lack of cohesion between stake holders, and the unique nature of each project. The chronic problem has been ignored for the most part as the industry has clung to tradtional methods to measure project successes, delivered to the customer on time, with a reasonable profit, accident-free, and the quality conformed to the specifications and satisfied the owners needs (Forbes, 2011, Dozzi, 1993, Teicholz, 2004, Sveikauskas, 2014). In the manufacturing arena, a successful company incorporates changes to lower the cost and improve quality of each product resulting in increasing production rates and decreasing costs to customers. In contrast, the construction industry costs have risen, waste has increased and productivity has declined since 1967 (Soares, 2013 vol 4, Sveikauskas, 2014).

Poor productivity in the construction industry has recently moved to top of industry executives' minds according to a survey conducted by the Economist Intelligence Unit in November and December of 2015. Their interview of 250 global construction professionals, 73% in a senior position for companies earning $500 million or more, cited low productivity, rising costs and waste as priorities for the industry (The Economist, 2015). Seventy-five percent of the construction professionals stated lagging productivity as a major challenge recognized by their leadership, though only 48 percent believed that their firms had a firm strategy to address the problem (The Economist). The biggest reported challenges to increasing productivity were a lack of skilled labor (35%), client's procurement methods (29%), governmental requirements (26%) and aggressive project timelines (26 %). (The Economist).

In 2011, the American Society of Testing and Materials International (ASTM) adopted a new standard ASTM E2691, Practice for Job Productivity Measurement (JPM). The standard is focused on the rate of productivity while at the same time measuring job progress. JPM measures quality of the construction outcomes as measured by observed completion of the projects accepted by the customer. Use of the standard will reduce the need for end-of-the-job inspection on projects by incorporating real time inspections into the JPM as the job progresses (Daneshgari, 2011).

New Technology

Several studies indicate a trend in the industry to incorporate new technological and management processes to advance production. Building Information Modeling (BIM) and augmented reality (AR) are used to increase collaboration between designers and builders. Design-Build delivery systems are returning to the Master Builder days of integrating the project in one firms control to reduce waste, increase trust and give the customer a single point of responsibility. Each of these processes focused on the "Project" level of management in acknowledgement of the uniqueness of each project. Robotics focuses to provide a solution to a diminishing craft worker population, which also falls into the "Work Task" management level. (Ingram (2016), Jones (2012), Rethinking productivity across the construction industry (2015), Forbes (2011), Soares (2013), Teicholz (2013). Lean construction is taking Lean manufacturing principles and applying them to the construction process.

Building Information Modeling (BIM)

In 2012, 71% of architects, engineers, contractors and owners report they have become engaged with BIM on their projects, a 75% growth surge over five years. (Jones, 2012) In the 2012 survey conducted by McGraw-Hill, all BIM users report that more of their projects involve BIM, and they are forecasting even greater implementation of it over the next two years: (Jones)

The American Institute of Architects (AIA) and the American General Contractors Association (AGC) have proposed draft BIM standards. The AGC recently released in 2012 through Consensus Docs 301 BIM Addendum address three levels of reliance, regarding dimension precedence in the model.

Use of BIM by Contractors has increased dramatically and it is estimated by McGraw that 74% of contractors have adopted BIM in the 2012 survey. (Jones, 2012) The survey indicates the greatest use in large firms with 90% versus medium to small firms at 49%. Contractors point to increased profits, maintaining repeat business and greater constructability analysis as reasons to expand their use of BIM. When asked, eighty percent of contractors project an increase use of BIM on their projects. (Jones)

Expansion of design build delivery systems, LEED, and LEAN has increased the use of collaboration between designers, owners and contractors. Each of these delivery systems places quantifiable delivery of a buildings lifetime performance. To ease technical obstacles BIM models should use a common platform enabling all parties to share solutions.

Using BIM to validate constructability has quickly become standard practice among contractors using models. Use of models in fabrication of shop drawings and details of the construction process has led to increased conflict resolution and speed of construction. Model driven fabrication has increased the ability of specialty trades and suppliers to perform off site work. Jobsite planning and the logistics are applied in a practical building approach and this has led to increased use of BIM by contractors (Jones, 2012).

In addition, BIM has moved to the jobsite and is making a great impression. Contractors are using model guided tools to precisely locate penetration, hangers, embeds and other site elements. This has also lead to an increase in off-site fabrication. Validation of as-built conditions can now be accomplished by laser integration, giving true dimensions and adjusting the model during the construction process. Scope packages can be used as field planning tools for the trades viewing the work area in 3D. Also by integrating radio frequency identification technologies (RFID), materials and equipment can be tracked without delay.

As new technological advances has led to increased use of mobile devices. Wireless integration and cloud type storage has cut the limitation of use these technologies, and the industry has increased their use. This may be one of the strongest reasons BIM use has grown within construction operations. The next phase may be time and planning in a virtual reality where a building is constructed virtually.

The Bechtel Corporation used BIM exchange format which workflows were integrated by assigning meta-data to AR graphic and then used to call up asset information. A two-way exchange was formed between the AR and BIM to capture and adjust the building model based on the reality of the construction process. The new Augmented Reality Experience Language (AREL) formatted AR systems was able to combine IFC standards and building models. When data was accessed from project cloud servers, site teams could retrieve and visualize potentially unlimited project data based on position. Using AR linked to BIM lead increased worker efficiency and safety. By having BIM data available to the field team, decisions making was maximized. Studies could be conducted in future stages where no building currently existed. By linking graphics, work could be visualized as the construction process moved forward. By studying the limitations and actions of the trains, employees were able to identify the most efficient method to install the transfer deck canopy. The process was recorded and played to the workers during the preplanning phase to aid in their visualization of how the installation would be accomplished. Actual installations recordings captured the installation which mirrored the virtual installation.

The BIM execution plan is a reflection of the indivduals and their roles and responsiblities. Seveal contractual guides have been implemented recently to provide framework. AIA E202-2008 BIM Protocol and AGC's ConsususDocs 303 have been introduced to define the appropriate uses for BIM. These documents are mainly tied to Design Build contracts though they can be used as a guide to build a Project Execution Plan. (Bullain, 2011)

Dr. Messner of Pennsylvania State University, lists a BIM Project Executison Planning Procedure. He identifies four major steps that must be taken to assure a successful plan is develeoped. (Messner, 2011)

1. Identify high-value BIM uses during the project planning, design, construction and operational phases.
2. Design the BIM execustion process by creating process maps;
3. Design the BIM deliverables in the form of informantion exchanges, and
4. Develop the infrastreucture in the form of contracts, comminication procedures, technology and qualtiy control to support the implementation.

The success of implentation getting everyone on the team to understand their role. The researchers know that BIM can provide significant project benenfits. The major threat to BIM use is the lack of commuication and sharing of the model. Contracts and industry standards have been slow to devleop although principles in LEAN with its incorporation of BIM is growing expontentially.

Robotics

Japan has lead the world in innovation of the manufacturing process, automation and their use of state of the art industrial robots. The adaptation of this technology has led to the successful development and use of robots in the Japanese construction industry. In 1993, during the inaugural meeting of the British Association for Automation and Robotics in Construction (BAARC) a wall-climbing robot was introduced which could be used for analyzing the condition of building facades to determine maintenance requirements of a building without the use of scaffolding (Hughes, 1993). At the 16th International Symposium on Automation and Robotics in Construction in 1999, the Swiss Federal Institute of Technology in Zurich presented results on a fully automatic shotcrete robot which could spray concrete on a surface independently (Kochan, 2000). At The Techonomy 2012 Conference in Tucson, Arizona Electrical Contractor and Inventor, Sam Stathis, introduced a construction robot that interprets designers BIM model and transfers the layout to the physical building eliminating the need for drawing interpretation (Healey, 2012).

According to the International Federation of Robots (IFR) and their 2013 executive summary, the total number of professional service robots sold in 2012 rose by relatively low 2% compared to 2011 to which 16,067 units were sold worldwide. In 2012, about 28,100 industrial robots were shipped to the Americas, 7% more than 2011, reaching a new peak level. Between 2007 and 2012, the compound annual growth rate of robots supplied to the Americas was about 8% on average. In the United States robot shipments increased from 2011 to 2012 to 9% a peak new level of 22,414 units. Though U.S. sales and use of robots lags behind Europe, Asia, and Australia, modest growth is expected through 2016.

Building construction robots can and are being used to perform concrete work, building demolition, structural steel erection, and painting. The robots for concrete work perform the tedious tasks of placement and finishing in horizontal and vertical planes. Greater control and quality is achieved by having robots place, screed, vibrate and finish the concrete without the fatigue a tradesman would experience. KUKA a robotics manufacture, provide their KR 60 robots that perform concrete formwork that can produce 70 parts per hour surpassing a worker's output and at a high level of quality.

In 2002, researchers responded to the American Institute of Steel Construction (AISC) request to reduce the time of steel erection by 25% with the Automated Steel Construction Testbed (ASCT) project. The project-integrated research in robotic crane employs tele-operated steel beam placement, laser-based site metrology, construction component tracking, and web-enabled 3-D visualization (Lytle, 2002). The project demonstrated the ability to perform autonomous steel beam pick and place, though it did require a human operator. By demonstrating the use of a robotic crane and lase-based SMS a digital model of the work site is created. By using the same measurement system the feedback for the closed loop process provide precise positioning of the steel (Lytle). Japanese contractors are using third generation steel erection robots to build multi story buildings. By eliminating the physical and mental stress associated with steel erectors standing on columns or walking on beams while handling heavy steel members, workers remain free from danger (Bentil, 1989). The robot is controlled remotely and hoists steel members to the proper required positions holding them in place for workers to bolt or weld the pieces (Bentil).

Exterior wall painting is performed by suspending a painting robot from the roof of a building and automatically lowering it to the ground. These painting robots produce a high quality product with minimal waste. The robots can be programed to spray different types of paints and produce different textures when fitted with airless nozzles. The cost of using scaffolding is eliminated as well as the safety risk to workers and the public (Bentil, 1989).

Lean Construction

Lean construction is a management strategy to reduce waste on a project. The integrated project delivery system is based on a team partnership being established early in the projects inception. The Construction Industry Institute (CII) has defined lean construction as the "continuous process of eliminating waste, meeting or exceeding all customer requirements, focusing on the entire value stream, and pursuing perfection in the execution of a constructed project" (CII, 2005). In 2011, the Associated General Contractors of America (AGC) and Lean Construction Institute launched the Lean Construction Education Program to educate the industry in the principles of Lean construction. They explain Lean construction," is driven to minimize costs and maximize value on each project completed, challenging all stakeholders to develop and apply better ways to manage the overall construction process….Throughout the construction process- planning, design, construction, activation, operation, maintenance, salvaging, and recycling- the holistic pursuit of continuous improvement drives more efficient, effective, and economic projects" (Abdelhamid, 2011, p. v).

Lean construction is deeply rooted in the work of Frank Gilbreth who in the 1890's used manufacturing methods in the construction operation. Building on the work of Fredrick Taylor's principles he developed the idea of what he called speed work. By removing all but necessary motions made by the bricklayers he was able to increase production and provided a "best method" to install brick. As the twentieth century came to a close the concept of "master builder" where the builder was the designer and was replaced with a more fragmented industry (Forbes, 2011).

In 1983, the Construction Industry Institute (CII) was established to identify improvement methods in the industry and identify solutions. The CII sponsored a study of productivity in steel erection and discovered only 11.4 percent of recorded work was value added, and in the industrial process piping sector only 7.5 percent (CII, 2004).

Reduction of buffers and waste are key to the Lean Construction principles and can easily fold in sustainable construction techniques. Tools, such as Kanban and quality circles, management concepts perfected in the manufacturing arena such as lean production, just in time delivery (JIT), Total Quality Management (TQM) are used. Reduction in variation by utilizing statistical control methods is addressed by utilizing methods developed by Dr. Edward Deming, similar to Six Sigma used in the manufacturing industry today (Abdelhamid, 2011). The project centric nature of a Lean project enables designers and contractors to reduce waste and incorporate solutions that are in the best interest of the project. Trust is essential as the team approach is used throughout the projects' life.

Off-site fabrication has been incorporated into the Lean movement so timely arrival of components can reduce storage and waste issues. Mechanical and electrical contractors have led the charge in this area by fabricating plumbing trees and using cable trays which have the components installed long before they are delivered to the job site. Similar models are used in other industries and "just in time" delivery can aid in loss of material and cost of storage. Key to the success is the early inclusion of the suppliers with expertise in lead times and restrictions in the planning of the project.

Each of the technological trends discussed above have made significant headway at the project level with the construction industrys ongoing struggle with production. Utilizing BIM as a delivery system does increase the communication between all stakeholders given there are not software interferences. Robots on the project site will make a marginal impact on the labor shortages in the short term until the costs are competitive with those of employing craft workers. Lean construction is in its infancy but shows promise if incorporated into a complex project with a sophisticated owner. As a group they have done little to change the downward trajectory in the last ten years (Teicholz, 2013).

The use of BIM has been touted as a labor saver by many though little research has be done to show the effect it has at the “work task” level. Generally it is applauded for the integration of drawings, estimate and schedule into a common format. Clash detection software saves rework and field delays. Nassar states in his conclusion of the study of BIM in the estimating process that, “BIM will increase the precision and accuracy of the quantity aspect of the estimate, it may very well also impact the precision and accuracy of the productivity aspect as well” (Nassar, 2010, p. 64).

Construction Robotics is still many years in the future. The SAM system was established by Construct Robotics and with a grant from the National Science Foundation (NSF) in 2013 it developed an operation masonry robot in 2015 (Podkaminer, Z., 2013). The mason will continue to perform the site setup and final wall quality; SAM is aimed to improve efficiency of repetitive tasks.

The CII concluded their study on RR191-11 Application of Lean Manufacturing Principles to Construction that stated in general all construction owners and contractors would benefit from the adoption of lean principles. Due to the dynamic nature of construction and because each contractor controls such as small portion of the construction value stream it is difficult to become a lean contractor (CII, 2004). Lean construction applications statistical control are limited to process variation using time as the primary variable as its self-reported at the task work level. The aim is to reduce the “time buffer” worker use to address process delays in production (Abdelhamid, 2011, Forbes, 2011). The steps are necessary for improvement and accuracy of the information and adds to process construction at the project managerial level, though they fall short in the application in manufacturing at the task level where workers control quality through dimensional limits of products they produce for the downstream clients. Lean construction focus remains on how the process is delivered rather than a focus of what has been delivered specifically (Seymour, 2013). Founder of the Lean Construction Institute, Glenn Ballard stated in his article *A response to critics of lean construction*, “the Lean Construction community has not tried to simply imitate lean in repetive manufacturing, but to ascribe to fundamental principles, then move to new domains, and adopt them” (Ballard, 2011, p. 17).

The construction industry is characterized by a large number of small firms and a few large ones. The smaller firms have difficulty adjusting to capital intensive methods of improvements listed above (Teicholz, 2004). Additionally, these technological advances may create unintended negative consequences at the task work level. As we move from a craft based industry to one of mass production on and off the project site the need to specify measurable tolerances for components and its effect on production increases. Generally the industry reacts to greater oversight and less leeway by increasing those costs to owners.

Construction Quality

The construction industry requires the contractor to submit at completion a set of drawings that show variations from the original contract. The American Institute of Architects defines, the process in the *AIA Best Practices Guide: Terminology: As-Built Drawings, Record Drawings, and Measured Drawing*; "as-built drawings are prepared by the contractor; show, in red ink, the on-site changes to original construction documents" (AIA, 2007, p. 2). Unlike the manufacturing sector, a contractor is not held accountable to meet strict build tolerances set by the owner. The construction contract drawings and specifications are more often used as a guide for end product. The belief that each project is unique and must be crafted has long shielded the industry from incorporation of the quality standards used for decades in the manufacturing and service industries (Forbes, 2011).

The five stages of quality control evolution according to Rounds and Chi (1984) and Feigenbuam (1991) mirror the Historical Summary of Operations Management. The periods are identified as the craftsman, foreman, inspection, statistical, total quality control and total quality management.

- Pre 1900's; The Craftsman Period. Each craft person exclusively controlled the quality of their work.
- 1900 – 1918; The Foreman Period developed as the industrial revolution and large scale factories emerged. The foreman assumed responsibility of the quality of the craft workers product.
- 1918 – 1937; The Inspectors Period began as manufacturing became more complex. The large volume of manufactured goods forced the industry to move to full time inspectors, freeing the foreman to manage workers.
- 1938 -1960; Statistical quality control emerged to aid in the inspection process, making the inspection process more efficient by utilizing sampling and control charts.

- 1960 -1980; Total Quality Control emerged as a four-phase process. Customer demands and inadequate and excessive in-plant quality costs in post product inspection led to high cost with little return on quality.
- 1980 – Present; Total Quality Management, in order to provide genuine effectiveness, control must start with the design of the product and end only with a product which satisfies the customers quality expectations (Feigenbaum, 1991).

Total Quality is a group of concepts used to comprehensively run a business in the most efficient quality minded method. W. Edward Deming's cycle of improvement, Fourteen Points, and the Seven Deadly Disease are targeted at the organizational level. Vilfredo Pareto's mathematical formula developed into the Pareto Principle and is commonly referred to as the 80/20 Rule. Philip Cosby introduced the Lean and Six Sigma tools focused on the improvement of the uniformity of products. Joseph Juaran's quality trilogy provided a framework to incorporate a culture of quality into an organization. Together with several other concepts the Total Quality Management Concept was enacted throughout the manufacturing industry (Goetsch D. D., 2003).

Total Quality Management (TQM), has been recognized as an enabler for performance improvement in the construction industry (Wilder, 2012). Many contractors still are reluctant to incorporate TQM into their organization due to the additional burden of documentation (Whiteman, 2004). Of late, there have been signs of a paradigm shift with regard to the reluctance on the part of the construction industry to implement quality management tools. (Goetsch, D., 2010). Incorporation will be required at the management level and funneled to the diverse projects and stakeholders.

Variation is the random or non-random diffence in a production process that can be quantified. The key to controlling quality is keeping the variation inherent in all production processes within an acceptable, pre-specified range. Controlling variation in the construction industry requires the establishment of parameters at the task worker level that can be quantified in a fashion similar to manufacturing. Lean construction is focused on those variations as part of the external process (Abdelhamid, 2011). The link between quality and productivity is fairly straightfoward. Productivity, as stated earlier, is the saleable output divided by the resources used to produce the output. Improvements in quality directly result in an increase in productivity (Goetsch, D., 2010). The link between productivity and quality can also be highlighted by the relatively new construction ASTM standard addressing construction productivity in terms of qualtiy rather than costs as stated in ASTM E 2691, Practice for Job Productivity Measurement (JPM) in 2011. JPM measures labor productivity of the installation process on the accepted work by the owner, which means it must meet their quality requirments (Daneshgari, 2011).

Quality is often defined by several common characterstics. It is a dynamic state in which products, services, and processes must meet or exceed the customer's expectation. In the manufacturing industry a product is developed, built and marketed to a consumer base. If the product does not meet the quality expectatons it is either not purchased or returned to the manufacture (Goetsch, D., 2010). The construction industry does differ in this regard. A product is ordered by the customer based on their design criteria. The greatest challenge for the contractor is to meet the expectations of that customer and do so in an economic way. Rejection of the product/project is not a viable option at the end of the building process.

The project specifications must be thorough enough to clarify the expected quality standard so the project can be priced, built, and delivered while meeting the expectations of the consumer. Recently, designers have been more reluctant to specify quality expectations and have incorporated by reference, the industry standards to spell out the expectations of the contract (Frank, 2012).

Reference Standards

In April, 1940 John R. Nichols published an article titled, *Tolerances in Building Construction,* in the Journal of the American Concrete Institute (ACI), and famously stated, "No building is ever plumb, level, straight, and true to dimension – that is, not exactly" (Nichols, 1940, p. 493). Nichols went on to explain that tolerances are proposed to allow for variations from exactly plumb, straight, level and true, for lines, levels and dimensions of reinforced concrete buildings. After much discussion and study, the first set of construction tolerances of concrete installation were adopted as "standards" by the American Concrete Institute (Nichols, 1940).

According to the AIA's *Architect's Handbook of Professional Practice*, specification development for a construction project is to be concurrent with the design process. The final specifications reflect decisions made by the owner and design team, should be comprehensive and with the project drawings provide enough information to the contractor to estimate costs of construction based on those quality requirements (Betts, 2000).

Specifications are divided into four major categories; descriptive, proprietary, performance and reference standards. Descriptive specifications require a written description for each element used in the project and the attributes that are essential to the project requirements. Proprietary specifications list only the products and manufacturers able to be used on the project. Performance specifications identify the criteria an assembly or product must meet during operation. These type of specifications have increased recently with the rise of green building standards and Lean construction, where the outcome is critical to the additional resources the building owner has invested to decrease the life cycle costs of the project. Reference standard specifications are published, standard specifications that are incorporated into specifications by reference (Betts, 2000, CMHC, 2014, Frank, 2012). The Construction Specifications Institute (CSI) *Manual of Practice* stipulates reference standards are requirements set by authority, custom, or general consensus and are established as accepted criteria, (Construction Specifications Instititute, CSI, 2005).

There are many agencies that meet the above criteria of CSI and publish reference standards that unfortunately often overlap standards of other organizations. Designers incorporate into the specifications verbiage such as "applicable standards" to further complicate the intended requirement for the project which must be met by the contractor (Frank, 2012). ASTM is a private organization providing more than 2,000 standards (ASTM International, 2015). The American National Standards Institute (ANSI) standards range from training techniques for craft-workers and project management to building component requirements. The International Organization of Standardization (ISO) has several standards that are often cited in the construction process or their clients (ISO 9000- Quality Management and IS0-14000 Environmental Management, ISO 45001- Occupational Health, etc.)

As an example of the extent and variation of standards incorporated the following condensed version of the published Campus Standards at The University of Texas at Austin by the Project Management and Construction Services (PMCS) is referenced. They are the group that handles all design, construction and renovation projects at the university that are less then $10-million (Project Mangement & Construction Services, 2016).

SECTION 03300 – CAST-IN-PLACE CONCRETE

A. The current editions of the applicable American Concrete Institute (ACI) Publications, to the extent applicable in each reference.

B. The current editions of the applicable American Society for Testing and Materials specifications, to the extent applicable in each reference.

C. Concrete Reinforcing Steel Institute (CRSI) Manual of Standard Practices.

SECTION 03400 – STRUCTURAL PRECAST CONCRETE

A. PCI Design Handbook.

B. PCI MNL-116 Manual for Quality Control for Plants and Production of Precast and Prestressed Concrete Products.

C. ACI 318 – Latest edition of Building Code Requirements for Reinforced Concrete.

D. ACI 301 Specifications for Structural Concrete for Buildings.

E. CRSI – Manual of Standard Practice.

F. American Welding Society (AWS) D1.1 – Structural Welding Code – Steel.

G. American Society for Testing and Materials (ASTM) – Standard Specifications

SECTION 04200 – MASONRY UNITS

A. Refer also to Section 07940 for general guidance concerning the specific preferences of UT-Austin for jointing of exterior vertical surfaces for concrete and masonry.

