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Spatial-Cognitive Ability and Its Relation to Information Delivery in the Construction Industry

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SPATIAL-COGNITIVE ABILITY AND ITS RELATION TO INFORMATION DELIVERY IN THE CONSTRUCTION INDUSTRY

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Construction skilled labor is fundamentally measured by productivity and quality of work, based upon an individual's ability to perform activities. Every individual has an innate talent in which they can understand the complexity of information to perform their activity. Construction activities often appear as inordinately complex multi-directional systems. The goal of this research was to understand differences in individual comprehension, and identify if complex information can be understood at the same rate by all levels of individual spatial-comprehension. This research was given direction by focus groups in North America conducted with pipefitters. Experiments then tested the influence of three information formats by assembling mock pipe. Traditional isometric drawings served as the baseline test, then the influence of adding 3D perspectives was assessed. The influence of added 3D perspectives allowed individuals with lower spatial-cognitive abilities to perform as efficiently as subjects with higher spatial-cognitive abilities, increasing overall productivity across ability levels.

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CHAPTER I
INTRODUCTION

Construction is the largest manufacturing industry in the US. Even though its partnering industry, engineering, has invested a tremendous amount of capital into 3D design systems, the engineering information provided to construction has degraded over the years. The same 2D format of information used for the craft today, was the same format provided decades ago. In the rare case a 3D model is provided to construction, it is not kept updated nor is the information necessary for construction. In the case of pipefitters, isometric engineering drawings have been the main information deliverable to the craft since the beginning of the 20th century. Pipefitters have some of the most complex designs issued in the industry, and are a key component to the critical path of a construction schedule. "Isometrics" are printed drawings that provide the basic technical information for creating construction installations. This research identified that the performance of craft professionals can be significantly improved by enhancing information delivery. As the industry moves forward with increasing complexity (CII 2013) and grows short of craft professionals (CII 2015), the method and format of information delivery must also advance.

The five resources required for proper execution of construction are: 1) materials, 2) information (e.g. vendor information, plans, and specifications), 3) tools and equipment, 4) craft skills, and 5) access (CII 2013). Information includes the textual and graphical details the craft needs to complete construction tasks and processes ranging from vendor information to engineering deliverables. Well-conveyed engineering information results in increased productivity (O'Connor 1985). Emmitt and Gorse (2003) discovered serious negative implications in delivering information mediums not preferred nor meaningful to the craft. Inefficient information delivery practices minimize time that the craft can spend on direct work (the time that the craft physically spend on activities – CII 2013). Furthermore, CII RT-252 found that 14.6% of rework events on one industrial site were due to design and engineering (CII 2011).

Liberda et al. (2003) asked industry professionals to rank 51 factors in 3 categories (human manpower, management, and the external environment) that affect construction productivity. Lack of information necessary to perform construction ranked 8th out of 51 factors commonly experienced by craft as barriers to productivity (Liberda et al. 2003). The importance of information was found to be even more critical in a study by Dai et al. (2009a) that surveyed close to 2,000 craft workers and found that 3 of the top 10 issues were related to both the availability and accuracy of engineering drawings (Dai et al. 2009a).

Recent research findings have discovered how the media format of information influences individual performance. Dadi (2014) involved a number of craft from various trades in completing a mock exercise where each worker completed a task using one of three different information formats, including a two-dimensional plan set, a digital 3D model, and a 3D physical printed model. Productivity measures based on direct work rates were significantly better when each worker used a 3D physical printed model to complete the task. In addition, the cognitive demand placed on each work was measured to be less when each worker used the 3D physical printed model. While these findings suggest that 3D physical printed models present a promising alternative or supplemental form of spatial information to the traditional forms of engineering information delivery, much work remains to be done in considering other forms of information delivery.

This research was unique in a number of aspects. This research focused on information systems regarding the pipefitters, considering their critical importance on most industrial construction projects. The specific objectives of this effort included the following:

1. Identify the preferred content (data and graphics) of how engineering and construction information is provided to pipefitting crews;
2. Identify the gaps between preferred content delivery of information and current content delivery mechanisms;
3. Identify pipefitters' perceptions of which innovative information delivery methods would most improve their performance; and
4. Quantify the influence that innovative information delivery methods can have on pipefitters' performance through both objective field studies and interviews of practitioners who are implementing an innovative information delivery method.