B. Reinforced Grouted Brick Masonry, Masonry Institute of America

C. Masonry Veneer (Second Edition), Masonry Institute of America

D. Reinforced Masonry Engineering Handbook (Fifth Edition Updated), Masonry Institute of America.

E. 1997 Masonry Codes and Specifications, Masonry Institute of America

F. Reinforcing Steel in Masonry, Masonry Institute of America

G. Technical Notes on Brick Construction, Brick Industry Association

SECTION 05100 – STRUCTURAL STEEL

A. AISC Specification for Structural Steel Buildings.

B. AISC Code of Standard Practice for Steel Buildings and Bridges.

C. AISC Specification for Structural Joints Using ASTM A325 or A490 Bolts.

D. AISC Manual of Steel Construction.

E. American Welding Society (AWS) D1.1 – Structural Welding Code – Steel.

F. American Society for Testing and Materials (ASTM) – Standard Specifications

SECTION 05200 – STEEL JOISTS & JOIST GIRDERS

A. AISC Specification for Structural Steel Buildings.

B. AISC Code of Standard Practice for Steel Buildings and Bridges.

C. Steel Joist Institute Specifications.

D. AISC Manual of Steel Construction.

E. American Welding Society (AWS) D1.1 – Structural Welding Code – Steel.

F. American Society for Testing and Materials (ASTM) – Standard Specifications.

SECTION 07500 - ROOFING SYSTEMS

A. National Roofing Contractors Association (NRCA) Roofing and Waterproofing Manual

B. Sheet Metal and Air Conditioning Contractors' National Association (SMACNA) Architectural Sheet Metal

SECTION 07940 - JOINTING OF EXTERIOR VERTICAL SURFACES

A. The Secretary of the US Department of the Interior's Standards for Rehabilitation.

B. Conservation of Building and Decorative Stone, 2 vols. John Asbury.

C. Technical Notes on Brick Construction, Brick Industry Association.

D. Masonry Veneer (Second Edition), Masonry Institute of America

SECTION 09 20 00- PLASTER AND GYPSUM BOARD

09 21 13 Plaster Assemblies

1. When used at ceilings or soffits, provide access panels at regular spacing where required for access.

09 21 16 Gypsum Board Assemblies

1. Follow industry standard STC levels for different occupancy types unless specifically directed otherwise by the UT Project Manager.

2. Gypsum board should meet LEED Standard 4MR (Recycled Content).

Four of fifty primary divisions and eight scoped based sections of the CSI's MasterFormat are represented in the example above, albeit a small sample, from a traditional commercial project. The extensive number of specifications incorporated by reference in this small sample appears to be standard practice by this university's project management team and is not unusual in the industry. While the expectation of client and designer, The University of Texas above, is that the contractor be familiar with each standard and tolerances, employing them to deliver a project that meets those expectations, unfortunately this is not the case (Frank, 2012).

Conflicts within the reference standard's tolerances are also common and add to the belief that the construction will remain craft based. To reduce costs of construction projects, owners, construction managers and general contractors have split work packages utilizing multiple sub-contractors to perform work that in the past was performed by a single contractor (Suprenant, 2011). The result has exposed conflicts in tolerances within an overall scope of work. In Suprernant and Malishch (2011), conflicts were discovered when smaller sub-contractors on a large project used entirely different tolerances for concrete formwork vs. concrete reinforcing steel. In some cases the concrete reinforcing steel was installed to the standard but not be encased by concrete formed and placed within tolerances for the standards applicable for concrete formwork. (Suprenant).

Summary

Based on the literature reviewed above, it is clear that a major challenge continues to exist for the construction industry to continue to improve quality and productivity superimposed on a background of a rapid decline of skilled workers. Reluctant to change for generations, the industry is embracing new technological advances in BIM and robotics, advances in operation management tools like Lean construction and TQM. The fragmented structure of the construction industry limits the effectiveness of these advances. Each of the concepts will likely have an impact the task worker level where production is measured. But each also introduces new challenges that have not been thoroughly studied for impact at the task worker level and an increased reliance of precision-based installation. In the manufacturing industry the use of measurable tolerances at the task worker level increased quality and production though in the construction sector data is limited. There exists a multitude of construction standards, often confusing and sometimes in conflict. A study by Bradford in 2014 of gypsum board installation identified that the most utilized standard as ASTM C840 in plan specifications (Bradford, 2014). There is a need to explore the systematic implementation of construction standards on productivity and quality.

CHAPTER THREE

RESEARCH DESIGN AND METHODOLGY

The purpose of this study is to determine the impact of implementing construction tolerances in a systematic method on production and quality measures. Based on a previous discussion of the literature and findings of Bradford 2014, the decision was made to investigate the impact of ASTM C 840 standards for installation of gypsum board.

Research Question

This research seeks to investigate the impact on production and quality measures for gypsum board installation when tolerances of ASTM C 840 (Appendix F) are actively incorporated.

Specifically,

- Are there measurable differences in time and the quality of installation of gypsum board when an installer receives the ASTM C 840 training in addition to the project plans and specifications?
- Is there a measurable difference in overall quality of gypsum board installation when ASTM C 840 is used as a guide to compliance as compared to the project plans specifications only?

Research Hypothesis

1. $H0_1{:}\mu1 = \mu2$. There is no statistical significant difference in the time it takes to install gypsum board when employing plan specifications vs. ASTM C 840.

HA_1:$\mu 1 \neq \mu 2$. There is a statistical significant difference in the time it takes to install gypsum board when employing plan specifications vs. ASTM C 840.

2. $H0_2$:$\mu 1 = \mu 2$. There is no statistical significant difference in the amount of fasteners used to install gypsum board when employing plan specifications vs. ASTM C 840.

HA_2:$\mu 1 \neq \mu 2$. There is a statistical significant difference in the amount of fasteners used to install gypsum board when employing plan specifications vs. ASTM C 840.

3. $H0_3$:$\mu 1 = \mu 2$. There is no statistical significant difference in quality of gypsum board installation when employing plan specifications vs. ASTM C 840.

$H0_3$:$\mu 1 \neq \mu 2$. There is a statistical significant difference in quality of gypsum board installation when employing plan specifications vs. ASTM C 840.

Population and Sample

In order to test these hypotheses it was necessary to identify a population of subjects who have minimal to no experience in the installation of gypsum board. This allowed the evaluation of the impact of the systematic implementation of installation standards. Equally important in evaluating the hypothesis was to define a study population that had a familiarity with basic construction terms and principles. The population for this experiment consisted of students from The University of Central Missouri attending the following classes; Construction Operations, Applied Construction Management, Introduction to Construction Management, Building Structures, Construction Seminar, Principles of Construction Management or Estimating. Students were taking the classes as part of their major program of study, minor program of study or as an elective in their program of study. Other inclusion criteria are the ability to read and write English, the ability to follow instructions and participate in a post experiment survey and the ability to install gypsum board fasteners and lift approximately 30 pounds.

The University of Central Missouri had approximately 120 students majoring in Construction Management during the 2016-2017 academic year. The graduating class averages 20 with a job placement rate of 95%. Students are required to have a major related internship, complete a capstone class, Construction Operations and take the American Institute of Constructors (AIC), Associate Constructor (AC) Certification Exam in order to receive a bachelor degree.

Enrollment per semester in Construction Operations, Applied Construction Management, Introduction to Construction Management, Building Structures and Estimating are a limited to a maximum of 20 students per section respectively. Depending on the student load, there may be multiple sections of each offered in a semester.

An attempt was made to identify an appropriate sample size given the limitations of the availability of the number of students per semester. There were two study groups; the control group and the intervention group. The power of a test is the probability that the test correctly rejects the null hypothesis (H_0) when the alternative hypothesis (H_1) is correct (Dattalo, 2008). As power increases, there is a decreasing chance of a Type II error or false negative rate (β). Therefore, power = 1-β. The power of a study is dependent on the statistical significance criterion used (0.05, 0.025, 0.01), the magnitude of effect and the sample size. The power analysis for this study was based on previous study by the researcher. It was found that there exists a 15% difference in the number of fasteners installed with ASTM C840 versus standard of practice. It is estimated that there will be 25% statistical power to detect a difference of 15% using a one-tailed test at a significance level of 0.05. Those preliminary calculations indicate that a group of 80 students divided randomly over two groups would be sufficient to demonstrate a difference between experimental groups.

Those assessing the quality of the installation of gypsum board by the two experimental groups will be students enrolled in Principles of Construction Management or Plans and Specifications at The University of Central Missouri. The Quality Assessors will be blinded to group allocation.

Study Variables

This study will include both independent and dependent variables.

Independent Variables

Treatment Group

Plan Specifications

Plan Specifications + ASTM standards

Dependent Variables

Installers

Installation time in seconds, predicted and actual.

Number of fasteners installed, predicted and actual.

Quality perception ranked by the installer on a Likert scale (1-10).

Quality Assessors

Overall quality assessment initial and post on a Likert scale (1-10).

Detailed quality assessment number of faults outside the tolerances.

Both Groups

Demographics

Educational Rank (freshman, sophomore, junior, senior, graduate).

Education path (major/minor/elective)

Age

Transfer student

Construction experience in years

Lab instructions-quality

Lab materials-quality

Lab experience-quality

Research Design

The research design chosen to evaluate the intervention employed in this study was a randomized, controlled study or RCT. (Chalmers, 1981). A RCT tests an intervention on groups of subjects participating in the study that are assigned randomly to groups. The standard group does not receive the intervention while the experimental receives the intervention under investigation. RCTs are the gold standard for studies in the medical field but many RCTs are carried out in the social science setting. Researchers in Transport Science have argued that public spending should only be justified as the result of RCTs demonstrating efficacy (Graham-Rowe, 2011). Safety studies implementing new interventions can be of a modified RCT design (Mitropoulos, 2009). RCTs have also been used in evaluating a number of classroom interventions measuring behavioral and academic performances of students (Walker, 2009). This study has been designed as a parallel- group RCT in which two groups are studied in a parallel fashion with one group receiving the intervention (ASTM C 840 training).

Randomization is the process by which each subject has the same chance of being assigned to either the intervention or the control. Randomization is used to remove subject or investigator bias. The purpose of randomization is to minimize selection bias when assigning subjects to groups allowing the true effect of the intervention to be determined while other variables are kept constant (Doman, 2009). Randomization produces groups that are comparable with respect to known or unknown risk factors and baseline characteristics and guarantees the validity of statistical tests (Suresh, 2011). The randomization process can be complicated using sophisticated computer programing or as simplified as flipping a coin. Block randomization is designed to randomize subjects into groups that result in equal sample sizes across groups over time. Blocks are small and balanced with predetermined group assignments (Altman, 1999). Simple randomization or Urn randomization is based on a single sequence of random assignments (Altman). In small trials this could be problematic resulting in unequal number of participants among groups. Since this experiment will include subjects from a variety of university classes it will be important to carry out proper randomization to insure no a prior knowledge of group assignment. Trials with inadequate or unclear randomization tend to overestimate effects by up to 40% (Schul, 2002). The method of randomization for this study will be a modified adaptive biased urn randomization (Schouten, 1995). Students will draw their group allocation from a "hat" where the allocations greatly outnumber the number of possible subjects to avoid the probability of being assigned to a group that is already overrepresented.

Eligibility of subjects for an RCT is typically assessed/defined prior to randomization to a study group but before the intervention. In this study the eligibility of the population will be defined by a set of inclusion and exclusion criteria defined previously. As mentioned, the study population was pulled from students attending UCM and participating in the following Construction Management classes; Construction Operations, Applied Construction Management, Introduction to Construction Management, Building Structures, Principles of Construction Management, Seminar Construction Management and Estimating.

The purpose of blinding is to eliminate a potential source of bias for the subject, investigator or monitor in a RCT. The "blind" conceals the treatment group allocation (Day, 2000). A study in which the subject only is blinded is referred to as a single-blind study. A double-blind study is one in which the subject and the investigator are blinded to the treatment group. In a triple-blind study, all parties are blinded to the treatment group of the subject. Sometimes it is necessary in a study for the group allocation to be un-blinded or open for example when it is necessary for the subject to participate actively in the study. Blinding is necessary when there is a subjective component to a study (Heinrich, 2003). In the case of this study, it was necessary to blind the subjects as much as possible to their group allocation. This was achieved by assigning the groups to different locations. Based on the classroom setting of the experiment, it was not possible to blind the investigator entirely to the group allocation of the subjects.

Data Instrumentation and Collection

Experimental Design:

The 126 students previously described completed the experiment in groups. Prior to randomization, the subjects viewed the gypsum board installation PowerPoint and video and were provided with materials outlined in the materials section. Each group of 20 subjects was randomly assigned (see research design) to the experimental (ASTM + plan specifications) or plan specifications only (PS) groups. Once assigned to a group, the subjects were randomly paired into 2 man “crews” (CW).

Pre-Experiment:

Subjects installed gypsum board in the context of a lab assignment and aware that they were part of an experiment. The plans and specifications of a Dental Clinic Remodel project form the basis of the experiment. Students signed a consent form compliant with Institutional

Review Board (IRB), requirements of the University of Central Missouri and Indiana State University.

All subjects were provided with Drywall/Gypsum Board Installation Lab Binder containing the following documents.

- Consent Forms Indiana State University and University of Central Missouri (Appendix C)
- Drywall/Gypsum Board Installation Lab Instructions (Appendix G)
- Drywall Installation PowerPoint Presentation (Appendix E)
- Dental Clinic Remodel Plans sheets; A1.10, A7.00, A7.10 and accompanying gypsum board installation specifications pages 277-283. Dental Clinic Remodel for Port Gamble S'Klallam Tribe, 31610 Little Boston Road NE, Kingston, WA. Architect, Tromod Hellwig (Hellwig, 2015).
- Specifications for Liftlite® Drywall (Liftlite Drywall, 2015).
- MSDS Liftlite® Drywall (Liftlite Drywall, 2015).
- Chapter 32 Walls & Ceiling Surfaces, Glencoe Carpentry & Building Construction, Copyright © 2010. Text cover, pages 923-30 (McGraw-Hill Education, 2010)
- RS Means Building Construction Cost Data 2011, Table 09 29, Gypsum Board. Book Cover and page 300, item 09 29 10-30 0300 highlighted (RSMeans, 2011).
- USG Sheetrock® Brand Installation and Finishing Guide. Entire text (USG, 2015)
- ASTM C 849 Standard Specifications for Application and Finishing Gypsum Board 2008 (Appendix F).

The experimental group received additional instruction on ASTM C 840 installation specifications and a handout detailing installation standards (Appendix G).

Gypsum Board Installation:

- Each CW installed 4 pre-cut pieces of ½ in gypsum board (see materials for description) to one grid of the gypsum board apparatus (see materials for description and appendix M) using instructions outlined during instructional PowerPoint and video.
- Each member of the CW estimated the time in seconds and number of fasteners required for installation using RS Means Cost Data 09 29 Gypsum Board provided in binder and after completion will note the actual time and number of fasteners.

  Post-Installation:
- Each subject completed a quality assessment of their own installation and a post-experiment demographics and feedback survey (Appendices B and G).

Quality Assessment:

Quality Assessors completed the following

- Assess the assigned entire apparatus consisting of 4 grids for overall impression of quality (Appendix D).
- Complete a detailed quality assessment of a single randomly assigned gypsum installation grid using ASTM C 840 subsections 7.1.3.1, 7.1.4, 7.1.5, 7.4, and 8.5 to compile a total of items out of compliance with the standard (Appendix G).
- Repeat the overall quality assessment.

Apparatus:

Each of the six apparatus were composed of two standard height wood wall sections connected at their midpoint with ceiling framing partially installed creating four sections (Appendix D). Gypsum board was installed by subjects in each quadrant of the apparatus. Each apparatus was used twice with gypsum board being removed prior to the second round of installations.

Construction materials:

Gypsum Board - Liftlite® Drywall ½ inch thick seven pieces per grid.

Four pieces 45.5 x 48 inches, one 72 x 48 inches, one 48 x 48 inches, and one piece 24 x 48 inches.

Fasteners - Grip-Rite #8 x 1.25-inch Bugle-Head Black Phosphate Drywall Screw

Tools each team:

Cordless drill, drywall screw installation bit, tape measures, rasp, and utility knife.

Personal Protective Equipment:

Hardhats, gloves and protective eyewear.

Data Analysis

Data was entered and analyzed using statistical package for social science (SPSS) version 21. Descriptive statistics was carried out on demographic and survey data to determine how well matched the two study groups were. Measures of central tendency and variability were carried out on all data to instruct further statistical analysis. Means with standard deviation were reported for quantitative normality distributed data and medians for quantitative data that was not normally distributed.

For hypothesis 1, the difference in mean time in seconds between the groups, for ASTM + plan specification (experimental group) and plan specification only (control group) will be compared by using independent sample t-test or in the case that the data is not normal distributed, the Mann Whitney U-test. A simple linear regression analysis will be performed to assess any association between time (outcome) and all possible associated baseline factors. For all factors associated at a 0.25 significance level a second stage multiple linear regression analysis will be performed at the univariate level and the final model will be developed by assessing the model adequacy by using coefficient of determination. P-value less than 0.05 will be considered as statistically significant.

For hypothesis 2, the difference in mean number of fasteners between groups for ASTM + plan specification (experimental group) and plan specification only (control group) will be compared in the same manner as hypothesis 1. A simple linear regression will be carried out in the same manner as hypothesis 1.

The Quality Assessors were evaluated by two separate methods. First, they evaluated the entire apparatus consisting of four grids using the same Likert scale as the self-assessment of the installers. In the second quality evaluation, as previously described, the Quality Assessors collected quality information based on quantifiable portions of ASTM C 840 on a single randomly assigned grid to create an overall total quality score. Independent samples T-test was used to compare the total number of quality faults. The quality assessors evaluated the grids using a 1 through 10 Likert scale. The pre and post ratings were compared by a paired sample T-test. Each grid was evaluated a minimum of two times by different assessors.

CHAPTER FOUR

RESULTS

Chapter Four will present the results of the impact of the systematic implementation of installation standards on the installation of gypsum board. The experimental rationale and design have been outlined in previous chapters. The results of this research will be presented in four parts. The first part will explore the demographics of the subjects participating in the research. The remaining three parts will present data, (Appendix H), collected in the investigation of the following questions presented in Chapter 3. Specifically,

- Are there measurable differences in time and the quality (as measured by number of fasteners) of installation of gypsum board when an installer receives the ASTM C 840 training in addition to the project plans and specifications?
- Is there a measurable difference in overall quality of gypsum board installation when ASTM C 840 is used as a guide to compliance as compared to the project plan's specifications only?

The demographics of the research population will be addressed with descriptive statistical methods. The remaining research questions will be addressed by assessing the differences between the experimental and control groups with respect to the following hypothesis,

1. $H0_1$:$\mu 1 = \mu 2$. There is no statistical significant difference in the time it takes to install gypsum board when employing plan specifications vs. ASTM C 840.

$HA_1: \mu 1 \neq \mu 2$. There is a statistical significant difference in the time it takes to install gypsum board when employing plan specifications vs. ASTM C 840.

2. $H0_2: \mu 1 = \mu 2$. There is no statistical significant difference in the amount of fasteners used to install gypsum board when employing plan specifications vs. ASTM C 840.

$HA_2: \mu 1 \neq \mu 2$. There is a statistical significant difference in the amount of fasteners used to install gypsum board when employing plan specifications vs. ASTM C 840.

3. $H0_3: \mu 1 = \mu 2$. There is no statistical significant difference in quality of gypsum board installation when employing plan specifications vs. ASTM C 840.

$H0_3: \mu 1 \neq \mu 2$. There is a statistical significant difference in quality of gypsum board installation when employing plan specifications vs. ASTM C 840.

Subject Demographics and Statistics

This section will present demographics and associated descriptive statistics of the subjects participating in the research experiment. Descriptive statistics is the term given to the analysis of data that helps describe, show or summarize data in a meaningful way such that, for example, patterns might emerge from the data (Statistics, Laerd, 2015). Conclusions regarding the stated hypothesis cannot be made based on the descriptive statistics employed in this section. Measures of central tendency will inform decisions regarding analysis of data based on mean or median and the best corresponding analysis methods to address the stated hypothesis. The measures of central tendency will be included with each specific analysis.

Baseline Demographics:

One-hundred twenty six subjects participated in the research divided over eight classes in the University of Central Missouri CM program (Table 2). Eighty-two (65.1%) participated as installers and 44 (34.9%) participated as quality assessors. Subjects self-identified their year in school as follows, freshmen n=26 (20.6%), sophomore n=24 (19.0%), junior n=34 (27.0%) and senior n=42 (33.3%). Age was divided into thirds, I=18-25, II=26-35 and III=36-50. Age distribution of the entire cohort was I n=114 (90.5%), II n=5 (4%) and III n=6 (4.8%). Thirty-six percent of subjects (45) identified themselves as being non-transfer students, 64% (60) identified as transfer students and 1 subject did not respond to the question. Construction Experience (CE) was divided into quartiles by years of experience (I= 0-1 year, II= 1-2 years, III=2-5 years, and IV = >5 years). CE distribution of the entire cohort by quartile was I: n=49 (39.2%), II: n=32 (25.6%), III: n=32 (25.6%) and IV: n=12 (9.6%) with 1 subject not responding to the question. Table 2 shows the distribution of subjects over the eight CM classes included in the study. Seventy-six subjects (60%) were enrolled in freshmen and sophomore level CM classes (1300, 1301, 2210 and 2325) with the remainder of the subjects were enrolled in upper level classes at the time of the experiment.

Table 1.

Course Demographics Participants.

Course Number	Course Title	Subject's n (%)
CMGT 1300	Introduction to Construction Management	16 (12.6)
CMGT 1301	Seminars in Construction Management	22 (17.4)
CMGT 2210	Plans and Specifications	22 (17.4)
CMGT 2325	Estimating	16 (12.6)
CMGT 3010	Applied Construction Management	12 (9.5)
CMGT 3320	Principles of Construction Management	18 (14.2)
CMGT 3350	Building Structures	6 (4.7)
CMGT 4400	Construction Operations	14 (11.1)

Baseline Demographics by Study Group:

The subjects were randomized in a 1:1 fashion between the control and experimental groups. Sixty-five subjects were in the control group and 61 subjects were in the experimental group indicating that randomization was not perfect. Overall the groups were well balanced. For year in school, more subjects in the experimental group were seniors as compared to the control group (40% vs. 27.6%). The control group was slightly younger with 92.5% vs. 88.5% of the experimental group reporting an age between 18 and 25 years. While over sixty percent of subjects in each group reported construction experience of less than or equal to two years (61.5% control, 67.2% experimental), more subjects in the experimental group indicated they had less than or equal to one year of construction experience (45.9% vs. 32.3%). The majority of subjects indicated Construction Management as their major educational path (76.9% control, 70.5% experimental). More subjects in the experimental group indicated “other” as the reason for being enrolled in CM coursework (14.7% vs. 3.1%). Course enrollment was fairly balanced between the two groups and in all likelihood reflective of the randomization of subjects during their class period. There were more subjects in the experimental group enrolled in CM 4400, Construction Operations; a reflection of more seniors identified in the experimental group as well. There was missing data for one subject in the experimental group for Age, Transfer Status and Educational Path.

Table 2.

Demographics Participants.

		Control 65 (%)	Experimental 61 (%)
School Rank			
	Freshman	14 (21.5)	12 (20)
	Sophomore	13 (20)	11 (18.3)
	Junior	20 (30.7)	14 (23.3)
	Senior	18 (27.6)	24 (40)
Age			
	QI	60 (92.5)	54 (88.5)
	QII	2 (3.1)	3 (4.9)
	QIII	3 (4.6)	3 (4.9)
Transfer Student			
	Yes	41 (63)	39(63.9)
	No	24 (36.9)	21 (35)
Construction Experience			
	QI	21 (32.3)	28 (45.9)
	QII	19 (29.2)	13 (21.3)
	QIII	19 (29.2)	13 (21.3)
	QIV	6 (9.2)	6 (9.8)
Educational Path			
	Major	50 (76.9)	43 (70.5)
	Minor	7 (10.8)	5 (8.1)
	Elective Major	4 (6.1)	3 (4.9)
	Other	2 (3.1)	9 (14.7)
Course Enrollment			
	CMGT 1300	8 (12.3)	8 (13.1)
	CMGT 1301	11 (16.9)	11 (18)
	CMGT 2310	13 (20)	9 (14.7)
	CMGT 2325	10 (15.4)	6 (9.8)
	CMGT 3010	6 (9.2)	6 (9.8)
	CMGT 3320	9 (13.8)	9 (14.7)
	CMGT 3350	2 (1.5)	4 (6.5)
	CMGT 4400	6 (9.2)	8 (13.1)

Eighty-two subjects served as installers for the study refer to table 3. Forty-two were randomized to the control group and 40 to the experimental group. In the control group, 42.8% of the subjects were identified as freshmen or sophomores compared to 38.9% in the experimental group. The percentage of seniors was greater by more than 15% in the experimental group (50% vs. 33.3%). The age distribution was virtually identical in both control and experimental groups. Slightly more subjects in the experimental group reported being a transfer student as compared to the control group (62.5% vs. 60%). The control group had 54.8% of subjects with two years or less of CE and 45.3% with >2 years of experience while the experimental group had 62.5% of subjects with two years or less of CE. As reported for the overall group, the majority of subjects indicated their educational path as major (78.6% control vs. 75% experimental) and the percentage for "other" in the experimental group was higher compared to control (10% vs. 4.8%). Installers were enrolled in courses 1300, 1301, 2325, 3010, 3350 and 4400. Equal numbers of subjects in each group came from courses 1301 and 3010. Numerically more subjects in the control group were in course 1300 and 2325 and in the experimental group there were more subjects in courses 3350 and 4400.

Table 3.

Installer Demographics.

		Control 42 (%)	Experimental 40 (%)
Year in School			
	Freshman	9 (21.4)	7 (17.5)
	Sophomore	9 (21.4)	9 (21.4)
	Junior	10 (23.8)	4 (10)
	Senior	14 (33.3)	20 (50)
Age			
	QI	39 (93)	37 (92.5)
	QII	2 (4.8)	2 (5)
	QIII	1 (2.3)	1 (2.5)
Transfer			
	Yes	25 (60)	25 (62.5)
	No	17 (40)	15 (37.7)
Construction Experience			
	QI	12 (28.6)	17 (42.5)
	QII	11 (26.2)	8 (20)
	QIII	14 (33.3)	11 (27.5)
	QIV	5 (12)	4 (10)
Educational Path			
	Major	33 (78.6)	30 (75)
	Minor	3 (7.1)	3 (7.5)
	Elective Major	4 (9.5)	3 (7.5)
	Other	2 (4.8)	4 (10)
Course Enrollment			
	CMGT 1300	9 (21.4)	7 (17.5)
	CMGT 1301	9 (21.4)	9 (22.5)
	CMGT 2310	0 (0)	0 (0)
	CMGT 2325	10 (23.8)	6 (15)
	CMGT 3010	6 (14.3)	6 (15)
	CMGT 3320	0 (0)	0 (0)
	CMGT 3350	2 (4.8)	4 (10)
	CMGT 4400	6 (14.3)	8 (20)

Forty-four subjects participated as quality assessors, 24 in the control group and 20 in the experimental group refer to table 4. In both the control and experimental group, the subjects identified having achieved a higher year in school with 62.4% and 65% respectively being upper-classmen. Juniors made up the largest group with 45.8% in the control group and 45% in the experimental group. This is in contrast to the Installer group of which the majority of subjects were underclassmen. One subject did not report data for age, transfer status, construction experience and educational path. As the numbers for the quality assessors are small, the impact of one missing data point can have a profound impact on percentages. More subjects in the control group were in the first tertile for age (91.7% vs. 80%). The majority of the subjects in each group identified themselves as transfer students (70.8% control vs. 65% experimental). In both the control and experimental groups, 75% of the subjects reported less than or equal to two years of construction experience. This was higher than both groups of the Installers and higher than the Overall group. "Major" as educational path was reported by 78% of the control group and 60% of the experimental group. Twenty-five percent or 5 subjects in the experimental group reported "other" as their educational path but the relatively low numbers of quality assessors drives the high percentage. All quality assessors were enrolled in courses 1301, 2310 and 3320 with all but 2 subjects in each group coming from courses 2310 and 3320.

Table 4.

Quality Assessor Demographics

		Control 24 (%)	Experimental 20 (%)
Year in School			
	Freshman	5 (20.8)	5 (25)
	Sophomore	4 (16.6)	2 (10)
	Junior	11 (45.8)	9 (45)
	Senior	4 (16.6)	4 (20)
Age			
	QI	22 (91.7)	16 (80)
	QII	0 (0)	1 (5)
	QIII	2 (8.3)	2 (10)
Transfer			
	Yes	17 (70.8)	13 (65)
	No	7 (29.2)	6 (30)
CE			
	QI	10 (41.6)	10 (50)
	QII	8 (33.3)	5 (25)
	QIII	5 (20.8)	2 (10)
	QIV	1 (4.1)	2 (10)
Educational Path			
	Major	18 (78)	12 (60)
	Minor	4 (16.6)	2 (10)
	Elective Major	0 (0)	0 (0)
	Other	2 (8.3)	5 (25)
Course Enrollment			
	1300	0 (0)	0 (0)
	1301	2 (8.3)	2 (10)
	2310	13 (54.1)	9 (45)
	2325	0 (0)	0 (0)
	3010	0 (0)	0 (0)
	3320	9 (37.5)	9 (45)
	3350	0 (0)	0 (0)
	4400	0 (0)	0 (0)

Research Question 1: Differences in Installation Time

Research question 1 investigated the impact of the active incorporation of ASTM C 840 tolerances for gypsum board installation on the installation time. Specifically, are there measurable differences in installation time between two different groups when one group uses project plans only and the other group uses plans plus ASTM C 840 standards? The research hypothesis tested was as follows;

- $H0_1{:}\mu1 = \mu2$. There is no statistical significant difference in the time it takes to install gypsum board when employing plan specifications vs. ASTM C 840.
- $HA_1{:}\mu1 \neq \mu2$. There is a statistical significant difference in the time it takes to install gypsum board when employing plan specifications vs. ASTM C 840.

The hypothesis was tested using the independent samples t-test. For this hypothesis, the independent variable was the control or experimental installer group. The dependent variable was time measured in seconds.

Independent-samples t-test Hypothesis 1

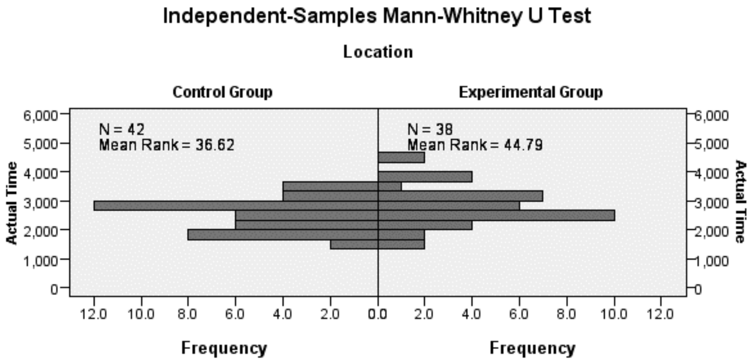
Independent-samples T-test Results:

According to the independent-samples t-test, there was not a statistically significant difference in installation time between the control group and the experimental group, M = 2523.24 vs. 2803.55, 95% CI [-565.85, 5.223], t (78) = -1.954, p = .054. Therefore the null hypothesis there is no statistical significant difference in the time it takes to install gypsum board when employing plan specifications vs. ASTM C 840 cannot be rejected.

Mann-Whitney U Test Hypothesis 1

Mann-Whitney U Test Results:

The Mann-Whitney U test can be used when data fails the assumptions of the independent-samples t-test and particularly in this case, is less sensitive to outliers (Mann, 1947). A Mann-Whitney U test was run on the Installers cohort to determine if there were differences in Actual Installation Time between the control group and the experimental group. Distributions of the engagement scores for the control group and the experimental group were similar, as assessed by visual inspection (Figure 9). Actual Installation Time for the control group (mean rank = 36.62) and the experimental group (mean rank = 44.79) were not statistically significantly different, U = 961, z = 1.571, p = .116. Therefore the null hypothesis there is no statistical significant difference in the time it takes to install gypsum board when employing plan specifications vs. ASTM C 840 cannot be rejected.



Total N	80
Mann-Whitney U	961.000
Wilcoxon W	1,702.000
Test Statistic	961.000
Standard Error	103.761
Standardized Test Statistic	1.571
Asymptotic Sig. (2-sided test)	.116

Figure 4. Mann-Whitney U Results, Hypothesis 1.

Multiple Linear Regression Hypothesis 1

Multiple Linear Regression Results:

Summary Statistics and Correlations

The total number of valid data points available for the multivariate analysis was 82 for hypothesis 1. It has been recommended that there be 10 events per variable (EPV) for multivariate work (Hayden, 2008, p. 123). Seven variables are being used included in the model so 82 cases should be sufficient for modeling work. The total n for each variable is 82, there was no missing data, so 82 is the basis for the regression model.

Table 5.

Summary Statistics, Model Variables.

Variable	Frequency	Mean	Std. Dev.
Actual Time	82	2723.30	771.92
Location (control vs experimental)	82	1.49	.503
Class Standing (1,2,3,4)	82	2.80	1.180
Transfer (Y/N)	82	1.39	0.491
CE (1,2,3,4)	82	2.17	1.040
Age (1,2,3)	82	2.10	0.372
Course Enrolled (1-7)	82	2429.73	1149.33
Educational Path (1,2,3)	82	1.46	0.932

Table 6.

Pearson Correlation Results

	Time	Location	Rank	Transfer	CE	Age	Course	Ed. Path
Time	1.000	.267*	-.048	.241	-.073	-.151	-.142	.025
Location	.267*	1.000	.100	.020	.028	-.125	.151	-.040
Rank	-0.48	.100	1.000	-.101	.178	.212*	.566*	.117
Transfer	.241*	.020	-.101	1.000	-.011	-.076	-.048	.140
CE	-.073	.028	.178	-.011	1.000	.212*	.188*	-.083
Age	-.151	-.125	.212*	-.076	.212*	1.000	.086	-.061
Course	-.142	.151	.566*	-.048	.188*	.086	1.000	-.038
Ed. Path	.025	-.040	.117	.140	-.083	-.061	-.038	1.000

(*Note* *=p<.05)

The Pearson correlation coefficients for the dependent variable (Actual Time) with each of the independent variables show a statistically significant correlation between the location of the experiment (representing control vs. experimental) and the transfer status of the subject. Within the independent variables, there are significant correlations between age and class standing, age and construction experience, construction experience and course enrolled and class standing and course enrolled.

Multiple Regression Results

The multiple regression model tested the Actual Time as the dependent variable and the independent variables of location, class standing, transfer status, CE, age, course enrolled and educational path as the independent predictor variables. The results of the ANOVA procedure for the F statistic shows that the model is statistically significant

$F(7,74)=2.179$, $p< .05$.

Based on the criteria for constructing this model, the only significant independent variables were location and transfer status. The remaining independent variables entered in the model did not significantly impact the regression equation.

Table 7.

Multiple Regression Coefficients

Variable	B	SE B	Β	t	Sig.
Constant	2269.72	640.94		3.541	.001
Location	419.11	166.52	.273*	2.517	.014
Class Standing	65.23	87.94	.100	.742	.461
Transfer	363.06	169.70	.231*	2.139	.036
CE	-27.69	82.04	-.037	-.338	.737
Age	-198.99	232.53	-.096	-.856	.395
Course Enrolled	-.144	.088	-.214	-1.637	.106
Educational Path	-20.70	90.85	-.025	-.228	.820

(Note: R^2=.171, * = p< .05)

A multiple correlation coefficient was reported of R=.413. The R^2 value is .171, indicating that the model only accounts for 17.1% of the variability in the dependent variable Actual Time. The adjusted R^2 for this model is .092, which is a decrease of .079. Therefore, based on a sample size of 82, the difference in variability between the sample and the overall population is 7.9%.

Summary and Regression Equation:

A multiple regression was run to predict Actual Installation Time from seven independent variables outlined above. The multiple regression model statistically significantly predicted $F(7,74)=2.179$, $p< .05$. adj. $R^2 = .092$. The variables of location and transfer status statistically significantly added to the model, $p < .05$. The final multi linear regression equation for Hypothesis 1 is:

Actual Installation Time= 2269 +(.273*Location) +(.231*Transfer) +(-.214*Course Enrolled)

+(.100*Class Standing)+(-.096*Age)+(-.037*CE)+(-.025*Educational Path) with Location and Transfer being statistically significant.

Research Question 2: Differences in Number of Fasteners Installed

Research question 1 investigated the impact of the active incorporation of ASTM C 840 tolerances for gypsum board installation on the number of Actual Fasteners Installed. Specifically, are there measurable differences in the number of fasteners installed between two different groups when one group uses project plans only and the other group uses plans plus ASTM C 840 standards. The research hypothesis tested was as follows;

- $H0_2: \mu 1 = \mu 2$. There is no statistical significant difference in the amount of fasteners used to install gypsum board when employing plan specifications vs. ASTM C 840.
- $HA_2: \mu 1 \neq \mu 2$. There is a statistical significant difference in the amount of fasteners used to install gypsum board when employing plan specifications vs. ASTM C 840.

The hypothesis was tested using the independent samples t-test. For this hypothesis, the independent variable will be the control or experimental installer group. The dependent variable will be the number of fasteners.

Independent-samples t-test Hypothesis 2

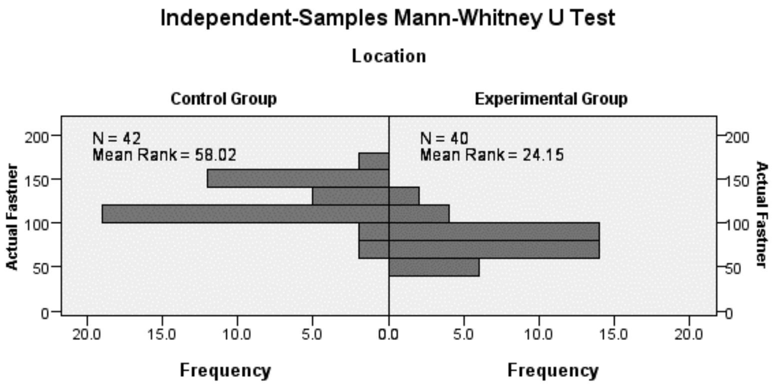
Independent-Samples T-test Results:

According to the Independent-samples t-test, there was a statistically significant difference in Actual Fasteners Installed between the control group and the experimental group, $M = 121.33$ vs. 79.98, 95% CI [32.10, 50.61], $t\ (80) = -8.896$, $p = .001$. Therefore the null hypothesis there is no statistical significant difference in the amount of fasteners used to install gypsum board when employing plan specifications vs. ASTM C 840 can be rejected in favor to the alternative hypothesis. There is a significant difference in the number of fasteners installed in favor of the experimental group.

Mann-Whitney U Test Hypothesis 2

Mann-Whitney U Test Results:

A Mann-Whitney U test was run on the cohort to determine if there were differences in Actual Fasteners Installed between the control group and the experimental group. Distributions of the engagement scores for the control group and the experimental group were similar, as assessed by visual inspection (Figure 4). Actual Fasteners Installed for the control group (mean rank = 58.02) and the experimental group (mean rank = 24.15) were statistically significantly different, $U = 146$, $z = -6.444$, $p = .001$. Therefore the null hypothesis there is no statistical significant difference in amount of fasteners installed when employing plan specifications vs. ASTM C 840 can be rejected.



Total N	82
Mann-Whitney U	146.000
Wilcoxon W	966.000
Test Statistic	146.000
Standard Error	107.695
Standardized Test Statistic	-6.444
Asymptotic Sig. (2-sided test)	.000

Figure 5. Mann Whitney U Test Hypothesis 2

Multiple Linear Regression Hypothesis 2:

Multiple Linear Regression Results:

Summary Statistics and Correlations

Table 8.

Summary Statistics, Model Variables.

Variable	Frequency	Mean	Std. Dev.
Actual Fasteners	82	101.16	29.495
Location (control vs experimental)	82	1.49	.503
Class Standing (1,2,3,4)	82	2.80	1.180
Transfer (Y/N)	82	1.39	0.491
Construction Experience (1,2,3,4)	82	2.17	1.040
Age (1,2,3)	82	2.10	0.372
Course Enrolled (1-7)	82	2429.73	1149.33
Educational Path (1,2,3)	82	1.46	0.932

Table 9.

Pearson Correlation Results

	Time	Location	Rank	Transfer	CE	Age	Course	Edu. Path
Act. Fastener	1.000	-.705*	.065	-.005	-.142	.022	.029	.049
Location	-.705*	1.000	.100	.020	.028	-.125	.151	-.040
Standing	.065	.100	1.000	-.101	.178	.212	.566*	.117
Transfer	-.005	.020	-.101	1.000	-.011	-.076	-.048	.140
CE	-.142	.028	.178	-.011	1.000	.212*	.188*	-.083
Age	.022	-.125	.212*	-.076	.212*	1.000	.086	-.061
Course	.029	.151	.566*	-.048	.188*	.086	1.000	-.038
Edu. Path	.049	-.040	.117	.140	-.083	-.061	-.038	1.000

(*Note.**=p<.05)

The Pearson correlation coefficients for the dependent variable (Actual Fasteners Installed) with each of the independent variables show a statistically significant correlation between the location of the experiment (representing control vs. experimental). Within the independent variables, there are significant correlations between age and class standing, age and construction experience, construction experience and course enrolled and class standing and course enrolled.

Multiple Regression Results:

The multiple regression model tested the Actual Fasteners Installed as the dependent variable and the independent variables of location, class standing, transfer status, CE, age, course enrolled and educational path as the independent predictor variables. The results of the ANOVA procedure for the F statistic shows that the model is statistically significant $F(7,74)=12.989$, $p< .05$. Based on the criteria for constructing this model, the only significant independent variables was location. The remaining independent variables entered in the model did not significantly impact the regression equation.

Table 10.

Multiple Regression Coefficients.

Variable	B	SE B	β	t	Sig.
Constant	170.56	18.01		9.467	.000
Location	-43.36	4.68	-.739*	-9.265	.001
Class Standing	3.132	2.472	.125	1.267	.209
Transfer	1.281	4.770	.021	.269	.789
CE	-4.207	2.306	-.148	-1.824	.072
Age	-5.853	6.536	-.074	-.896	.373
Course Enrolled	.003	.002	.104	1.081	.283
Educational Path	-.362	2.554	-.011	-.142	.888

(*Note*: R^2=.551, * = p< .05)

A multiple correlation coefficient was reported of R=.743. The R^2 value is .551, indicating that the model only accounts for 55.1% of the variability in the dependent variable Actual Time. The adjusted R^2 for this model is .509, which is a decrease of .042. Therefore, based on a sample size of 82, the difference in variability between the sample and the overall population is 4.2%.

Summary and Regression Equation

A multiple regression was run to predict Actual Fasteners Installed from seven independent variables outlined above. The multiple regression model statistically significantly predicted F (7,74)=12.989, p< .05. adj. R^2 = .509. Only the variable of location statistically significantly added to the model, $p < .05$. The final multiple linear regression equation for

Hypothesis 2 is:

Actual Fasteners Installed= 170.56 +(-.739*Location) +(-.148*CE) +(.125*Class Standing) +(.104*Course Enrolled)+(-.074*Age)+(.021*Transfer)+(-.011*Educational Path) with Location being statistically significant.

Research Question 3: Quality of Installation

Research question 3 investigated the impact of the active incorporation of ASTM C 840 tolerances for gypsum board installation on the number of Quality of Installation. Specifically, are there measurable differences in the quality of installation between two different groups when one group uses project plans only and the other group uses plans plus ASTM C 840 standards. The research hypothesis tested was as follows;

- $H0_3$:$\mu 1 = \mu 2$. There is no statistical significant difference in quality of gypsum board installation when employing plan specifications vs. ASTM C 840.
- $H0_3$:$\mu 1 \neq \mu 2$. There is a statistical significant difference in quality of gypsum board installation when employing plan specifications vs. ASTM C 840.

The hypothesis was tested using the independent samples t-test. For this hypothesis, the independent variable will be the control or experimental group. The dependent variable will be the number of Total (quality) Faults. A total of 126 quality tests carried out in research question 3 with 80 in the control group and 66 in the experimental group.

Independent-samples t-test Hypothesis 3

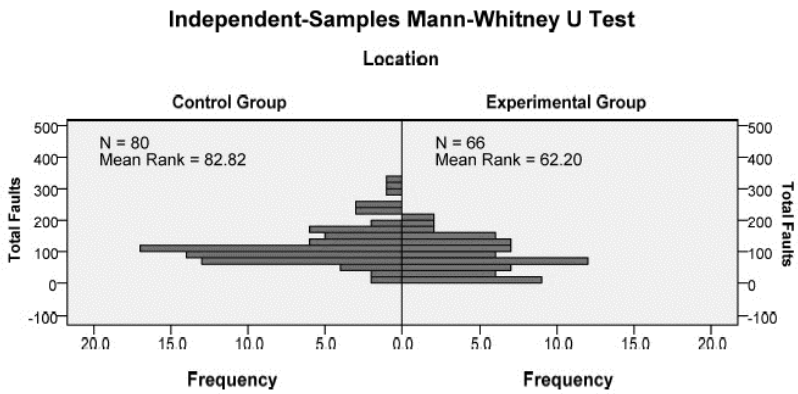
Independent-samples t-test results:

In hypothesis 3, the assumption of homogeneity of variances was violated. A Welch t-test was run to determine if there were differences in total (quality) faults between the control and experimental groups (Howell, Statistical methods for psychology, (7th ed.), 2010). According to the Welch t-test, there was a statistically significant difference in total (quality) faults between the control group and the experimental group, M = 118.80 vs. 86.11, 95% CI [12.183, 52.205], t (144) = 3.312, p = .001. Therefore the null hypothesis there is no statistical significant difference in the total (quality) faults assessed in the installation of gypsum board when employing plan specifications vs. ASTM C 840 can be rejected.

Mann-Whitney U Test Hypothesis 3

Results:

Due to the presence of outliers a Mann-Whitney U test was run on the cohort to determine if there were differences in total (quality) faults between the control group and the experimental group. Distributions of the engagement scores for the control group and the experimental group were similar, as assessed by visual inspection (Figure 5). Total (quality) faults for the control group (mean rank = 82.82) and the experimental group (mean rank = 62.20) were statistically significantly different, U = 1,894, z = -2.934, p = .003. Therefore the null hypothesis there is no statistical significant difference in the quality of gypsum board installation as measured but total (quality) faults when employing plan specifications vs. ASTM C 840 can be rejected.



Total N	146
Mann-Whitney U	1,894.000
Wilcoxon W	4,105.000
Test Statistic	1,894.000
Standard Error	254.304
Standardized Test Statistic	-2.934
Asymptotic Sig. (2-sided test)	.003

Figure 6. Mann Whitney U Test, Total (quality) Faults

Paired Samples t-test: Pre and Post QC Rating

Results:

A paired samples t-test was conducted on the pre and post QC rating of gypsum board installation by the quality assessors. There was a statistically significant difference in QC reporting in the pre QC rating compared to the post QC rating, M = 1.473 95% CI [1.029, 1.917], t (128) = 6.565, p < .001, d= .57 There was a statistically significant difference between means (p < .05), and therefore, we can reject the null hypothesis and accept the alternative hypothesis. The effect size was .57 or a medium effect (Cohen, 1988).