In many ways, this research builds on Dadi (2014) and Sweany (2014) by focusing more on the influence of information's format on direct productivity. It also critically examines the relation between individuals' cognitive abilities and their effectiveness of using different formats of information. Individuals have different capabilities to effectively visualize engineering information that is traditionally provided to them in a two-dimensional format, which equates to how effective and efficient they are in performing an actual task related to the information format. A guiding question to this research included if the use of 3D information from engineering to supplement 2D information is way to help level the playing field of different capabilities. As the construction industry experiences increased complexity and emerging craft shortages (Albattah et al. 2015), the format of engineering information provided to crafts must also advance.

CHAPTER II

LITERATURE REVIEW

This review discusses a brief history of construction literature – what factors have affected productivity, and the ways in which information has been communicated in the past. Last, the review discusses how information delivery is perceived by the craft, entering discussion of worker cognitive abilities and recent discoveries in this area.

2.1 The Role of Information and Influence on Craft Productivity

Productivity is the ratio of a process inputs to outputs (CII 2013). Construction productivity has been defined by the US Bureau of Labor Statistics as economic inputs to outputs (Bureau of Labor Statistics 2013). By minimizing the amount of labor or work hours committed by the craft and increasing their efficiency, productivity will maximized. Productivity can be minimized by three factors: work practices, technology, and other (external conditions, i.e. weather, plant conditions and absenteeism) (CII 2013). However this research examines the first factor – technology and its integration into information delivery.

Dai, Goodrum and Maloney (2009a) conducted a series of surveys of 1,996 craft professionals employed in U.S. construction to include: industrial/remediation, electricity generation, industrial processes and petrochemical. The surveys found and organized 83 factors that could serve to identify problems from the crafts' perception. The 83 factors were scaled mainly on severity and frequency, which provide guidelines for what changes should be implemented, and where, to cause the greatest improvement in construction productivity for the future. Results indicated that craft professionals were able to discern the factors that adversely affected their productivity. The greatest factors affecting productivity were: tools and consumables, materials, engineering drawing management and construction equipment.

Effective drawing management often controls the amount of time that the craft can spend on direct work and alleviates vast amounts of rework (Fayek et al. 2004). Productivity metrics from the Construction Industry Institute, based upon 359 large construction projects, concluded that larger projects (greater than $100 million) had lower rework occurrences since they most likely had the best information delivery processes, they could afford better planning, namely, building information modeling (Hwang et al. 2009).

2.2 Building Information Modeling – BIM

There are generally three types of ways that information can be delivered to the craft: two-dimensional models, three-dimensional physical models and Building Information Models (using a computer interface). BIM may be used to complement common forms of delivery (by adding value such as visual aid). BIM is a computer software tool that has many construction industry applications in addition to visual representation. Some of these application include, but are not limited to: scheduling construction phases, tracking construction progress (i.e. consistent and non-redundant data: Goodrum 2014), integrating data attributed to building components (i.e. behavioral data or specifications), safety modeling and clash detection.

Lee, Dossick and Messner (2013) measured BIM acceptance among construction organizations from over one hundred users by means of Structural Equation Modeling (SEM). The SEM yielded some interesting results touching on why organizations resisted BIM acceptance. Many organizations perceived BIM as unsuitable for their particular craft, mostly they did not view the benefits of BIM as worth the cost. Subjects were often unaware of the holistic impacts BIM has on project productivity. Resisting subjects viewed BIM as an unnecessary technology adding unneeded expense to the project. In reality, it takes experience and a better understand of BIM to fully understand the long term benefits that can be added to a project.

If owners do employ BIM on their projects, engineering and management teams can use this resource to aid craft workers in information delivery. In its most primitive use, BIM produces a three-dimensional model of what is to being constructed. When engineers produce accurate, to-scale building information models, every visual aspect and orientation of the design is made accessible to view. Engineers can use these views to print the designed model into one of two forms: physical models (physical three-dimensional models), or a series of pictures with different orientations of the model on paper – similar to a screenshot – called three-dimensional model shots.

2.3 Three-Dimensional Physical Models and Three-Dimensional Model Shots

Physical models have existed in the construction industry as training and communication aids for decades. The models were utilized in a number of ways. One instance was construction sequencing – modeling equipment and material handing through existing construction (Oglesby et al. 1989). Another, craft workers interactively handled the physical model by taking the plastic pieces apart and understanding the erection sequences and assembly layout (Oglesby et al. 1989). These trendy physical models have been phased out by BIM alone, and are rarely implemented in construction anymore. Now, three-dimensional physical models are mostly printed monolithically (not as interactive pieces that may be assembled/re-assembled), called rapid prototyping technology. This delivery medium is printed by a three-dimensional printer. The process of producing physical models is fast, but more expensive for printer material costs than paper printing.