Summary

This chapter has presented a summary of the results of the impact of the systematic implementation of installation standards on the installation of gypsum board.

The first part of the chapter used basic demographics to describe the subjects that participated in the research. The baseline demographics were presented for the entire group, the group of installers and the quality inspectors. Almost 2/3 of subjects participated as installers and the remainder as inspectors. There was a high rate of transfer students in all groups as were subjects who indicated Major as their educational path. The installers and quality assessors had almost no overlap in the class being taken at the time of the experiment. Other interesting demographics will be discussed in Chapter Five.

The remainder of the chapter investigated the three research hypotheses stated at the beginning of this chapter. Hypothesis 1, the difference in installation time between the two groups was found to be non-significant by both the Welch's t-test and the Mann-Whitney U test (Table 11). This result is interesting as there was no impact on time when the experimental group was asked to employ an unfamiliar standard for the first time in addition to plan specifications. A linear multiple regression showed a significant impact on installation time of location (control vs. experimental) and transfer status.

Hypothesis 2, the difference in Actual Fasteners Installed was found to be significantly different by both the independent samples t-test and the Mann-Whitney U test with the experimental group using less fasteners vs. the control group (Table 11). A linear multiple regression showed a statistically significant impact on Actual Fasteners Installed by location (control vs. experimental).

Hypothesis 3 investigated the perception of quality both represented as total (quality) faults and quality assessor's perception of quality. Both the independent samples t-test and the Mann-Whitney U test found statistically significant differences in total faults in favor of the experimental group. A paired samples t-test showed that there was a statistically significant difference in QC reporting between pre and post ASTM C 840 training (Table 11).

Table 11.

Summary of Test Results.

Hypothesis		Test	Outcome
$H0_1: \mu 1 = \mu 2$	No significant difference in time	Independent samples t-test	Accept
		Mann Whitney U	
		Multiple Regression	
$H0_2: \mu 1 = \mu 2$	No significant difference fasteners	Independent samples t-test	Reject
		Mann Whitney U	
		Multiple Regression	
$H0_3: \mu 1 = \mu 2$	No significant difference in quality	Independent samples t-test	Reject
		Mann Whitney U	
		Paired Samples t-test	

The results from Chapter Four, implications and opportunities will be discussed in more detail in Chapter Five.

CHAPTER FIVE

FINDINGS RECCOMENDATIONS AND CONCLUSIONS

The construction industry is being challenged to improve the outcomes of the building process. Falling behind other industries in worker productivity, quality products, and facing a skilled worker shortage the industry is looking for solutions to correct a downward trend. Current research and industry outreach have been focused on a macro approach to right the ship. There is a need to study outcomes on worker productivity and quality when tolerances are actively employed. The focus of this research explores the impact on production, material use, and quality when workers are trained to use existing tolerances at the micro level. This chapter will review the purpose of the study, the research hypotheses and the methodology. Findings will be discussed as well as implications for the construction industry with recommendations for future research.

Statement of the Purpose

Use of objective reference standards as opposed to more subjective measures may aid the performance of the lesser skilled worker and lead to less rework. The purpose of this study is to measure the impact on worker productivity and quality when measurable and quantifiable parameters are used.

This study will utilize reference standards in the installation of gypsum board as a surrogate. It is assumed that the results of this study can be incorporated into other phases of the construction process.

The purpose of this study is to determine the impact of implementing construction tolerances in a systematic method on production and quality measures. Based on a previous discussion of the literature and findings of Bradford 2014, the decision was made to investigate the impact of ASTM C 840 standards for installation of gypsum board.

Specifically,

- Are there measurable differences in time and the quality of installation of gypsum board when an installer receives the ASTM C 840 training in addition to the project plans and specifications?
- Is there a measurable difference in overall quality of gypsum board installation when ASTM C 840 is used as a guide to compliance as compared to the project plans specifications only?

Research Hypothesis

1. $H0_1$:$\mu 1 = \mu 2$. There is no statistical significant difference in the time it takes to install gypsum board when employing plan specifications vs. ASTM C 840.

HA_1:$\mu 1 \neq \mu 2$. There is a statistical significant difference in the time it takes to install gypsum board when employing plan specifications vs. ASTM C 840.

2. $H0_2$:$\mu 1 = \mu 2$. There is no statistical significant difference in the amount of fasteners used to install gypsum board when employing plan specifications vs. ASTM C 840.

HA_2:$\mu 1 \neq \mu 2$. There is a statistical significant difference in the amount of fasteners used to install gypsum board when employing plan specifications vs. ASTM C 840.

3. $H0_3{:}\mu1 = \mu2$. There is no statistical significant difference in quality of gypsum board installation when employing plan specifications vs. ASTM C 840.

$H0_3{:}\mu1 \neq \mu2$. There is a statistical significant difference in quality of gypsum board installation when employing plan specifications vs. ASTM C 840.

This interventional research utilized a randomized group of construction management students from The University of Central Missouri to represent a cohort of “unskilled” workers and inspectors to model the impact of the first exposure to the implementation of a building standard. The student subjects conducted the experiment in the setting of the normal laboratory portion of a class period during the Fall 2016 semester. The subjects were randomized to two groups and assigned to install gypsum board to a standardized apparatus (Appendix D) based on plan specifications only or plan specifications and ASTM C 840 standards. Subjects were asked to estimate the time it would take to install, capture the actual time to install, actual number of fasteners installed and rate the quality of the installation in a pre-specified manner. A separate group of quality assessors assessed the quality of the installation both prior to and after ASTM C 840 training, by total quality faults and by faults by location. Baseline demographics were captured and analyzed for all subjects including age, construction experience, year in school, transfer status, course enrolled, and educational path. The demographics captured were chosen for their impact on the skill level of the subject. Additionally, information was collected to insure groups were treated equitably with respect to experimental condition. Institutional Review Board approval was received by Indiana State University and The University of Central Missouri to conduct this experiment.

Methodology

One-hundred twenty six subjects participated in the research divided over eight classes in the University of Central Missouri CM program. Eighty-two (65.1%) participated as installers and 44 (34.9%) participated as quality assessors.

Once the data collection was collected, the raw data was compiled for analysis with SPSS software. A combination of descriptive and inferential statistical techniques was used to analyze the data. The research hypothesis 1-3 used an independent samples t- test, a Welch t-test and Mann-Whitney U Test. Research hypothesis 1 and 2 also used a multiple regression analysis. Additional analysis of data of hypothesis 3 data was analyzed by a paired t-test. A Type-1 error rate of .05 was used for hypothesis testing. G*Power software was used to perform a power analysis for each research hypothesis based on the obtained sample size.

Research Findings

Hypothesis 1 explored the impact of the impact of the implementation of an additional standard on the time to complete the installation of gypsum board. Specifically, does it take longer to install gypsum board when you require the installers to not only follow the plan specifications but also employ the ASTM C 840 standard. There were 42 control and 38 experimental subjects. A Welch t-test was run to determine if there were differences in time to install gypsum board. There were 3 outliers in the data as assessed by inspection of a boxplot. Installation times were normally distributed as assessed by Shapiro-Wilk's test ($p>.05$). There was homogeneity of variances for the two groups as assessed by Levene's test for equality of variances ($p=.249$). There was not a statistically significant difference in installation time between the control group and the experimental group, M = 2523.24 vs. 2803.55, 95% CI [-

565.85, 5.223], *t* (78) = -1.954, *p* = .054. Similarly, for the Mann Whitney U test, Actual Installation Time for the control group (mean rank = 36.62) and the experimental group (mean rank = 44.79) were not statistically significantly different, *U* = 961, *z* = 1.571, *p* = .116. So it must be concluded that there is no difference in the installation time between the group using plans specifications only and the group using plans plus the ASTM C 840 standard. Thus in this limited setting, it can be concluded that it takes no additional time to follow the ASTM C 840 standard when installing gypsum board.

A multiple linear regression evaluated the impact baseline characteristics as a surrogate for experience on the dependent variable of time. There was linearity as assessed by partial regression plots and a plot of studentized residuals against the predicted values. Independence of residuals was assessed by a Durbin-Watson statistic of 1.050. There was homoscedasticity, as assessed by visual inspection of a plot of studentized residuals versus unstandardized predicted values. The studentized deleted residuals were not greater than -3SD but were slightly greater than +3SD. There were leverage values >.2 (.389) but no Cook's distances above 1. The assumption of normality was met, as assessed by Q-Q plot. The final MLR equation was a follows:

Actual Installation Time= 2269 +(.273*Location) +(.231*Transfer) +(-.214*Course Enrolled) +(.100*Class Standing)+(-.096*Age)+(-.037*CE)+(-.025*Educational Path) with Location and Transfer being statistically significant.

Location defines control vs. experimental showing that in terms of a multiple regression, there is a statistically significant impact on the MLR equation of the control vs. experimental groups. Significant also, is the transfer status of the subject. It is unclear why transfer status influenced this result. To be clear, while there were significant predictors, R^2 was quite modest for this model calling into question the validity of this model.

Hypothesis 2 explored the impact of adding ASTM C 840 to plan specifications on the number of fasteners installed. Number of fasteners installed was chosen as an endpoint because of its direct impact on material costs and a calculated impact on installation time, ie. it is known how much time it takes to install each fastener so the differences in fasteners can be translated into time. There were 42 control and 40 experimental subjects. There were five outliers in the experimental group as assessed by the inspection of a boxplot. The number of fasteners installed by each group was normally distributed, as assessed by Shaprio-Wilk's test ($p>.05$). The assumption of homogeneity of variances was met as assessed by Levene's test for equality of variances ($p=.118$). According to the independent samples t-test (M = 121.33 vs. 79.98, 95% CI [32.10, 50.61], t (80) = -8.896, p = .001.) and the Mann Whitney U test (U = 146, z = -6.444, p = .001.), there was a significant difference in the number of fasteners installed in the control group vs. the experimental group with less fasteners being installed in the experimental group. A multiple linear regression evaluated the impact baseline characteristics as a surrogate for experience on the dependent variable of number of fasteners installed. There was linearity as assessed by partial regression plots and a plot of standardized residuals against the predicted values. The Durbin-Watson statistic was .904. There was homoscedasticity as assessed by the inspection of a plot of studentized residuals versus unstandardized predicted values. There were no studentized deleted residuals greater than $\pm$ 3 SD and no values for Cook's distance above 1.0. There were leverage values >.2 (.389). The multiple regression model statistically significantly predicted $F (7,74)=12.989$, $p< .05$. adj. R^2 = .509. Only the variable of location statistically significantly added to the model, p < .05. The final MLR equation was as follows:

Actual Fasteners Installed= 170.56 +(-.739*Location) +(-.148*CE) +(.125*Class Standing) +(.104*Course Enrolled)+(-.074*Age)+(.021*Transfer)+

(-.011*Educational Path) with Location being statistically significant. Fifty-percent of the variability in the dependent variable, Actual Fasteners Installed, is accounted for by the model.

Hypothesis 3 explored the impact of adding ASTM C 840 to plan specifications on the quality of gypsum board installation. The quality assessor cohort of subjects measured quality in a number of ways. Overall quality was measured on an ordinal scale pre and post ASTM C 840 training of the randomized quality assessor cohort (control vs. experimental). In addition, quality assessors tabulated faults according to individual requirements of the standard and overall total quality faults. Additional information was captured from the installer cohort regarding the impression of the quality of their installation.

A Welch t-test was run to explore the differences between the number of Total (quality) Faults between the control and experiment groups as assessed by the quality assessors. There were 80 tests in the control group and 66 in the experimental group. There were 3 outliers in the experimental group as assessed by inspection of a boxplot. Total Faults were normally distributed for the control but not the experimental group as assessed by Shapiro-Wilk's test ($p>.05$). The assumption of homogeneity as not violated, as assessed by Levene's test for equality of variances ($p=.569$). According to the Welch t-test, there was a statistically significant difference in Total (quality) faults between the control group and the experimental group, M = 118.80 vs. 86.11, 95% CI [12.183, 52.205], t (144) = 3.312, p = .001. The Mann Whitney U test also showed the Total (quality) Faults for the control group (mean rank = 82.82) and the experimental group (mean rank = 62.20) were statistically significantly different, U = 1,894, z = -

2.934, $p = .003$. Both tests concluded there was a statistically significant difference in Total (quality) Faults between the control and experimental groups with fewer faults occurring in the experimental group.

A paired t-test was conducted to determine if there were significant differences in the impression of overall quality after the quality assessors were ASTM C 840 trained. No outliers were detected that were more than 1.5 box-lengths from the edge of the box in a boxplot. The assumption of normality was not violated as assessed by Shapiro-Wilk's test (p=.101). There was a statistically significant difference in QC reporting in the pre QC rating compared to the post QC rating, $M = 1.473$ 95% CI [1.029, 1.917], t (128) = 6.565, $p < .001$, d= .57. So it can be concluded that after ASTM C 840 training, the quality assessors' impression of quality of gypsum board installation changed and quality ratings decreased.

Discussion of Findings

Demographics

The overall intent of this research is to explore opportunities to avenues other than manpower to positively impact the shortage of unskilled worker. Chapter 2 discussed the shortage of unskilled workers in the construction industry. According to Merriam-Webster, unskilled worker performs labor that requires relatively little or no training or experience for its satisfactory performance (Merriam-Webster, 1988). To answer the questions regarding the effect of employing the ASTM C 840 standard on gypsum board installation, an "unskilled" worker group needed to be modeled. As previously described, the subjects for this study were UCM students enrolled in Construction Management classes. The study was limited to this group for several reasons; it was assumed that like an unskilled worker entering the construction industry, there would be a baseline interest in construction, the subjects would have access and class time to conduct the experiment in the CM facilities and the subjects would have baseline familiarity with construction tools and safety requirements.

The subjects were divided into two groups, installers who worked in pairs to install gypsum board in the control group or the experimental group and quality assessors who worked independently to assess the quality of the installation of either the control group or the experimental group. Results of the installation and quality assessment have been reported above.

The installers (n=82) were mostly between 18-25 yrs. (92%), which is a similar age to the unskilled worker starting in construction (Johnson, 2013). The majority reported having less than 2 years of construction experience (54.8% control vs. 62.8% experimental). For the purposes of the demographic survey, CE was undefined and could be a combination of summer internships or summer jobs. Given the age of the group, it is unlikely that many of the installers had been employed full time in construction before entering school full-time.

The quality assessor group (n=44) were also mostly between 18-25 yrs. (91% control vs. 80% experimental) but there was a larger cohort >36 yrs. old (8.3% vs. 10%). This would adequately reflect the real world where a quality control inspector would be expected to be older. However, the majority of the quality assessors (75%) also reported that they had less than 2 years of CE.

Overall, the subjects of this experiment reflected the unskilled worker population as closely as possible considering the controlled nature of this experiment.

Included in the demographic survey were questions to determine the effectiveness of the instructions, equipment and the overall experience (Appendix B). Those questions were analyzed by location (control vs. experimental) and role (installer vs. quality assessor) to identify any possible inconsistencies in training or materials that would affect the ability to carry out the experiment. Ninety-five percent of subjects agreed or strongly agreed that lab instructions were clear with no significant differences by location or role. Ninety-three percent of subjects agreed or strongly agreed that tools and materials were adequate with no significant differences by role or location. Ninety-four percent of subjects agreed or strongly agreed that the experiment was an overall positive experience with no significant differences between role or location.

Hypothesis 1

Hypothesis 1 found that there was not a statistically significant difference in the time it took to install gypsum board when installers used plan specifications plus ASTM C 840 standards. The mean installation time for the control group was numerically faster at 2523.24 s vs. 2803.55 s for the mean installation time of the experimental group but this difference was not statistically significant. This was somewhat surprising considering the experimental group was required to digest not only the plan specifications but also an additional standard. The natural expectation would have been to see a statistically significant difference between the two groups in favor of a faster installation time by the control group. So it can be concluded that the addition of the ASTM C 840 standard to the plan specifications in this experimental setting did not significantly add to the mean installation time.

In interpreting the finding of installation time, it is important to remember that data was collected on only one installation by each installer pair. By performing the same activity repeatedly under the same conditions, it is well known that it takes less and less time to perform that same activity (Gates, 1972). Greater familiarity with the task, better coordination and more effective use of tools and materials lead to a learning effect with construction activities (Oglesby, 1989).

In theory, a learning curve can be divided into three parts (figure 7) (Thomas, 1986).

During the middle part of the curve, as workers become more familiar with the process, productivity improves and the learning curve drops sharply. The mathematical equation of the middle part of the learning curve is as follows:

$Y=AX^n$ "Straight Line Model Equation" (Thomas, 1986).

Y is the cost, man-hours or time to perform a repeated generic unit X

A in the cost, man-hours or time to perform the first unit

n is the slope of the logarithmic line and $n = -(\log_{10}L/\log_{10}2)$ where L is the learning curve expressed as a percentage.

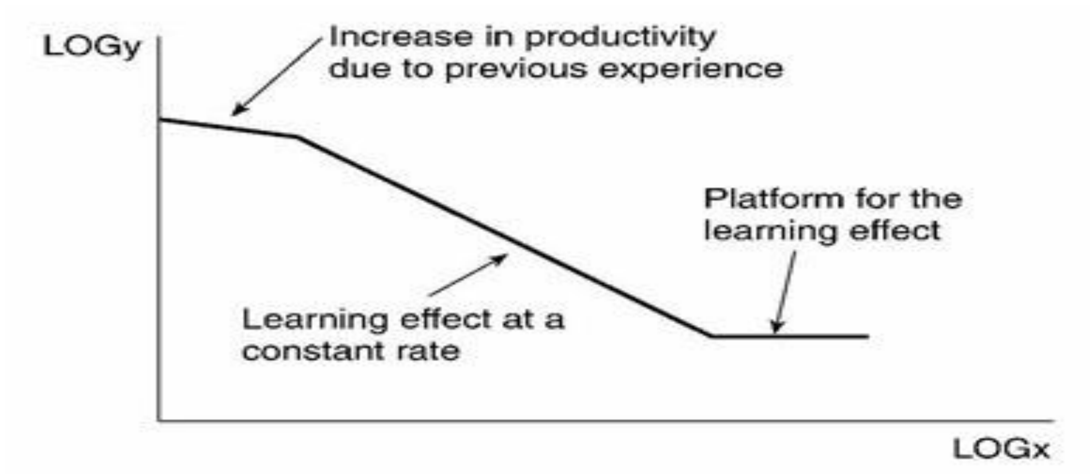


Figure 7. Theoretical Learning Curve (Buggey, 2007)

To create a learning curve for the control and experimental groups for this research, L was estimated at 80% (Chase, Operations Management for Competivitive Advantage (11th ed.), 2006, p. 141). According to RS Means Estimating Guide, 2011, a two-man crew should be able to install 2000 square feet in an eight hour shift (RSMeans, 2011, p. 300). Therefore, 2000 sq. ft. was described as 1 "unit" for the purposes of calculating the learning curve. For this research, the control and experimental groups installed 112 sq. ft. of gypsum board at a rate of 159.7 sq.

ft./hr. and 137.4 sq. ft./hr. respectively using the mean time in seconds. Those values were used to calculate the amount of time it would take to install 1 unit (2000 sq. ft.) of gypsum board. For the control group, it would take 13.24 hours to install 1 unit of gypsum board. For the experimental group, it would take 14.59 hours to install 1 unit of gypsum board. A learning curve for both groups was created using an EXCEL program (www.barringer1.com/Papers_files/LearningCurveCalculator.xls) with the results are presented in Figure 8. It is estimated that it would take the control group between 4 and 5 days to reach the rate of 8 hours to produce 1 unit (2000 sq. ft.) as specified in RS Means. For the experimental group, it is estimated to take between 6 and 7 days to reach the rate of 8 hours to produce 1 unit based on the initial mean installation time.

By using the Straight Line Equation where; Y is 8 hrs., A is the current rate of the control or experimental group and n is -.322 or 80% learning curve, solving for X will give the exact time in days it will take to reach the desired rate of production. The control group will reach the desired rate in 4.78 days and the experimental group will reach the desired rate in 6.46 days.

Based on the original premise that the control cohort in this research represents an unskilled worker group installing gypsum board with plans only and the experimental cohort represents the same group with the addition of the ASTM C 840 standard. This research shows that in adding the additional standard, it will only take the experimental group 1.68 additional days to increase their production rate to that of the control group based on time alone.

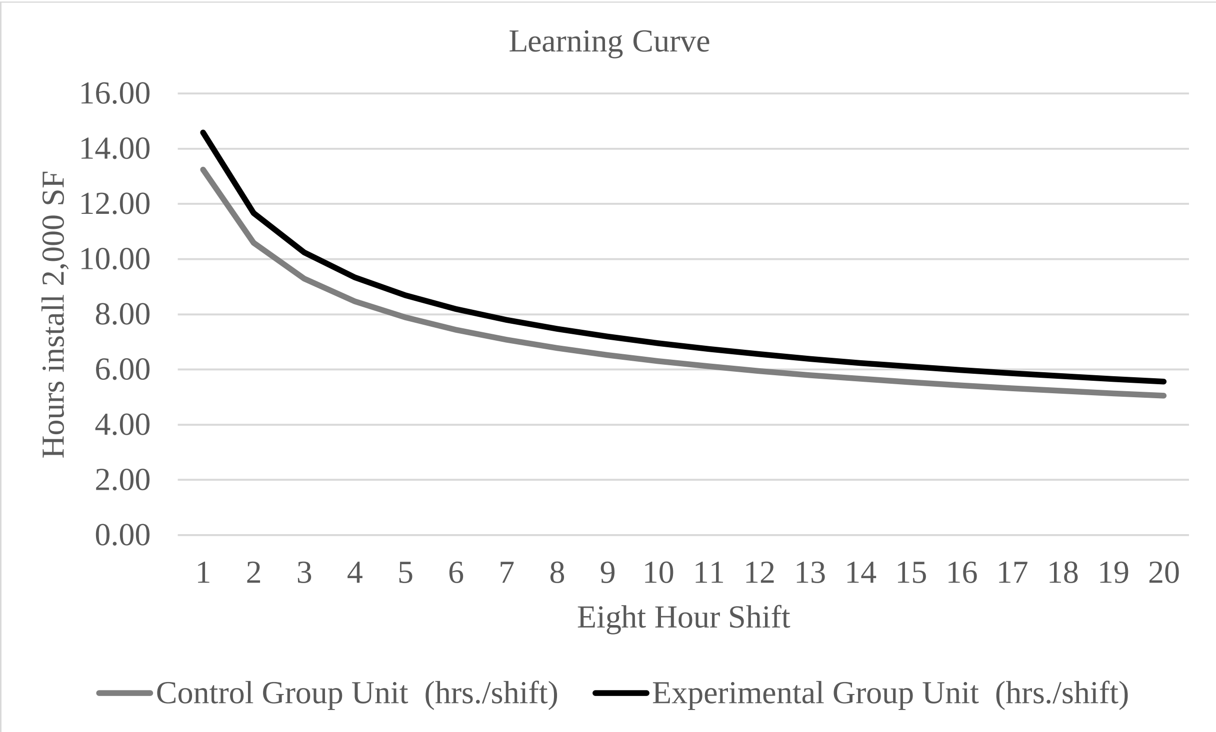


Figure 8. Learning Curve

Hypothesis 2

Hypothesis 2 found a statistically significant difference between the mean number of fasteners installed by the control group and the experimental group when ASTM C 840 was used in addition to plan specifications (121.33 vs. 79.96). All subjects were provided with the same materials and resources for the installation of gypsum board in the form of a notebook including Wall and Ceiling Surface Installation, Glencoe Carpentry and Building Construction Text, USG Sheetrock Brand Installation and Finishing Guide and ASTM C 840 standard (Appendix F). The experimental group received additional instruction and materials outlining the ASTM C 840 standards of installation of gypsum board. Carpentry and Building Construction serves as an entry level training text in many vocational and construction programs.

Similar requirements for the installation of gypsum board have been found between

ASTM C 840 and Carpentry and Building Construction and are as follows:

- Spacing of ceiling joists for 5/8"- 24" on-center for perpendicular and 16" on-center for parallel installation.
- Maximum stud spacing for ½" gypsum board 24" on-center for either perpendicular or parallel installation.
- Installation of field fasteners installed in the ceiling joist and perimeter of sheet a maximum distance of 7" nails and 12" screws was specified for all three references on a 5/8" panel.
- Installation of field fasteners installed on the ½" wall framing studs and sheet perimeter is a maximum distance of 8" for nails and 12" for screws.

However, differences in the installation of the gypsum board requirements of the same assembly were noted between the reference standard and the construction text.

- Double nailing in the field on 12" centers was not addressed in the textbook but was approved in ASTM C 840-8.4.3 as an acceptable installation method.
- Use of floating interior corners is addressed in ASTM C 840 as an acceptable way to reduce fasteners on the perimeter of covered corners, which is not addressed in the text.
- Per ASTM C 840- 7.1.4 state fasteners perimeter attachment into partition top and bottom plates is not required or recommended unless the wall is a fire assembly or shear wall. The construction text requires perimeter fasteners in both top and bottom plate of the partition assembly.

Applying the ASTM C 840 standard 7.1.4, addressing top, bottom and perimeter fasteners to the example below, equated to a 20.37% (n=528) reduction in the number of fasteners used.

Example: A residential living room of 24’-0” x 24’-0” with a standard 8’-0” ceiling will require the following materials:

- 768 SF or 24 sheets of ½” Gypsum board for the wall
- 576 SF of 18 sheets 5/8” Gypsum board for the ceiling
- 1296 wall fasteners maximum 8” OC, each sheet will require 54 fasteners

The experimental group saw a 34% reduction in the number of fasteners used over the control group in this research. A general prediction of number of fasteners needed is 0.3 lbs./100 sq. ft. or 66 fasteners /112 sq. ft. for this experiment (USG Corporation, 2015). Accordingly, the experimental group used more than estimated in this experiment so the true reduction in number of fasteners is likely overestimated. But any reduction in number of fasteners used represents a savings in fastener costs but also a savings in the cost to finish the gypsum board resulting in an overall reduction in labor and materials needed to complete the project within the guidelines of building codes and building specifications.

Hypothesis 3

Hypothesis 3 used the quality assessor group to rate the installer group in a number of ways. The quality assessors were randomized to control and experimental groups and asked to rate the quality of the gypsum board installation on a Likert scale from 1-10 without considering. Then the assessors tallied the total quality faults based on ASTM C 840 standard and again used the same Likert scale to rate the overall quality of the installation.

The assessment tool for tabulating the total number of quality faults was built directly from the ASTM C 840 section covering the installation of fasteners allowing each quality fault to be directly related to the standard. There was a statistically significant difference in quality faults between the control and experimental groups with a 27.4% decrease in favor of the experimental group. A Kruskal-Wallis H test for Total Quality Faults by location was statistically significantly different for edges and perimeter only. This is not surprising as in the previous section it was determined that major differences between ASTM C 840 and the industry norm was fastener installation around the top and bottom edges and the perimeter.

The pre QC rating was done without the benefit of standards and there was no statistically significant difference between the two groups. The post QC rating done after the tabulation of the Total Quality Faults was lower in both groups but again not statistically significantly different between groups. This seems to indicate a “tolerance” on the part of inspectors of quality when the measure was subjective that disappeared after being trained on an objective measurement tool. This is similar to results found in a study of consumer perceived tolerances of floor tile grout lines (Forsythe, 2006). A paired t-test verified that there was a statistically significant difference in the pre and post QC rating of gypsum board installation with post ASTM C 840 ratings being lower.

Limitations

Limitations to this study include the narrow scope of the study question, the study population, the highly controlled environment and the lack of previous published literature on research of this type. There are many simultaneous events and procedures being carried out on a construction site. In order to study the effect of implementing standards, the research question had to be defined almost artificially narrow to avoid confounders that would make it difficult to examine the hypothesis. Thus the portion of the ASTM C 840 standard involving installation with fasteners was chosen. Along with this, the environment was in a highly controlled setting between two secure campus buildings with limited space. The subjects of the experiment were students chosen to model unskilled workers albeit with different skill sets and interests though demographically matched by age and experience with unskilled construction workers. Each subject did the experiment only once based on limits of time and space though repeated measurements would have affected the learning curve. Every attempt was made to keep the groups blinded to their assigned group though it was not possible to control all conversations within and outside class periods as all experiments did not occur on the same day. Only one type of framing and fastener combination was tested. The framing of the apparatus was completed by another construction management class at the University of Central Missouri, which could have had an impact on installation and quality assessment. There were relatively few missing data points, which were limited to demographic data. The questionnaires were not validated for this experiment, as there was no previous research in this specific area and limited data in the literature.

Future Directions

An immediate future recommendation for this research would be to investigate the impact of ASTM C 840 on gypsum board installation in an identical or very similar fashion on a group of unskilled workers just entering the construction industry. This could be realized through creating alliances with The Builders' Association Education and Training Center of Kansas City. This would provide the opportunity to validate these data and/or refine the methodology. In addition, this process needs to be expanded in a controlled fashion to integrate other standards being deployed during the construction process prior to implementation to the field.

Real world evidence needs to be collected by inspecting active job sites to compare and contrast real time gypsum board installation with ASTM C 840 standards. Members of professional associations can be surveyed regarding utilization and attitudes towards tolerances and standards.

Work needs to be done with local Association of General Contractors and Associated Builders and Contractors to implement streamlined training programs to address recently identified worker shortages (AGC , 2016). Technology can be used to develop wireless apps to easily assess standards and tolerances on the job site.

REFERENCES

Abdelhamid, T. (2011). *AGC's Lean Construction Education Program Unit 1 Variation in Production Systems.* Arlington: The Association of General Contractors.

Aft, L. S. (1998). *Quality Improvement Using Statistical Process Control.* Orlando, FL: Harcourt Brace Jovanovich.

AGC . (2016). *Preparing the next generation of skilled construction workers.* Arlington, VA: The Associated General Contractors of America.

AIA. (2007). *AIA best practices terminology: as-built drawings, record drawings, mesured drawings.* Washington D.C: American Institue of Architects.

Allen, E. I. (2014). *Fundamentals of building construction, materials and methods 6th ed.* Hoboken New Jersey: John Wiley & Sons, Inc.

Altman, D. B. (1999). Statistics notes, treatment allocation in controlled trials: why randomize? *BMJ*, 703-4.

Andrews, R. (2013). *Construction quality management programs: Keys to successful project delivery.* Schaumburg, IL: Zurich .

ASTM International. (2015). *ASTM construction standards, supporting the building industry.* Retrieved from ASTM International: http://www.astm.org

ASTMC840. (2008). Standard Specification for Application and Finishing of Gypsum Board. West Conshohocken, PA: ASTM International.

Ballard, G. K. (2011). A response to critics of lean construction. *IGLC Special Issue*, 13-22.

Ballast, D. (2011). *Initiative on Dimensional Tolerances in Construction Surface Compliance Design Issues.* Washington, DC: Uniited States Government Access Board Research .

Belay, A. K. (2012). Adoption of quality managment practices, an investiagation of its relationship with laborproductivity for labor-intesive manufacturing companies. *Quality Management Practices*, 77-100.

Bentil, K. (1989). *The Future of Robots in Construction.* Washington D.C.: American Association of Cost Engineers.

Betts, G. (2000). *The architect's handbook of professional practice, 13th ed.* Washington D.C.: John Wiley & Sons, Inc.

Borcherding, J. L. (2004). *An assessment of implementation requirments for the Tier II construction strategy.*

Bradford, C. M. (2014). Challenges in the identification and implementation of reference standards in gypsum board installation; a study of 20 projects. *50th ASC Annual International Conference Proceedings.* Washington, DC: Associated Schools of Construction.

Buggey, T. (2007). Storyboard for Ivan's morning routine. *Journal of Positive Behavior Interventions, 9(3)*, 151.

Bullain, V. D. (2011). The Importance of Planning in Implementing a Collaborative BIM Execution Plan. *Journal of Building Information Modeling*, 23-24.

Chalmers, T. S. (1981). A method for assessing the quality of a randomized control trial. *Controlled Clinical Trials 2(1)*, 31-49.

Chase, R. J. (2006). *Operations management for competivie advantages 11 ed.* New York, NY: McGraw-Hill Iwin.

Chase, R. J. (2006). *Operations Management for Competivitive Advantage (11th ed.).* New York, N.Y.: McGraw-Hill.

CII. (2004). *Application of lean manufacturing principles to construction 191-11.* Austin, TX: Construction Industry Institue.

CII. (2005). *Lean Princples in Construction 191-1.* Austin: Construction Industry Institue.

CMHC. (2014, October 1). *Construction Tolerances*. Retrieved from Canada Mortgage and Housing Corporation CMHC: http://www.cmhc-schl.gc.ca/en/inpr/bude/himu/coedar/upload/Construction-Tolerances.pdf

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences (2nd ed.).* Hillsdale, NJ: Lawerence Erlbaum Associates.

Construction and the internet - new wiring. (2000). *The Economist 354(8153)*, 68.

Construction Specifications Instititute, CSI. (2005). *The project resource manual: CSI manual of practice 5th ed.* Atlanta, GA: McGraw-Hill.

Construction Web Links. (2003, June 9). *Construction Web Links.* Retrieved March 29, 2013, from ConstructionWebLinks.com: http://www.constructionweblinks.com/Resources/Industry_Reports_Newsletters/June_9_

Daneshgari, P. M. (2011, March 24). Mearsuring productivity in construction. *Electrical Construction and Maintenance*.

Dattalo, P. (2008). *Determining sample size: balancing power, precision, and practicality*. New York: Oxford University Press, Inc.

Day, S. A. (2000). Statistics notes: blinding in clinical trials and other studies. *BMJ 321*, 504.

Doman, M. M. (2009). *Successful clinical trials: a handbook for the 21st century*. Philadelphia, PA: Wolters Kulwer.

Dozzi, S. A. (1993). *Productivity in construction NRCC-37001*. Ottawa: National Research Council Canada.

Feigenbaum, A. (1991). *Total quality control 3rd ed.* Singapore: McGraw Hill.

Field, A. (2013). *Discovering statiatics using ibm spss statiistics 4th ed.* London: Sage Publications.

Fiori, C. M. (2003). What's wrong with Working Construciton? How Image and Diversity Issues are affecting the Shortage of Skilled Labor. *ASCE Construction Research Congress.* Honolulu, HI March.

Fisk, E. R. (2010). *Construction Project Adminstruation 9th Ed.* Upper Saddle, NJ: Prentice Hall.

Forbes, L. A. (2011). *Modern Construction, Lean Project Delivery and Integraed Practices.* Boca Raton: CRC Press.

Forsythe, P. (2006). Consumer-percieved appearance tolerances in construction management. *Engineering, Construction and Architectural Management*, 307-318.

Frank, G. C. (2012). *Construction Qualtiy, Do It Right or Pay The Price.* Upper Saddle River, NJ: Pretence Hall.

Gates, M. S. (1972). Learning and experience curves. *Journal of Construction Division. ASCE, 98 (CO1) March Proceedings 8778* (pp. 79-101). Reston, VA: American Society of Civil Engineers.

Gilbert, S. (2012). *Characterization of the US Construction Labor Supply, US Department of Commerce.* Washington DC: National Institute of Standards and Technology.

Goetsch, D. D. (2003). *Quality management: introdcution total quality management for production, processing, and services, 4th ed.* New York: Prentice Hall.

Goetsch, D. D. (2010). *Quality Management for Organzational Excellance, Introduction to Total Quality.* New York: Pretence Hall.

Graham-Rowe, E. S. (2011). Can we reduce car use and, if so, how? a review of teh available evidence. *Transportation Research Part A: Policy and Practice 44 (5)*, 401-418.

Halpin, D. S. (2011). *Construction Management 4th ed.* Hodoboken, NJ: John Wiley & Sons.

Hayden, M. (2008). *Multi-Factor ANOVA & Multiple Regression.* Terre Haute, IN: Quality Council of Indiana.

Healey, J. (2012, November 13). Coming soon: Robots that help build buildings. *Los Angeles Times*, p. 5.

Heinrich, J. (2003). *Benefits of blind analysis techniques.* Retrieved from University of Pennsylvania: http://www-cdf.fnal.gov/physics/statistics/notes/cd6576 blind.pdf

Hellwig, T. (2015, Feb. 3). *Dental Clinic Remodel for Port Gamble S'Klallam Tribe.* Retrieved from Builders Exchange of Washington: http://www.bxwa.com

Hillis, D. D. (2012). *Improving Profability Through Green Manufacturing; Creating a profitable and environmentally compliant manufacturing facility.* Hoboken: Wiley.

Howell, D. (2010). *Statistical methods for psychology 7th ed.* Belmont, CA: Wadsworth.

Hughes, R. (1993). Robots in Construction: BAARC meeting. *The Industrial Robot 20.2*, 18.

Ibbs, W. V. (2012). *Change and the loss of productivity in construction: a field guide.* Berkley, CA: Ibbs Consulting.

Ingram, K. (2016, March 16). *Changing perceptions: why now is the time for the construction industry to embrace change.* Retrieved from The IFS Blog: http://blog.ifsworld.com/2016/03/ why-now-is-the-time-for-the-construction-industry-to-embrace-change

JE Dunn Construction. (2013, May 22). *Kaffman Center for the Performing Arts*. Retrieved from JE Dunn Construction: http://www.jedunn.com/portfolio/0/1303661

Johnson, M. (2013). *Attracting young people into construction field positions.* Falls Church, VA: Foundation of the Wall and Ceiling Industry.

Jones, S. A. (2012). *The buisness value of BIM in North America: mulit-year trend analysis and user ratings (2007-2012).* Bedford, MA: McGraw-Hill.

King, R. (1961, March). Technology and Social Progress. *Political Science Quarterly Vol. 76 No. 1*, pp. 3-10.

Kochan, A. (2000). Robots for automating construction- an abundance of research. *The Industrial Robot 27.2*, 111-113.

Laerd Statistics. (2015). *Statistical tutorials and sofware guides 2015.* Retrieved from Laerd Statistics: http://statistics.laerd.com/

Liftlite Drywall. (2015, March 18). Retrieved from Continental Building Products: http://www.continental-bp.com

Lytle, A. S. (2002). Development of Robtic Structural Steel Placement System. *Proceedings of the 19th International Symposium on Robotics in Construction* (pp. 263-268). Gaithersburg, MD: NIST, BFRI Construction Metrology and Automation Group.

Mann, H. W. (1947, March). On a test of whether on of two random variables is stochastically larger than the other. *The Annals of Mathematical Statistics Vol. 18, No. 1,* pp. 50-60.

Manpower Group. (2012). *2012 Talent Shortage Survey Research Results.*

McGrath-Champ, S. R. (2011). From on skill shortage to the next: the Australian construcion industry and geographies of global labour market. *Journal of Industrial Relations 53(4),* 467-485.

McGraw-Hill Education. (2010). *Glencoe Carpentry & Building Construction.* Woodland Hills, CA: McGraw-Hill.

Merriam-Webster. (1988). *Webster's Ninth New Collegiate Dictionary.* Springfield, Massachusetts, U.S.A.: Merriam-Webster.

Messner, J. I. (2011). A Structured Planning Procedure for BIM. *Journal of Building Information Modeling*, 21-22.

Mitropoulos, P. C. (2009). The role of production and teamwork practices in construction safety:a cognitive model and an empirical case study. *Journal of Safety Research 40*, 265-275.

Nassar, K. (2010). The effect of building information modeling on the accuracy of estimates. *Associated Schools of Construction Proceedings of te 46th Annual Internatioinal Conference.* Boston, MA: Associated Schools of Construction ASC.

New ASTM construction productivity standard released. (2010, May 26). Retrieved from ConstructionPro Week: Construction Advisor Today Issue 57 : http://www.constructionpronet.com

New York Times. (1911, April 2). Bricklaying Yields to Science for the First Time. *New York Times*, p. 1.

Nichols, J. (1940). Tolerances in building construction. *Proceedings of the American Concrete Institute 36 (4)*, 493-96.

Oglesby, C. P. (1989). *Productivity improvement in construction.* New York, N.Y.: McGraw-Hill.

Podkaminer, Z. (2013, July 29). Construction robotics awarded NSF SBIR Phase II grant for semi-automated masonry (SAM) robotic system. Victor, New York, USA.

Project Mangement & Construction Services. (2016, April 22). *Project Management & Construction Services, Campus Standards*. Retrieved from Building the University of Texas at Austin: https://pmcservices.utexas.edu/dcstandards/campus.html

Rounds, G. C. (1985). Total quality management for construction. *ASCE Journal of Construction Engineering and Managment 111(21).*

RSMeans. (2011). *RS Means Building Construction Cost Data.* Kingston, MA: Reed Construction Data.

Sabol, L. (2008). *Challenges in cost estimating with building Information modeling.* Washington DC: Design + Construction Stategies.

Sangl, A. (2013, June 21). ERO:Concrete Recycling Robot. New York, New York, USA.

Schouten, H. (1995). Adaptive biased urn random in small strata when blinding is impossible. *Biometrics 51 (4)*, 1529-35.

Schul, K. G. (2002). Allocation concealment in randomized trials: defending against deciphering. *Lancet 359*, 614-618.

Seymour, D. (2013). Lean construction: the contribution of ethnograpy. *Lean Construction Journal* , 36-46.

Soares, R. (2013 vol 4). Reengineering management of construction projects. *International Journal of Buisness and Social Sciences*, 1-6.

Suprenant, B. M. (2011). Internal tolerances conflicts in concrete consruction. *Concrete International*, 31-34.

Suresh, K. (2011). An overview of randomization techniques: an unbiased assessment of outcomes in clinical research. *J Hum Repod Sci 4(1)*, 8-11.

Sveikauskas, L. R. (2014). *Productivity growth in construction.* Washington D.C.: U.S. Bureau of Labor Statistics.

Teicholz, P. (2004, April 14). Labor Productivity Declines n the Construction Industry:Causes and Remedies. *AECbytes Viewpoint. Issue 4*.

Teicholz, P. (2013, March 14). Labor Productivity Decllines in the Construction Industry: Causes and Remedies (a second look). *AECBytes Viewpoint*.

The Economist. (2015). *Rethinking productivity across the construction industry.* London: The Economist Intellinence Unit Limited.

Thomas, H. M. (1986). Learning curve models of construction productivity. *Journal of Construction Engineering and Managment, ASCE, 112(2)*,, 245-57.

Torbica, Z. M. (2000). An Assessment Model for Quality Performance in Residential Construction. *The American Professional Constructor*, Volumne 24, 1.

US Census Bureau. (2016, April 28). Industry Snapshot Construction (NAICS 23). Washington DC.

USDA. (2011). *E-5 Appendix E Construction Tolerances part 645 national engineering handbook 2.* Washington: directives sc egov. usda.gov.

USG. (2015). *USG Sheetrock Brand Installation and Finishing Guide.* Chicago, IL: USG Corporation.

Volti, R. (1995). *Society and technolgical change 3rd ed.* New York: St. Martins Press.

Walker, H. S. (2009). A randomized controlled trial of the first step to success early intervention. demonstration of program efficacy outcomes in a diverse, urgan school district. *Journal of Emotional and Behavioral Disorders 17 (4)*, 197-212.

Whiteman, D. E. (2004). TQM Implementaton Inhibiting factors of Implementing total quality management on construction sites. *The TQM Magazine,* 166-173.

Wilcox, D. J. (2012). Augmented reality: bringing BIM to life. *Journal of Building Information Modeling*, 18-19.

Wilder, R. (2012, Fall). Raising the bar in contractor selecton. *The VOICE,* pp. 37-39.

Young, N. W. (2008). *Building Information Modeling (BIM): Transfroming Design and Constructon to Achieve Greater Industry Productivity*. Bedford, MA: McGraw-Hill.

APPENDIX A : PROTOCAL

Installer Cohort;

1. The subjects were randomly assigned in groups of 2 man crews and assigned to an installation apparatus in either the control group (TEC building) or experimental group (COT building).
2. All subjects were given identical PowerPoint instructions on gypsum board installation (appendix E).
3. All subjects were given the same reference materials in a notebook form regarding gypsum board installation including ASTM C 840 standards (see Appendix F).
4. The experimental group (COT) was given additional detailed verbal and written instruction on installing gypsum board according to ASTM C 840 standards (Appendix G, Installer Experiment Group Training Handout).
5. Using identical materials and tools (Appendix D), the installer groups installed gypsum board on one side of the apparatus recording time in seconds and number of fasteners on the lab report provided (Appendix G).
6. All subjects completed a demographic survey and an assessment of the experiment (Appendix B).

Quality Assessor Cohort;

1. Subjects from classes included in the quality assessor cohort of the experiment were randomized to assess the quality gypsum board installation installed by either the control group (TEC building) or experimental group (COT building).
2. Quality assessors rated the quality of installation on a Likert scale (Appendix G).
3. Quality assessors were then provided tools and information to re-assess the installation according to ASTM C 840 capturing number of quality faults (Appendix G).
4. Quality assessors then re-rated the overall quality of installation as in step 3 using the same Likert scale (Appendix G).
5. All subjects completed a demographic survey and an assessment of the experiment (Appendix B).

APPENDIX B : PARTICIPANT QUESTIONERS

Participant Questionner Installer

1. Select the location you participated in the laboratory activity.
    a. TEC 107
    b. COT 108
2. Please select the answer that reflects your standing at the university.
    a. Freshman
    b. Sophomore
    c. Junior
    d. Senior
    e. Graduate Student
    f. Other
3. Select the answer that best describes you educational path at the university.
    a. This course is required for my major.
    b. This course is required for my minor.
    c. This course is an elective in my major degree.
    d. Other or not listed.

4. Select the answer that best reflects your age today.
    a. Under 18 years of age
    b. Between 18 and 25 years of age
    c. Between 26 and 35 years of age.
    d. Between 36 and 50 years of age.
    e. Over 50 years of age.
    f. I prefer to not answer this question.

5. You are a student that transferred college credit hours to this university.
    a. True
    b. False

6. Which answer best describes you construction experience outside of the university?
    a. 0 – 1 year
    b. 1 – 2 years
    c. 2 -5 years
    d. More than 5 years.

7. The instruction provided for the lab was appropriate and clear.
    a. Strongly agree
    b. Agree
    c. Neither Agree nor Disagree
    d. Disagree
    e. Strongly Disagree.

8. The tools and material furnished were adequate for the lab.
    a. Strongly agree
    b. Agree
    c. Neither Agree nor Disagree
    d. Disagree
    e. Strongly Disagree

9. You understood how to use the electronic plan table.
    a. Strongly agree
    b. Agree
    c. Neither Agree nor Disagree
    d. Disagree
    e. Strongly Disagree

10. Your overall experience with the lab was positive.
    a. Strongly agree
    b. Agree
    c. Neither Agree nor Disagree
    d. Disagree
    e. Strongly Disagree

11. What improvements, (instructions, tools, and materials) would you suggest to improve a student experience in this lab?

____
____
____
____

Participant Questioner Inspector

1. Select the location you participated in the laboratory activity.
    a. TEC 107
    b. COT 108

2. Please select the answer that reflects your standing at the university.
    a. Freshman
    b. Sophomore
    c. Junior
    d. Senior
    e. Graduate Student
    f. Other

3. Select the answer that best describes you educational path at the university.
    a. This course is required for my major.
    b. This course is required for my minor.
    c. This course is an elective in my major degree.
    d. Other or not listed.

4. Select the answer that best reflects your age today.
    a. Under 18 years of age
    b. Between 18 and 25 years of age
    c. Between 26 and 35 years of age.
    d. Between 36 and 50 years of age.
    e. Over 50 years of age.
    f. I prefer to not answer this question.

5. You are a student that transferred college credit hours to this university.
    a. True
    b. False

6. Which answer best describes you construction experience outside of the university?
    a. 0 – 1 year
    b. 1 – 2 years
    c. 2 -5 years
    d. More than 5 years.

7. The instruction provided for the lab was appropriate and clear.
    a. Strongly agree
    b. Agree
    c. Neither Agree nor Disagree
    d. Disagree
    e. Strongly Disagree.

8. The tools and material furnished were adequate for the lab.
    a. Strongly agree
    b. Agree
    c. Neither Agree nor Disagree
    d. Disagree
    e. Strongly Disagree

9. You understood how to use the electronic plan table.
    a. Strongly agree
    b. Agree
    c. Neither Agree nor Disagree
    d. Disagree
    e. Strongly Disagree

10. Your overall experience with the lab was positive.
    a. Strongly agree
    b. Agree
    c. Neither Agree nor Disagree
    d. Disagree
    e. Strongly Disagree

11. What improvements, (instructions, tools, and materials) would you suggest to improve a student experience in this lab?

APPENDIX C: PARTICIPANT INFORMED CONSENT

Indiana State University Informed Consent

CONSENT TO PARTICIPATE IN RESEARCH

The Impact of Strict Tolerances on Gypsum Board Installation and Quality

You are being asked to participate in a research study conducted by Assistant Professor Curtis Bradford in the Department of Construction Management in the College of Technology at the University of Central Missouri. Mr. Bradford is also a PhD Candidate in Technology Management from Indiana State University. The data collected from this study will be used to complete his dissertation. His committee is comprised of Chair, Dr. Ronald Woolsey, College of Technology, UCM and other committee members Dr. David McCandless, College of Technology, UCM and Dr. Mehran Shahhosseini, Indiana State University, College of Technology. Dr. Shahhousseini will serve as the faculty sponsor for this study at Indiana State University. Please read the information below and ask questions about anything you do not understand, before deciding whether or not to participate.

We are inviting you to participate in this study. It is up to you whether you would like to participate. If you decide not to participate, you will not be penalized in any way. You can also decide to stop at any time without penalty. You must be at least 18 years of age and enrolled in a Construction Management (CMGT XXXX) course to participate in this study.

- **PURPOSE OF THE STUDY**

This study will measure speed of production and standard of quality in the installation of gypsum board to a wood wall partition when specifications and industry standards are employed.

- **PROCEDURES**

As a part of your regular classroom lab activity, you will be participating in an experiential lab installing gypsum board on a wood apparatus. You will be randomly paired into 2 man "crews" (CW). Your crew will then be randomly assigned to one of two groups.

Procedures:

Pre-lab:

All participants will receive a lecture and handouts on the specifics of gypsum board installation for the experiment relevant to their group.

Lab exercise:

Each crew will attach seven, precut, ½ inch thick pieces of sheet rock to one face of a pre-assembled apparatus using the instructions outlined during the directional lecture.

Post-lab exercise:

Each crew will self-assess the quality of their gypsum board installation including # of fasteners, time of installation (in seconds) and over-all quality of installation on data sheet. Each participant will complete a post-experiment survey to capture baseline demographics (your age, class rank, and construction experience), information on the utility of the materials (digital plan scale, iPads etc.) and limitations of the experiment.

IRB Number: 900774-2
Date of IRB Approval: 10/7/16
Date of Study's Expiration: 10/6/17

If you volunteer to participate in this study, the data you capture in the lab exercise (time, fasteners, quality and the post-experimental survey) will become part of the research study described in the first paragraph above along with the other student subjects who volunteer to participate in the study. This study will take about ninety minutes of your normal class lab time to finish and will not require any time outside of your regular class period. You will have the chance to ask questions about the study before, during and after the study. Your individual results and data will be anonymous. Your instructor will not know if you choose to participate in the study portion of the lab exercise and the Principal Investigator, Curtis Bradford, will not know if you chose to participate until after the conclusion of the Fall 2016 semester. As with all UCM CM experiential lab classes, you will receive full-credit for participation in the lab. If you are unable to participate in the lab portion, you will be given the option of an alternative assignment per UCM CM department policy and experiential lab standard practice.

- **POTENTIAL RISKS AND DISCOMFORTS**

The risks associated with participating in this study are similar to the risks for any of the experiential labs in the UCM CM program. The risk of permanent physical, psychological or confidentiality is minimal. To minimize any potential discomfort regarding the decision to participate, your instructor will not be present when you decide or consent to participate in this study. Any accidents resulting in injury during this experiential lab will be covered by the UCM CM policy.

- **POTENTIAL BENEFITS TO SUBJECTS AND/OR TO SOCIETY**

This new lab is being evaluated by a number of classes simultaneously for implementation into the UCM CM curriculum. You will benefit from participating in this new experiential lab by getting firsthand experience in gypsum board installation and quality methods. The anticipated benefit to society of the research study portion of this lab is the discovery of new methods to provide and deliver skills and training for entry-level workers performing work that in the past has been reserved for seasoned workers. The results of this research will be communicated to the student participants after the data are analyzed. You will receive full credit for a hands-on laboratory assignment from your instructor for participating in this lab activity.

- **CONFIDENTIALITY**

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law. Confidentiality will be maintained by not linking participant names to data collected. Each participant will be randomly assigned to a group, crew and work grid. After your data is compiled, it will be delivered to Dr. Aaron Sauer who will de-identify all data before giving the information to Mr. Bradford for analysis. All raw data and consent forms will remain secured by Dr. Sauer. Consent forms will not be available to Mr. Bradford or other faculty members until the completion of the Fall 2016 semester.

- **PARTICIPATION AND WITHDRAWAL**

You can choose whether or not to be in this study. You may still participate in the lab exercise without participating in the research study and still receive full credit for the activity. If you volunteer to be in this study, you may withdraw at any time without consequences of any kind or loss of benefits to which you are otherwise entitled. There is no penalty if you withdraw from the study and you will not lose any benefits to which you are otherwise entitled. You may withdraw your data at the end of the study or at anytime during the study. If you wish to do this, please tell the professor monitoring the lab before you turn in your materials. If you wish to withdraw from the study after the lab is completed, please contact Dr. Aaron Sauer, UCM Department of Construction Management by email at sauer@ucm.edu or by phone at 660-543-8214. You will have until the end of the Fall 2016 semester to withdraw your data from the study.

- **IDENTIFICATION OF INVESTIGATORS**

If you have any questions or concerns about this research, please contact myself at cbradford@ucmo.edu, Dr. Woolsey, woolsey@ucmo.edu, or Dr. McCandless, mccandless@ucmo.edu. All can be reached by phone also at (660) 543-4439. At ISU, Dr. Mehran Shahhosseini, Mehran.shahhosseini@indstate.edu or by phone at (812) 237-3368.

- **RIGHTS OF RESEARCH SUBJECTS**

If you have any questions about your rights as a research participant, please contact the Human Subjects Protection Program at UCM (660) 543-4621 and/or Indiana State University Institutional Review Board (IRB) by mail at Indiana State University, Office of Sponsored Programs, Terre Haute, IN 47809, by phone at (812) 237-8217, or e-mail the IRB at irb@indstate.edu.The IRB is an independent committee composed of members of the University community, as well as lay members of the community not connected with ISU. The IRB has reviewed and approved this study.

I understand the procedures described above. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

____
Printed Name of Subject

______________________________ ____________________
Signature of Subject Date

IRB Number: 900774-2
Date of IRB Approval: 10/7/16
Date of Study's Expiration: 10/6/17

University of Central Missouri Informed Consent

Approved 4/21/2016

CONSENT FORM

Identification of Researchers: This research is being performed by Assistant Professor Curtis Bradford in the department of Construction Management in the College of Technology at the University of Central Missouri.

Purpose of the Study: This study will measure speed of production and standard of quality in the installation of gypsum board to a wood wall partition.

Request for Participation: We are inviting you to participate in this study. It is up to you whether you would like to participate. If you decide not to participate, you will not be penalized in any way. You can also decide to stop at any time without penalty. A questioner will be presented if you do not wish to answer any of the questions, you may simply skip them. You may withdraw your data at the end of the study. If you wish to do this, please tell us before you turn in your materials. Once you turn in the materials, we will not know which survey or test is yours.

Exclusions: You must be at least 18 years of age *and enrolled in a Construction Management (CMGT XXXX) course* to participate in this study.

Description of Research Method: This study involves working in a lab activity by installing gypsum board on a wood apparatus in a team of two. After completing a short survey will be given is will ask you about your age, class rank, gender, and construction experience. This study will take about ninety minutes of your class lab time to finish. After you finish, we will explain the purpose of the study in more detail. You will also have a chance to ask questions. Please note that we cannot give you your individual results because the data are anonymous.

Privacy: All of the information we collect will be *confidential*.

Explanation of Risks: The risks associated with participating in this study are similar to the risks of everyday life. Any medical treatments provided if an injury occurs will be at the expense of the participant.

Explanation of Benefits: You will benefit from participating in this study by getting firsthand experience in gypsum board installation and production and quality research. We will provide you with a full credit for a hands-on laboratory assignment with your instructor.

Questions: If you have any questions about this study, please contact me at cbradford@ucmo.edu or I can be reached by phone also at (660) 543-8219. If you have any questions about your rights as a research participant, please contact the Human Subjects Protection Program at (660) 543-4621.

If you would like to participate, please sign a copy of this letter and return it to me. The other copy is for you to keep.

I have read this letter and agree to participate.

Signature: ______________________ Printed name:__________________________

Date: ____

Person obtaining consent: ___________________________

APPENDIX D: DESIGN, MATERIAL, EQUIPMENT AND COST ESTIMATES

Apparatus Design

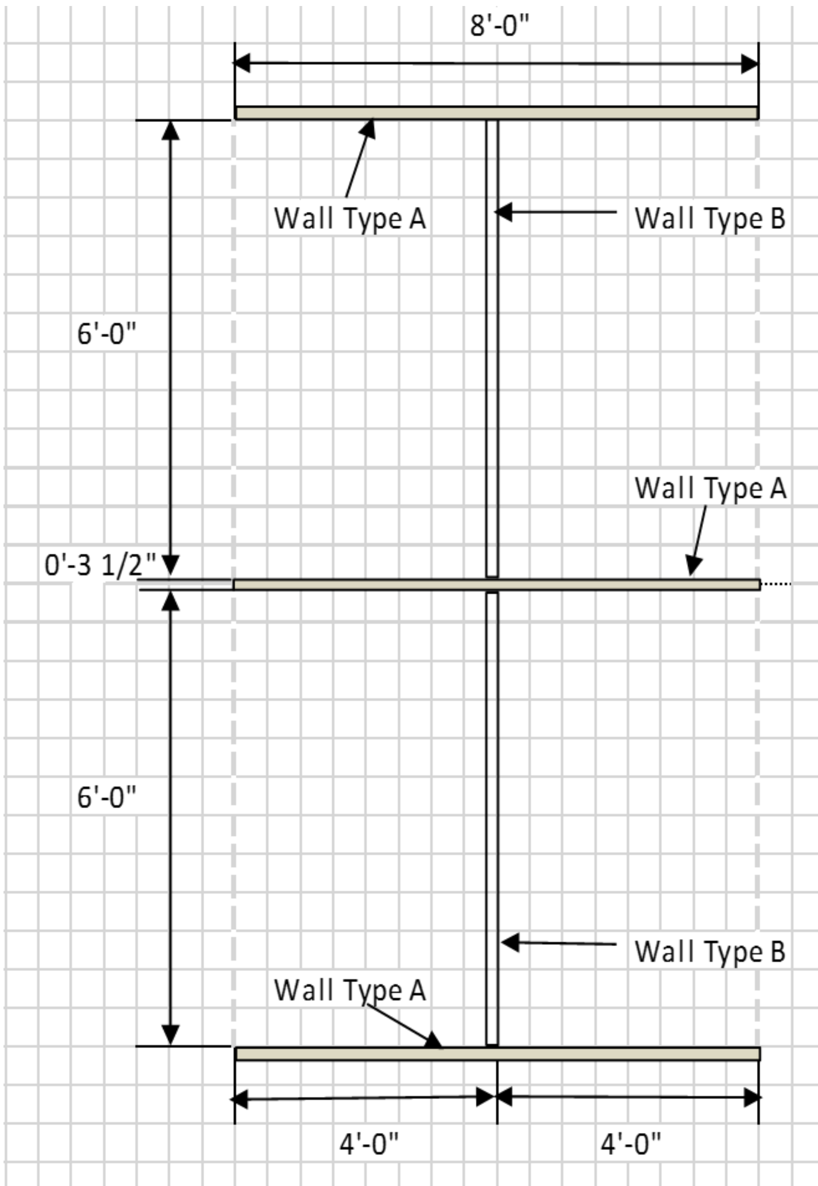


Figure 1

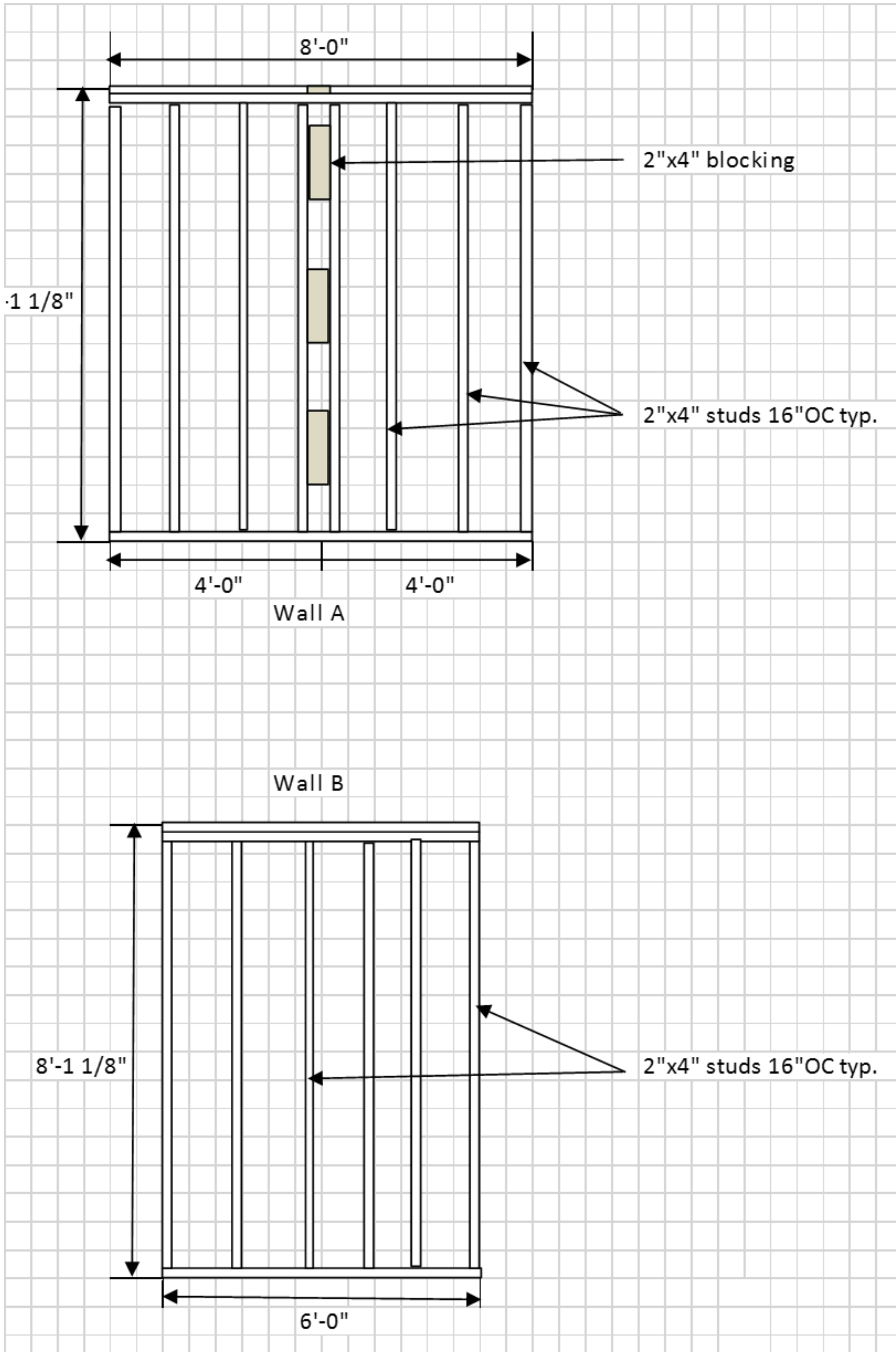

8'-0"
2"x4" blocking
-1 1/8"
2"x4" studs 16"OC typ.
4'-0"
4'-0"
Wall A
Wall B
8'-1 1/8"
2"x4" studs 16"OC typ.
6'-0"

Figure 2

Material List, Equipment and Estimated Costs

Wall Apparatus Estimate								
Wall Type A	3	EA		EA	EXT	EA $	SUB $	TOTAL $
	8	EA	2x4 precut studs	3.19	$76.56			
	3	EA	2 x 4 - 8' plate	2.38	$21.42			
Wall Type B	2	EA						
	6	EA	2x 4 precut studs	3.19	$38.28			
	3	EA	2X4 -6' plate	2.36	$14.13			
Screw fasteners					$12.00			
Sub total	1	EA	one framing apparatus			$162.39		
Framing apparatus	6	EA	use two times				$974.34	
Gypsum Board								
Sheet Rock Walls	14	EA	1/2" 4 x 8 sheets	7.35	$102.90	$617.40		
Screw Fasteners					$10.00	$60.00		
Subtotal	1	EA				$677.40		
Sheetrock	2	EA	two rounds				$1,354.80	
Total Estimate Materials			*maximum N of 96*					**$2,329.14**

Installation Tools					
Screw Gun	1	EA	each team of two		
Timer	1	EA	each team of two		
Utility knife	1	EA	each team of two		
Tape Measure 25'	1	EA	each team of two		
Ext. Cord min 25'	1	EA	each team of two		
Step Stool/ladder	1	EA	each team of two		
Straight edge/level 4'	1	EA	each team of two		
Number of N	20	EA	Total ten teams per round maximum		

Material Order Sheet	
216	2x4-precut
54	2x4-8'-0"
18	2x4-12'-0"
168	4x8-1/2" S/R
15 lb	1 1/4 SR screw
15 lb	3" Deck screw

Assessment Tools					
Tape Measure 25'	1	EA	Inspector		
Clip Board pencil	1	EA	Inspector		
Step Stool	1	EA	Inspector		
Calculator	1	EA	Inspector		
depth mic	1	EA	Inspector		
straight edge 4-8 foot	1	EA	Inspector		

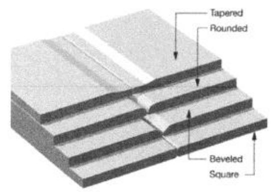
APPENDIX E : INSTALLER TRAINING PRESENTION

10/15/2016

DRYWALL INSTALLATION

CURTIS BRADFORD

DRYWALL EDGES



INTRODUCTION

- Gypsum Board is also called, drywall, wallboard, or sheetrock.
- It is paper covering a gypsum substrate.
- It can serve as a fire barrier and/or the base substrate for wall finishes.
- As a finish group, occupants judge it's appearance as an indicator of quality in the buildings construction.

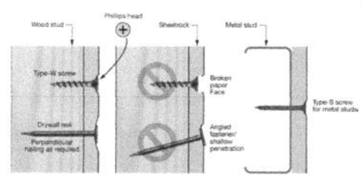
SKIN

- The paper skin provides strength and stability of the core.
- In addition, to holding the panel to the framing members it reduces moisture and mold penetration.
- Breaking the skin in with fasteners reduces the properties of the panel and should be avoided.

TYPES OF PANELS

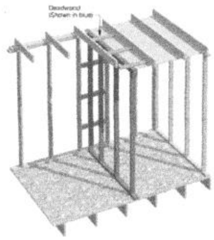
- Standard wall and ceiling panels
  - 3/8", 1/2", and 5/8" with finished face paper
  - Tapered edges for joint tape and drywall compound
- Can be made from 99% recycled material

FASTENER INSTALLATION



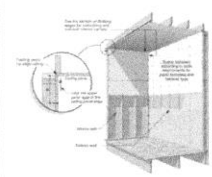
10/15/2016

FRAMING MEMBERS AND DEADWOOD



INSTALLATION

LOWES INSTALLATION



- The material has been precut to accommodate the following sequence.
  - Back wall first top then bottom, one is 6'0" the other two, 2'0" and 4'0"
  - Either side wall top then bottom pieces four pieces cut around 45 ½" each.

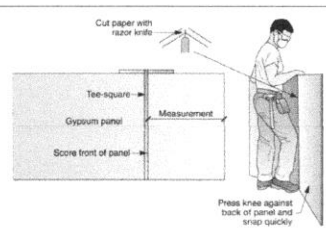
INSTALLING PANELS

- Panels can be installed perpendicular or parallel to the framing members.
- In the lab we will install using the perpendicular orientation.
- Always try to use the end factory edges at intersections.

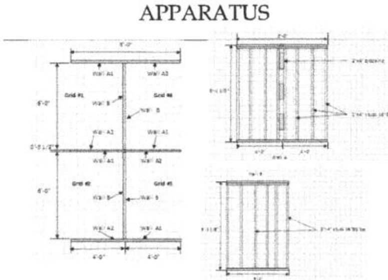
LAB INSTRUCTIONS

- Please review the Lab notebook prior to starting.
- Six apparatuses have been divided into four sections. Half in TEC Lab the other half COT Lab. When identifying your work area please these markers.
  - TEC building X1, Y2, Z4, etc.
  - COT building A2, B3, C1, etc.

CUTTING



APPARATUS



WHAT YOU NEED TO GET STARTED.

4' Straight Edge- level, square, straight wood
Pencil- no pens the ink bleeds through the paper.
Timer- your phone will work.
Drill with Drywall screw setter- one per team
Ladder or sawhorse to reach the top of the walls.
Utility knife, rasp/file to fit pieces.
Safety glasses
Tape measure- one per team
Pry bar, lever, or hammer to lift bottom sheets.

STEPS (CONT.)

- When you are satisfied your wall is ready for the finishing step stop the timer and right down the time it took to complete.
- Count all of the screws you installed and write that number down as well.
- Rate your installation on the 1-10 scale.
- Answer the participant questions, both sides of the page.

STEPS

- Sign consent forms and hand it to the instructor. One copy is for you.
- Two person teams are randomly selected
- Fill out your estimation Lab worksheet with your estimates of time and fasteners.
- Half of the teams will work in the COT Lab the other in the TEC.
- Get your supplies and tools needed select a work area.

STEPS (CONT)

- Pick up your work area and put the tools away.
- Turn in to the instructor your questioner, lab installation sheet, and lab notebook (binder).
- When everyone has completed the drywall lab a total time and quality rating will determine which team is the "UCM Rockers of the Semester". Stay tuned an email will be sent out near finals week.
- Thank you for your participation and feedback.

STEPS (CONT.)

- Check the framing for issues, layout, loose, etc.
- Time starts when you move the first sheet leaning up on the back wall.
- Install the back wall first top piece(s) first, then bottom sheet lift it up so they meet.
- Install sidewalls, use the factory edges to make a nice inside corner. If it hangs out the front of the wall just leave it.

QUESTIONS?

- No.... Well lets get to rock'n

10/15/2016

APPENDIX F: ASTM C 840-08

ASTM C 840-08 Standard Specification for Application and Finishing of Gypsum Board

7. Application of Gypsum Board

7.1.3.1 Gypsum board applied to walls shall be applied with the bottom edge spaced not less than ¼ in (6 mm) above the floor.

7.1.4 Fastening Gypsum Board to the framing. When used at edges or ends, fasteners shall be spaced not more than 1 in. (25 mm) from edges and not less an 3/8 in. (9.5 mm) from edges of gypsum board (except where floating angles are used).
Perimeter fastening into the partition plate or sole at the top and bottom shall not be required except where fire rating, structural performance, or other special conditions require such fastening.
Application of fasteners shall proceed from the center or field of the gypsum board to the ends and edges.

7.1.5.1 Nails shall be driven with the heads slightly below the surface of the gypsum board, avoiding damage to the face and the core board, such as breaking the paper or fracturing the core.

7.1.5 Screws shall be driven to provide screw head penetration just below the gypsum board surface without breaking the surface paper of the gypsum board or stripping the framing member around the screw shank.

7.1.9 The external corners shall be protected with a metal corner bead or other suitable type of corner protection that shall be attached to supporting construction with fasteners or a crimping tool nominally 6 in. (152 mm) on centers.

7.4 Joints between gypsum boards shall be constructed with the gypsum board edges in moderate contact.

8. System I: Application of Single-Ply Gypsum Board to Wood Framing Members

8.4.2 Single Nailing- Nails shall be spaced a maximum of 7 in. (177.8 mm) on centers on ceilings and a maximum of 8 in. (203.2 mm) on centers on walls (figure 1).

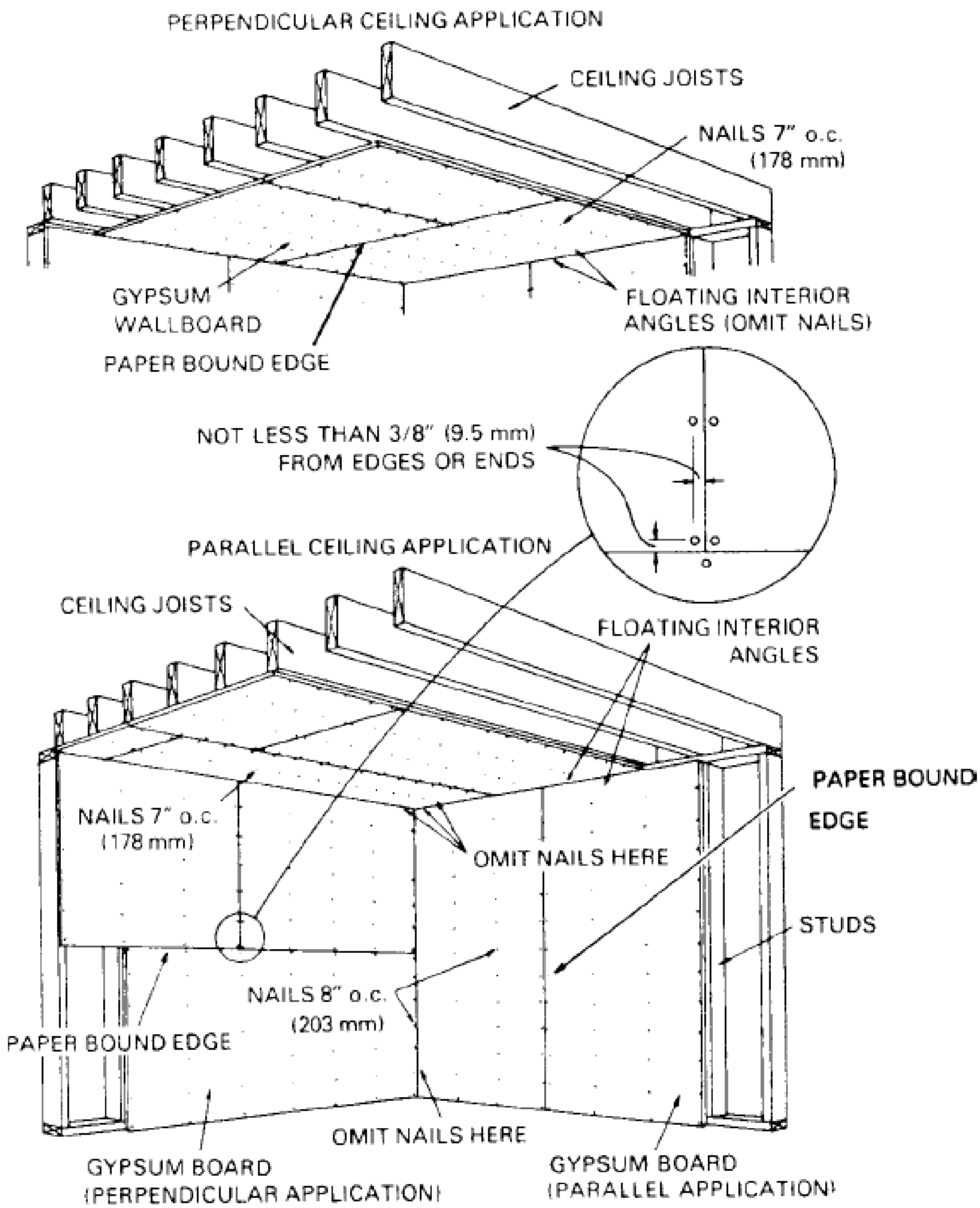


Figure 1. Single Nail installation (ASTMC840, 2008)

8.4.3 Double Nailing- Nails shall be spaced 12 in. (305 mm) in the field with a minimum of 2 in. (51 mm) and maximum 2 ½ in. (63.5 mm) between the pairs (figure 2).

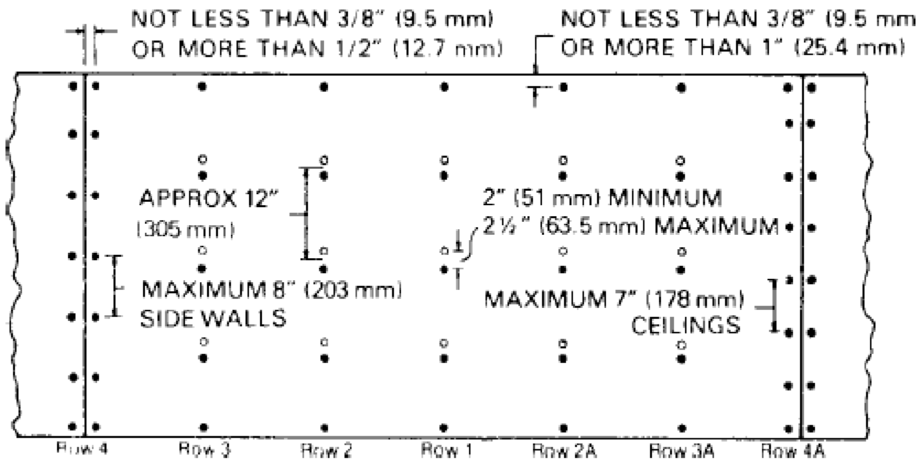


Figure 2. Double Nailing (ASTMC840, 2008)

8.4.3.4 Single nailing shall be used on the perimeter of the gypsum board, unless otherwise specified.

8.5 Spacing of Screws- Screws shall be spaced not more than 12 in. (304.8 mm) on centers along framing members for ceilings 16 in. on center for walls where framing members are 16 in. on centers. Screws shall be spaced not more than 12 in. on centers along framing members for ceilings and walls where the framing members are 24 in. (209.6 mm) on centers.

APPENDIX G: LAB REPORTS

Gypsum Board Installers Lab Report

CMGT XXXXX
Drywall Lab

Name ________________________
Apparatus Letter and Number_____

Overview:
We will be installing ½" drywall on a wood frame walls that is U shaped (see attachment). Two walls are appoximatley 4'-0" in length and 8-'0" in height. These walls will intersect with a third wall which is approximatley 6'-0" in length and 8'-0" tall. Each sheet has been precut to ease installation. 4 pieces are 48" x 45-1/2" and are intended for the side walls. The back whall has three pieces of drywall 1- 72" X 48", 1- 24" X 48", and 1- 48" X 48". The sheets have been cut so the back wall is installed first then both side walls. Screw fastners are to be installed with a drywall screw setter attachement to a drill.

After viewing the installation video you will be randomly seperated and paired. Half of the group will work in the TEC lab the other half in the COT lab. To aid in your lab, the USG wallboard installation guide, Text selection from Modern Carpentry, PGST Dental Clinic Remodel project specification 09.25.00 Gysum Board, and drawings.

Evaluation of your work will be based on the speed of installation and quality to the construction industry standard.

1. RS Means Building Construction Cost Data states two carpenters should install 2000 SF of gypsum board on wood walls and ceilings in one eight hour day in other words 125 SF per hour. This includes all measuring prepatory work such as cutting to size and distribution. You and you team member will install 112 SF on three walls with a prepared board that is distrubuted.

    a. How long do you think it will take to install the gypsum board in this lab in minutes and seconds?
    b. How long did it actually take in minutes and seconds?

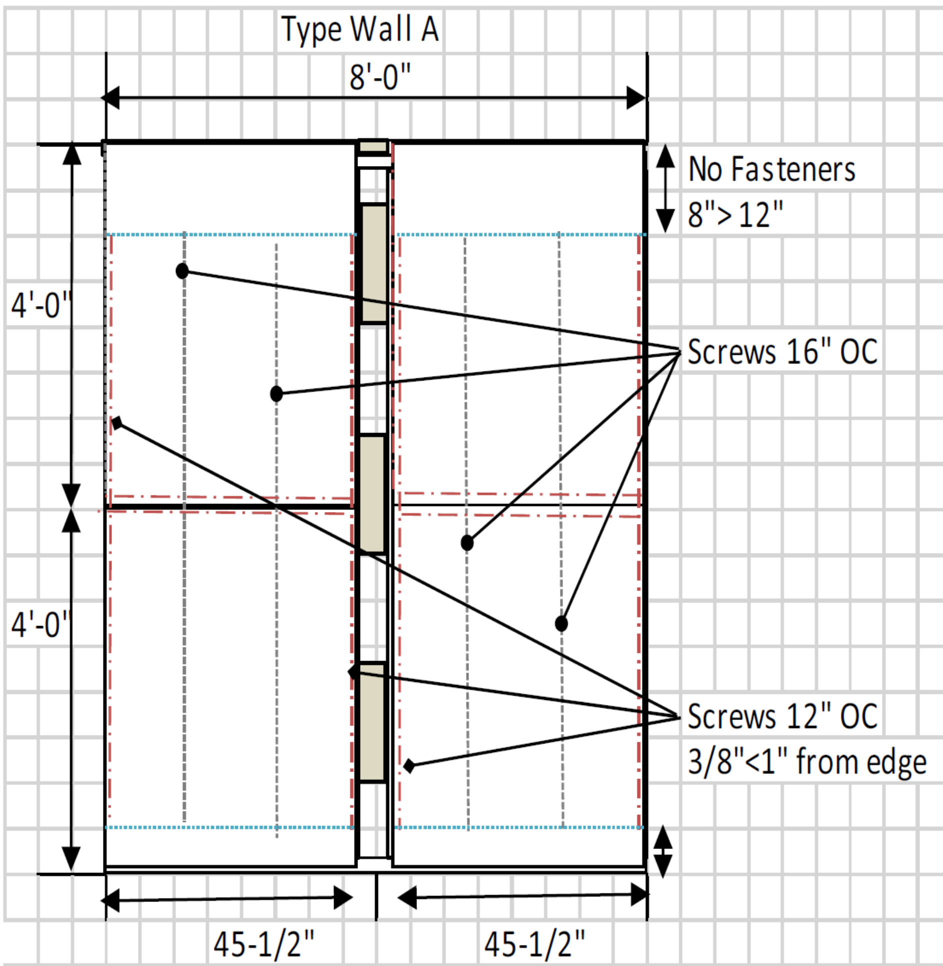
2. An important aspect of any project is the cost of material in our case fastners (screws). According to the USG installation guide for 0.3 pounds/59 screws are requried to install 100 SF of ½" gypsum board.
    a. How many screws do you anticipate using during the installation?
    b. What was the final count of screws your team used?

3. Quality of installation is vital to the cost of a project as the intial cost of installation. How do you rate your finished project in terms of quality on a ten point scale. A rank of 10 reperesenting "Exceeds quality standards" and 1 representing "major rework needs to be done prior" to the next phase of construction.

Exceeds Industry Standard **10 9 8 7 6 5 4 3 2 1** Requires rework

Installers Experiment Group Training Handout

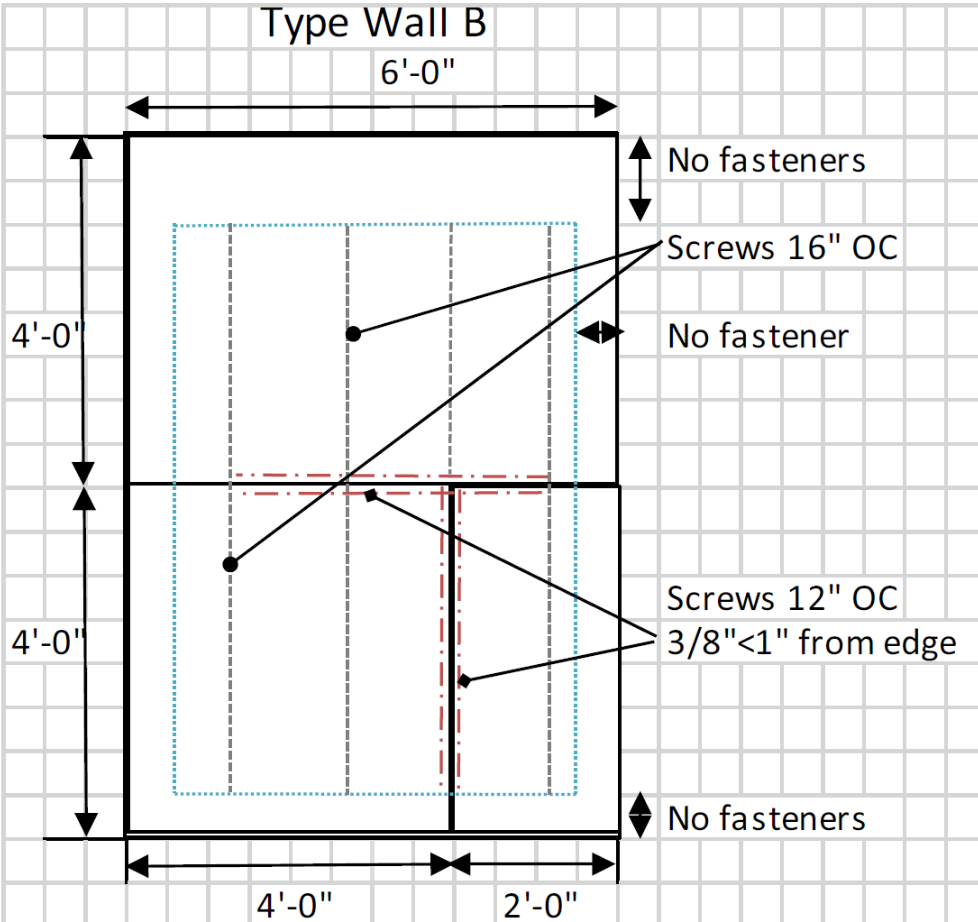
Drywall Lab
Installation Training Handout
ASTM C 840



Screws 12" OC and 3/8"> 1" from edge
Screws maximum 16" center of stud
No fasteners needed floating corner

Check framing prior to installation to assure layout of panel
Top screw 8"< 12" from ceiling panel
Install B wall first no fasteners used on corners
Place pieces together with factory edge max gap of 1/16"
No fasteners should be placed in the top or bottom plates.
Minimum distance from the bottom piece and floor is 1/4"

Drywall Lab
Installation Training Handout
ASTM C 840



Screws 12" OC and 3/8"> 1" from edge
Screws maximum 16" center of stud
No fasteners needed floating corner

Check framing prior to installation to assure layout of panel
Top screw 8"< 12" from ceiling panel
Install B wall first no fasteners used on corners
Place pieces together with factory edge max gap of 1/16"
No fasteners should be placed in the top or bottom plates.
Minimum distance from the bottom piece and floor is 1/4"

Quality Assessors Inspection Lab Report

DRYWALL INSTALLATION INSPECTION LAB
QUALITY ASSESSORS ASTM C 840

Date___________
Grid Letter _____
Grid Number____
Parameters assessed by Quality Assessors

The items listed below are from reference standard ASTM C 840-08. Each question addresses specific requirements of the standard. To aid in consistency of this inspection several attachments have been added. The first orientates the walls in each grid. The second is a sketch of the wall sections as designed.

7.1.3.1 Gypsum board applied to walls shall be applied with the bottom edge spaced not less than ¼ in (6 mm) above the floor.- **Did the wall meet the criteria? Yes/No**

Wall A1 ___ A2____ B____ Total No answers (0-3) walls _______

7.1.4 Fastening Gypsum Board to the framing. When used at edges or ends, fasteners shall be spaced not more than 12 inches on center on walls and a maximum distance of 1 in. (25 mm) from edges and not less than 3/8 in. (9.5 mm) from edges of gypsum board (except where floating angles are used). – **Number of fasteners not in compliance or missing.**

Wall A1 ___ A2____ B____ Total number ________

Perimeter fastening into the partition plate or sole at the top and bottom shall not be required**. Number of fasteners installed in the top or bottom plate.**

Wall A1 ___ A2____ B____ Total number ________

7.1.5 Screws shall be driven to provide screw head penetration just below the gypsum
Board surface without breaking the surface paper of the gypsum board or stripping the framing member around the screw shank- **Number of fasteners not in compliance**

Wall A1 ___ A2____ B____ Total number ________

7.4 Joints between gypsum boards shall be constructed with the gypsum board edges in moderate contact. - **Number of joints that did not meet this criteria.**

Wall A1 ___ A2____ B____ Total number ________

8.5 Spacing of Screws- Screws shall be spaced not more than 12 in. (304.8 mm) on centers along framing members for ceilings 16 in. on center for walls where framing members are 16 in. on centers. Screws shall be spaced not more than 12 in. on centers along framing members for ceilings and walls where the framing members are 24 in. (209.6 mm) on centers.- **Number of fasteners not in compliance or missing.**

Wall A1 ___ A2____ B____ Total number ________

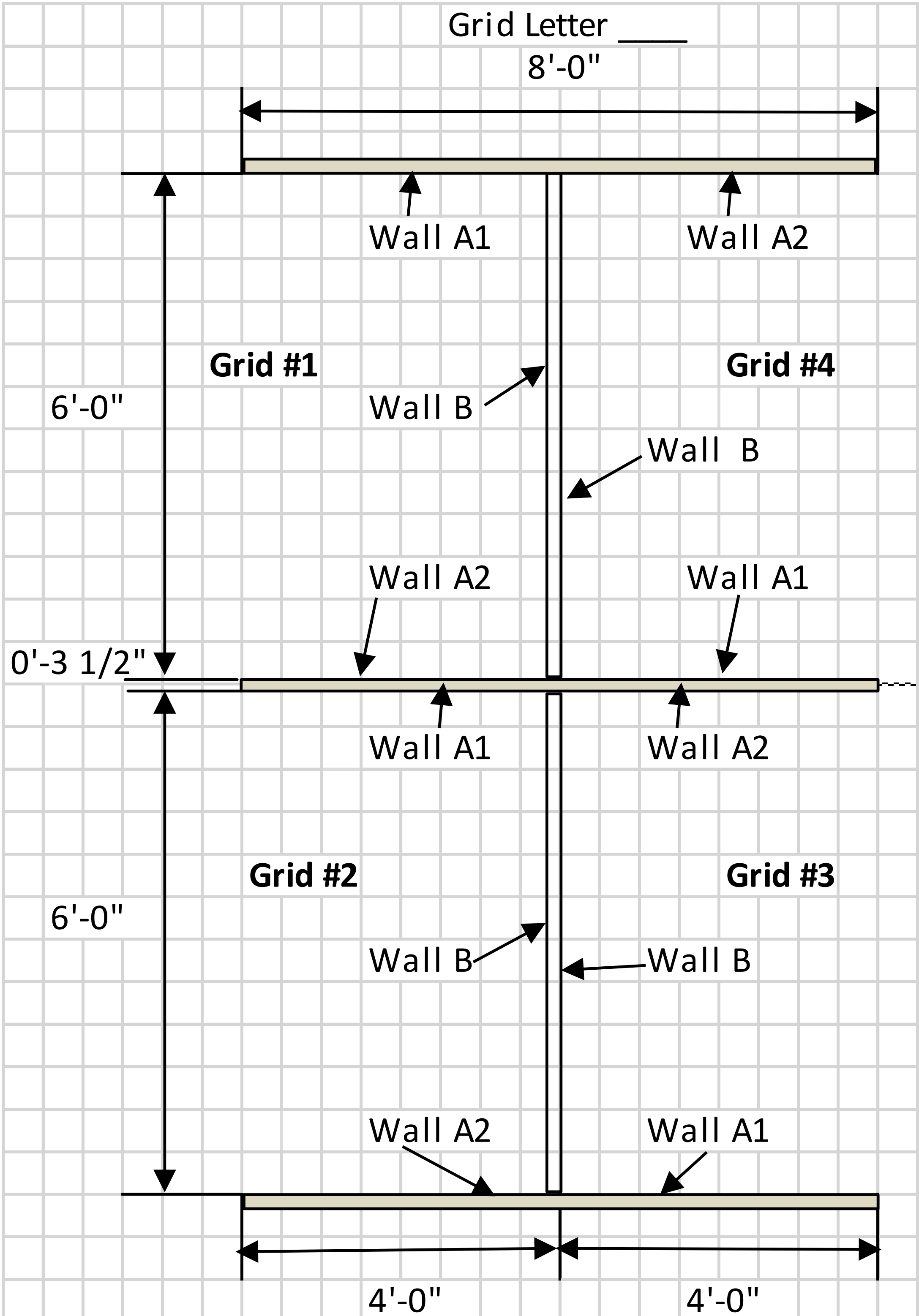
Total number of items that need to be addressed prior to passing ASTM C 840 criteria?

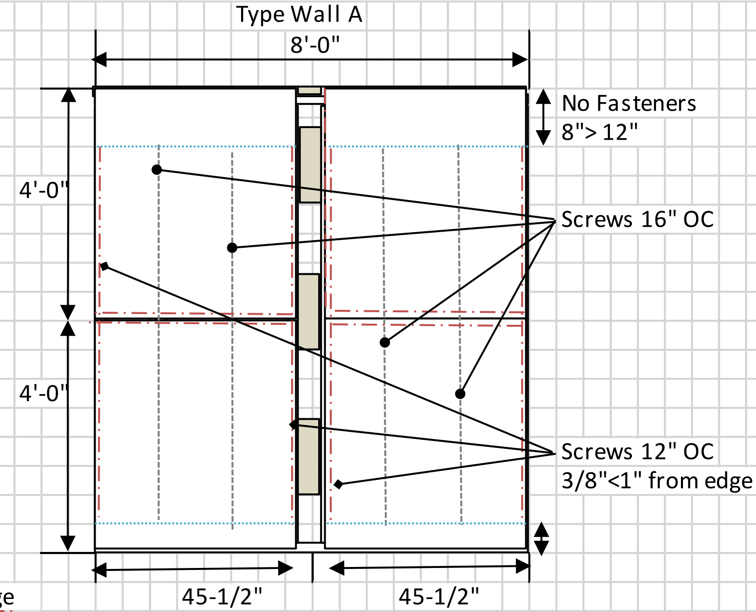
Grand Total __________

Now that you have completed your inspection please rate the overall quality on a ten point scale. Is it ready for the next step finishing? A rank of 10 represents the work "does exceed quality standards" and a 1 representing "major rework needs performed" prior to the next phase.

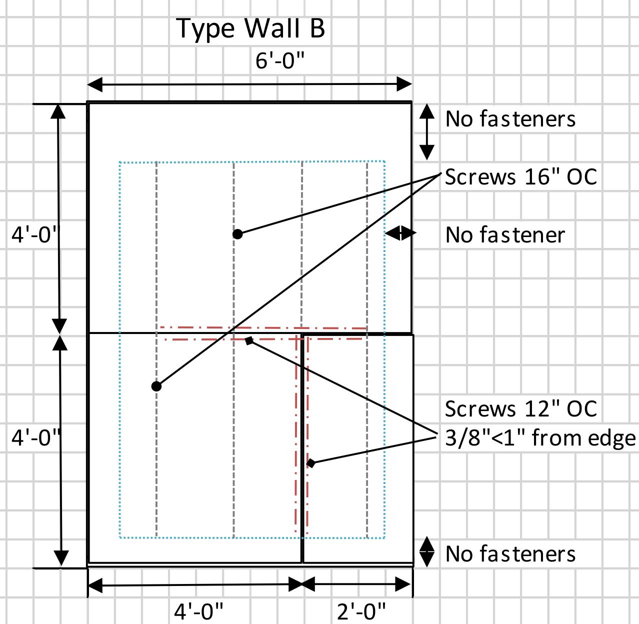
Exceeds Industry Standard 10 9 8 7 6 5 4 3 2 1 Requires rework

DRYWALL INSTALLATION INSPECTION LAB
QUALITY ASSESSORS ASTM C 840





Screws 12" OC and 3/8"> 1" from edge
Screws maximum 16" center of stud
No fasteners needed floating corner



Check framing prior to installation to assure layout of panel
Top screw 8"< 12" from ceiling panel
Install B wall first no fasteners used on corners
Place pieces together with factory edge max gap of 1/16"
No fasteners should be placed in the top or bottom plates.
Minimum distance from the bottom piece and floor is 1/4"

APPENDIX H: DATA COLLECTED

Installer Data

Role	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Time Seconds		Number Fasteners		Quality	Course	Grid
Code for data analysis as No Answer = 0, A=1, B=2, C=3, D=4,											Estimate	Actual	Estimate	Actual	1-10	CMGT	Number
1	1	2	1	2	1	3	1	1	3	2	2385	1650	65	120	8	1300	4.1
1	1	1	1	2	1	2	2	2	2	1	2400	1650	75	120	8	1300	4.1
1	2	1	1	2	2	1	2	1	3	2	1230	2717	60	96	7	1300	4.2
1	2	4	1	2	1	1	1	2	3	1	1230	2717	60	96	7	1300	4.2
1	2	3	1	2	1	3	2	1	2	1	1200	3084	75	96	2	3350	4.3
1	2	4	3	2	1	1	2	1	2	2	1200	3084	75	96	8	3350	4.3
1	1	1	1	2	1	1	2	1	4	2	1800	2292	50	117	10	1300	4.4
1	1	3	1	2	1	1	1	2	1	1	2730	2291	70	117	10	1300	4.4
1	1	4	4	2	1	1	2	1	0	2	3600	3032	60	152	7	1300	5.1
1	1	1	1	2	1	1	2	2	4	2	3000	3032	64	152	8	1300	5.1
1	1	4	1	3	1	1	1	0	0	0	3600	3600	59	101	2	3350	8.3
1	1	3	1	2	2	1	2	0	0	0	2400	3600	68	101	1	3350	8.3
1	2	1	1	2	2	1	2	1	3	1	2420	2580	60	75	7	1301	5.2
1	2	2	1	2	2	2	2	2	0	2	2420	2580	60	75	6	1301	5.2
1	1	4	1	2	2	1	1	1	1	1	1800	2880	130	140	3	3010	5.3
1	1	4	3	2	2	1	1	2	1	2	1380	2880	46	140	3	3010	5.3
1	2	2	1	2	2	2	1	0	0	2	3900	2736	50	80	7	1301	5.4
1	2	2	4	2	2	2	2	2	0	1	3600	2736	50	80	7	1301	5.4
1	2	4	3	2	2	2	2	2	1	2	3600	2432	60	75	7	3010	6.1
1	2	3	4	2	1	1	1	1	1	1	3600	2432	60	75		3010	6.1
1	2	1	1	2	2	2	2	1	3	2	3600		100	54	8	1301	6.2
1	2	4	1	2	2	3	2	1	3	1	3600		100	54	3	1301	6.2
1	1	1	4	2	2	1	1	1	1	1	2784	2160	64	114	10	3010	6.3
1	1	4	2	2	1	2	1	1	1	2	2730	2160	18	114	7	3010	6.3
1	1	2	2	2	1	3	2	2	2	2	915	1870	80	145	8	1300	6.4
1	1	2	1	3	1	3	2	1	2	2	915	1870	80	145	8	1300	6.4
1	1	1	1	2	2	2	2	1	3	2	2100	2700	60	144	8	1301	10.2
1	1	4	1	2	1	1	1	1	0	1	2100	2700	60	144	8	1301	10.2
1	1	4	2	3	2	2	2	2	2	2	2137	2956	72	106		3010	10.3
1	1	2	3	2	1	1	2	2	2	2	2100	2956	70	106	6	3010	10.3
1	2	3	1	2	1	4	2	1	3	1	1500	2427	96	77	7	1300	10.4
1	2	1	1	2	1	1	1	2	2	2	1500	2427	46	77	7	1300	10.4
1	2	1	1	2	1	1	2	1	2	2	1200	2700	50	49	6	1301	11.2
1	2	2	1	2	2	3	1	2	3	2	1200	2700	50	45	6	1301	11.2
1	2	2	1	2	2	3	1	1	1	1	2400	4500	50	67	5	2325	11.3
1	2	3	1	2	1	3	2	2	2	1	2400	4500	50	67	5	2325	11.3
1	2	4	1	2	1	2	2	2	0	2	1200	2467	20	43	4	1301	12.1
1	2	1	1	2	2	2	1	1	3	1	1800	2467	30	43	4	1301	12.1
1	2	2	1	2	1	2	1	2	2	2	3600	3257	67	75	7	1300	12.2

Installer Data (continued)

Role	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Time Seconds		Number Fasteners		Quality	Course	Grid
Code for data analysis as No Answer = 0, A=1, B=2, C=3, D=4,											Estimate	Actual	Estimate	Actual	1-10	CMGT	Number
1	2	1	1	2	1	1	2	4	2	2	3600	3257	67	75	7	1300	12.2
1	2	3	4	2	1	4	1	2	5	1	3900	3844	65	73	5	1301	12.3
1	2	2	1	2	1	3	2	2	2	2	3600	3844	50	73	6	1301	12.3
1	1	1	3	2	2	2	2	2	3	3	3600	2880	70	116	8	3010	1.1
1	1	4	2	2	1	2	1	1	2	1	4114	2880	128	116	8	3010	1.1
1	1	3	1	2	1	4	1	2	2	1	2400	1907	65	161	7	3350	1.2
1	1	4	1	2	2	4	1	1	2	1	2400	1907	65	161	7	3350	1.2
1	1	1	1	2	2	1	2	2	3	2	3600	3360	65	153	5	1300	1.3
1	1	4	2	3	2	2	2	2	2	2	3600	3360	120	153	5	1300	1.3
1	2	3	3	2	1	3	1	1	3	1	3345	3195	78	85	6	3010	1.4
1	2	3	1	2	1	3	1	2	4	2	2400	3360	78	85	6	3010	1.4
1	2	4	1	2	1	1	1	1	0	1	3600	2293	80	101	7	4400	2.1
1	2	4	1	2	2	1	1	1	2	2	1500	2280	72	101	5	4400	2.1
1	2	4	1	2	1	1	2	0	3	1	3030	2607	100	123	6	4400	2.2
1	2	4	1	2	2	3	1	2	3	1	2122	2607	135	123	6	4400	2.2
1	1	2	1	2	1	4	1	4	2	2	1800	2865	120	103	8	2325	2.3
1	1	2	1	2	1	1	1	1	1	1	3383	2865	120	103	7	2325	2.3
1	1	4	1	2	1	1	1	1	3	1	2130	2638	80	118	7	1301	2.4
1	1	3	1	2	1	1	2	2	3	2	1845	2638	108	116	4	1301	2.4
1	1	3	1	2	1	3	2	1	2	2	1837	1800	96	73	8	2325	3.1
1	1	1	1	2	1	3	2	2	2	2	1837	1800	96	73	8	2325	3.1
1	1	4	1	2	1	4	1	1	1	1	2400	2061	80	120	7	4400	3.2
1	1	4	1	2	1	4	2	2	3	2	2400	2040	50	100	7	4400	3.2
1	1	4	2	2	2	3	1	2	1	1	1440	1800	140	87	5	2325	3.3
1	1	4	1	4	1	4	2	2	3	2	2430	1815	140	87	5	2325	3.3
1	2	4	1	2	1	3	2	2	2	2	2647	3063	72	85	7	4400	3.4
1	2	4	1	2	1	2	1	2	3	1	3615	3063	70	84	4	4400	3.4
1	1	3	1	2	1	1	1	2	3	1	2100	3033	70	147	8	2325	7.1
1	1	2	1	2	2	3	2	2	3	2	2700	3000	65	147	7	2325	7.1
1	2	4	1	2	2	3	2	2	0	2	3240	3955	66	86	3	4400	7.2
1	2	4	1	2	2	3	2	1	2	1	4800	3900	100	86	3	4400	7.2
1	1	2	1	2	1	3	2	2	2	2	2700	2487	100	122	7	2325	7.3
1	1	2	1	2	2	3	1	1	2	1	2310	2476	70	122	8	2325	7.3
1	1	4	4	2	2	3	1	1	0	1	2910	2689	70	116	6	1301	8.1
1	1	1	1	2	1	2	1	1	0	1	4800	2689	76	116	6	1301	8.1
1	1	2	1	2	2	2	1	1	3	1	3300	2340	70	104	7	2325	8.4
1	1	2	1	2	2	2	1	2	3	1	4500	2367	75	104	8	2325	8.4
1	2	4	3	2	2	3	2	2	3	2	2887	2185	72	83	9	2325	9.1
1	2	3	1	2	1	1	3	2	3	2	2730	1752	66	104	8	2325	9.1
1	2	4	1	2	1	1	3	2	0	2	2730	1752	66	104	8	4400	9.3
1	2	4	1	2	1	3	1	1	0	1	3226	1425	67	75	8	4400	9.3
1	2	4	1	4	1	4	2	3	1	2	3180	1425	67	75	8	4400	8.3
1	2	4	1	2	1	3	1	2	3	2	2580	2185	74	83	8	4400	8.3

Inspector Data

Inspection Data

Location	Grid	Inspection Rating		Inspection check list number of faults per section listed						Sum Num.
		Pre	Post	7.1.3.1	7.1.4a	7.1.4b	7.1.5	7.4	8.5	Faults
2	1.1	5		2	12	0	11	2	52	79
2	1.1	7		3	12	0	11	5	52	83
2	1.1	6	4	2	12	0	11	2	52	79
2	1.1	9	5	0	14	22	17	4	61	118
2	1.2	4		0	21	0	21	2	26	73
2	1.2	4	5	0	21	0	21	2	26	70
2	1.2	3	5	0	21	0	21	2	26	70
2	1.2	8	3	0	24	20	40	4	74	162
2	1.3	7	4	0	16	0	18	4	45	83
2	1.3	5	3	0	13	0	13	6	33	65
2	1.3	4	5	0	13	0	12	5	12	42
2	1.3	10	2	0	31	25	77	8	51	192
2	1.4	8		0	22	0	6	3	16	47
2	1.4	5	7	3	6	0	8	3	16	36
2	1.4	5	7	0	6	0	8	3	16	33
2	1.4	10	7	0	31	16	16	4	32	99
2	2.1	4	1	3	4	0	75	1	47	130
2	2.1	4	1	3	4	0	66	1	39	115
2	2.1	4	3	0	12	0	66	0	34	100
2	2.1	8	6	0	7	0	66	3	66	142
2	2.2	2	2	1	2	14	34	4	45	100
2	2.2	3	1	3	4	18	76	1	67	169
2	2.2	4	5	0	4	9	61	1	48	123
2	2.2	8	4	0	19	23	87	3	84	216
2	2.3	5		1	8	0	0	1	35	45
2	2.3	5	1	2	9	1	3	2	31	48
2	2.3	6	8	0	9	1	0	0	7	17
2	2.3		7	0	27	1	8	2	85	123
2	2.4	3	2	1	2	0	49	0	46	78
2	2.4	4	1	3	24	0	73	3	33	136
2	2.4	3	5	0	13	0	66	3	30	112
2	3.1	7	3	3	20	0	70	8	45	146
2	3.1	5	4	3	20	0	70	8	45	148
2	3.1	4	4	3	20	0	70	8	45	146
2	3.2	6	5	0	12	0	24	8	43	87
2	3.2	3	5	3	14	0	57	5	42	121
2	3.2	3		3	15	0	57	7	21	103
2	3.2		5	0	12	0	69	2	75	158
2	3.3	7	8	0	0	0	3	4	20	27
2	3.3	6	8	3	2	0	8	6	32	51
2	3.3	5		3	0	0	24	6	36	69
2	3.4	3	4	0	11	0	39	5	66	121
2	3.4	3	3	3	18	0	52	8	77	156
2	3.4	3		3	29	0	30	8	71	133
1	4.1	8	4	1	21	13	40	3	35	113
1	4.1	8	4	1	21	13	40	4	28	107
1	4.1	8	1	0	0	19	82	0	71	172
1	4.1	3	3	0	51	29	93	3	111	287

Inspection Data (continued)

Location	Grid	Inspection Rating		Inspection check list number of faults per section listed						Sum Num.
		Pre	Post	7.1.3.1	7.1.4a	7.1.4b	7.1.5	7.4	8.5	Faults
1	4.2	7	9	1	7	13	16	4	14	55
1	4.2	8	8	1	7	4	16	4	16	48
1	4.2	8	2	0	0	24	29	0	36	89
1	4.2	3	3	0	58	29	52	2	113	254
1	4.3	7	6	0	14	14	69	2	15	116
1	4.3	7	6	0	14	14	72	4	12	116
1	4.3	6	3	1	0	7	86	0	60	154
1	4.3	4	2	0	68	30	94	4	114	310
1	4.4	5	8	1	16	13	29	4	10	73
1	4.4	7	7	1	16	13	30	5	12	61
1	4.4	8	1	0	0	11	35	0	80	126
1	4.4	4	3	0	23	28	68	3	113	235
1	5.1	1	1	1	51	27	110	11	27	227
1	5.1	7	7	0	6	28	7	2	28	63
1	5.1	5	5	1	18	19	71	6	22	137
1	5.2	3	3	0	43	22	18	4	85	172
1	5.2	7	2	1	3	34	14	0	62	114
1	5.2	8	8	0	6	21	8	1	32	68
1	5.3	4	1	1	47	23	114	5	58	248
1	5.3	8	7	0	7	24	3	2	20	56
1	5.3	3	4	2	3	18	95	2	21	141
1	5.4	8	2	0	37	22	42	7	72	180
1	5.4	7	6	0	10	27	19	0	36	92
1	5.4	9	7	0	11	21	18	4	26	80
1	6.1	7		1	31	29	27	4	72	164
1	6.1	6	2	1	17	29	28	7	36	117
1	6.1	6	5	1	14	29	21	8	27	100
1	6.1	8	3	1	21	28	23	4	31	108
1	6.2	6		0	31	27	20	5	83	166
1	6.2	4	4	0	11	27	29	6	34	107
1	6.2	5	6	0	14	27	17	6	34	98
1	6.2	7	1	0	22	27	26	2	53	130
1	6.3	6	4	0	31	28	20	4	21	104
1	6.3	6	4	0	15	28	22	8	32	105
1	6.3	8	4	0	17	29	36	4	22	108
1	6.4	6	5	1	41	28	4	4	10	88
1	6.4	5	8	1	16	29	6	8	29	86
1	6.4	7	5	1	28	27	8	4	41	109
2	7.1	7	4	0	13	26	83	6	65	193
2	7.1	6	4	0	3	1	65	2	5	76
2	7.2	7								
2	7.2	6	7	0	1	0	11	3	0	15
2	7.3	8	2	0	15	25	95	5	65	205
2	7.3	8	6	0	2	1	37	1	3	44
2	8.1	1	1	0	2	0	51	0	46	99
2	8.1	9	1	0	10	0	30	1	29	109
2	8.1		4	0	0	0	51	2	46	99
2	8.1	8	8	0	0	0	3	3	0	6

Inspection Data (continued)

Location	Grid	Inspection Rating Pre	Inspection Rating Post	Inspection check list number of faults per section listed 7.1.3.1	7.1.4a	7.1.4b	7.1.5	7.4	8.5	Sum Num. Faults
2	8.3	3	3	0	0	0	35	0	43	78
2	8.3	8	1	0	0	0	39	3	18	60
2	8.3		7	0	0	0	21	0	20	31
2	8.3	1	5	1	3	0	3	0	3	10
2	8.4	7	8	0	0	0	3	3	0	6
2	8.4		6	0	9	0	38	0	20	64
2	8.4	8	1	3	3	3	3	3	3	18
2	9.1	8	5	0	2	0	2	1	10	15
2	9.1	7	4	0	0	14	8	0	9	31
2	9.1		10	0	0	0	0	0	0	0
2	9.3	6	4	0	3	0	31	1	9	44
2	9.3	9	6	0	6	0	20	0	0	26
2	9.3	9	8	0	3	0	0	0	0	3
1	10.2	8	7	0	6	38	19	1	1	70
1	10.2	7	7	0	16	24	21	4	8	73
1	10.2	2	2	0	48	23	26	3	67	167
1	10.3	9	8	0	7	29	23	0	33	92
1	10.3	8	7	0	13	30	5	0	13	61
1	10.3	4	4	0	20	28	30	0	109	187
1	10.4	8	7	0	1	28	69	1	52	151
1	10.4	8	6	0	22	27	24	2	15	90
1	10.4	3	6	0	15	28	75	3	110	232
1	11.1	6	4	0	12	28	30	5	76	151
1	11.1	3	5	3	3	28	6	1	28	66
1	11.1	1	3	2	2	25	17	3	20	78
1	11.1	8	4	2	36	32	17	3	16	104
1	11.1	5	3	0	33	33	41	0	26	133
1	11.2	7	2	0	59	39	77	2	153	330
1	11.2	5	3	3	33	33	40	3	16	104
1	11.2	3	1	3	3	3	3	3	3	18
1	11.2	4	4	3	33	33	41	2	26	125
1	11.2	5	4	0	36	32	17	3	16	104
1	11.3	7	4	2	4	32	17	3	16	104
1	11.3	7	7	0	2	28	16	1	14	61
1	11.3	4	5	3	1	28	6	1	18	66
1	11.3	7	5	0	1	27	6	1	31	66
1	12.1	6	3	3	17	29	10	4	28	91
1	12.1	8	5	0	24	10	23	1	104	162
1	12.1	8	5	3	4	0	8	0	7	22
1	12.1	7	8	0	3	0	3	3	3	12
1	12.1		6	0	3	0	30	0	9	42
1	12.2	5	4	3	34	27	25	4	32	125
1	12.2	8	4	0	21	29	84	4	107	245
1	12.2	5	4	0	4	7	38	0	39	88
1	12.2	3	2	0	4	7	38	2	21	72
1	12.2	6	1	3	30	30	30	30	30	150
1	12.2	5	2	0	4	7	38	0	33	82
1	12.3	7	4	3	17	26	8	0	32	86
1	12.3	5	5	3	17	26	8	0	32	87
1	12.3	5	8	0	0	23	1	0	12	36
1	12.3	3	6	3	17	26	8	0	32	87

Inspector Questioner

Role	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Course
Code for data analysis as No Answer = 0, A=1, B=2, C=3, D=4,											CMGT
2	2	3	1	2	2	2	2	2	0	2	3320
2	2	3	1	2	1	2	2	2	3	2	3320
2	2	4	1	3	1	1	2	2	0	1	3320
2	2	1	4	2	2	1	2	1	3	1	1301
2	2	3	1	2	1	1	2	2	3	1	3320
2	2	3	1	2	2	1	2	2	1	2	3320
2	2	3	1	2	1	4	2	2	2	2	3320
2	2	3	4	4	1	1	1	1	3	1	1301
2	2	3	2	2	1	2	2	2	4	2	3320
2	2	4	1	2	2	3	1	1	3	1	3320
2	2	4	0	0	0	0	0	0	0	0	3320
2	1	3	1	2	1	1	2	2	2	1	3320
2	1	3	1	2	1	1	1	1	1	1	3320
2	1	2	2	2	2	1	3	3	4	3	3320
2	1	2		2	1	2	1	1	1	1	1301
2	1	4	1	2	2	2	1	1	3	1	3320
2	1	3	1	2	1	1	2	1	3	2	3320
2	1	3	2	2	2	3	2	2	2	2	3320
2	1	4	1	4	1	4	2	2	3	2	3320
2	1	3	1	2	1	3	3	1	3	1	3320
2	1	3	1	2	1	2	2	1	3	2	1301
2	2	1	4	2	2	1	2	1	3	1	2310
2	2	1	1	2	2	1	2	1	3	2	2310
2	2	1	1	2	1	1	2	1	3	3	2310
2	2	4	1	4	1	4	1	1	2	1	2310
2	2	2	1	2	1	1	2	1	1	3	2310
2	2	3	4	2	1	1	1	2	3	2	2310
2	2	3	2	2	1	2	2	2	2	2	2310
2	2	2	4	2	1	3	1	1	4	2	2310
2	2	1	1	2	1	2	1	1	3	1	2310
2	1	3	1	2	1	1	1	2	3	1	2310
2	1	1	1	2	2	1	2	2	0	2	2310
2	1	4	2	2	1	1	1	1	2	1	3320
2	1	3		4	1	1	1	1	1	1	2310
2	1	3	2	2	1	2	2	2	2	2	2310
2	1	1	1	2	2	3	2	2	2	1	2310
2	1	1	1	2	1	1	4	3	4	3	2310
2	1	2	1	2	1	2	1	1	1	1	2310
2	1	4	1	2	1	2	2	2	2	2	2310
2	1	3	1	2	1	3	2	2	2	2	2310
2	1	1	1	2	1	1	2	2	2	1	2310
2	1	2	1	2	2	2	2	2	3	2	2310
2	1	1	1	2	2	2	1	1	3	1	2310
2	1	3	1	2	1	3	1	2	1	1	2310