Three-dimensional model shots are screen-shots, static pictures, of a computer animated drawing or BIM file. The model shots may be printed or viewed on a computer screen. The printed views may be attached to the backs of engineering drawings that represents them, compiled in a sequential fashion, called two-sided drawings or Two-Sided Isometric drawings (Ford, Bacon and Davis 2014). Similar to the physical model, the three-dimensional model shot is a scaled, realistic adaptation of what is to be constructed onsite. Both information types are capable of aiding craft workers to encode engineering drawings.

2.4 Engineering Drawings – The Encoded Message

The way in which engineering management sends their instructions to the craft workers for construction is a standard set of engineering drawings. These drawings are also known as blueprints (Dadi 2013), which are given in different formats depending on craft demand. Formats include: isometric drawings, plan sections, detailed sections or other. The current information format delivered to craft workers is exclusively in a two-dimensional paper format that provides detailed, technical information to all craft workers in order to carry out their tasks (Emmitt et al. 2003). However, the current method of information being portrayed in the engineering drawings is all too often unclear. The information is meant for the eyes of an engineer in front of their computer, not tailored for a construction worker in the field.

Sheetmetal, electrical, plumbing, and pipefitting craft workers traditionally use isometric drawings as the basis for their work. Isometric drawings are given on two-dimensional pieces of paper that come in the form of either 8.5”x11” or 11”x17” set on an axis of 45, 90 and 135 degree orientations to allow for directional distinction of the design’s geometric properties.

One drawback to the Isometric drawings is the absence of scaling, the lengths of members in a design are not proportionate. For example, a 20 ft. member will appear be longer than a 4 ft. member on the drawing, yet may appear to be only twice as long. The purpose for leaving out scaling is to leave space for dimensions and annotations. This requires the craft workers to read the texted dimensions, then recreate an accurate three-dimensional image in their mind.

Pipefitters are typically issued work packages that include content such as material quantities, joint specifications, and brief statements about the estimated effort and duration required for the assembly and a series of isometrics that compose an entire assembly. Individual isometric drawings depict a single pipe spool and, in order to fit the spools together, annotations indicate which drawings show adjacent spools (Dadi 2014). Filing through the stack of paper to conceptually piece it together is no easy task. It requires a greater degree of spatial-cognitive ability than interpreting one drawing by itself.

Imagine an engineer creating a design on a computer-aided drawing program sitting at their desk. An engineer submits the drawing into the field with many annotations that describe an unscaled installation. This design makes sense to an engineer, not to a craft worker. Emmitt and Gorse (2003) agree that the drawings are intended to be used by the architect or engineer, who design them, this leaves the craft worker to interpret a “message” (Dadi 2013). The craft worker must have the conceptual ability to recreate a three dimensional, full scale model of the design that was delivered. The following diagram serves as a simple illustration of the information delivery process:

Figure 2-1 Information Delivery Process

The way in which these engineering drawing packages are delivered is not capable of being intuitive enough for entry-level workers to understand. To fully grasp engineering drawing packages it takes extensive experience.

However, it is not only the conceptual barrier of processing two-dimensional drawings that has caused inadequate information delivery. Drawing management, drawing design errors made by engineers, drawing legibility, and slow rates of responses to requests for information from management (Goodrum et al. 2006; Dai et al. 2009a, Dai et al 2009b) are additional problems that have existed in communication. However, this study focused solely on improving information formats despite other information delivery issues. This study analyzed technologies that will help aid craft workers conceptualize isometric engineering drawings with more ease. Some individuals benefit more than others by their innate spatial-cognitive ability.

2.5 Cognitive Analysis

Ekstron (1976) found that any information format in the workforce must be fully understood in order to perform a task successfully, but realistically, each worker has a finite ability in which they can understand information, called "cognitive ability." Engineering information formats are complex and require workers to use "spatial orientation" to interpret information, manipulating patterns and shapes in their mind to create an image. Lohman (1979) listed the process of spatial orientation in a series of steps: encoding, remembering, transforming, and matching information. Rieber (1995) reported that mentally reassembling orthographic displays leads to ambiguities, omissions, and interferences. As such, filing through a stack of 2D isometric drawings to visualize an entire 3D pipe module requires a significant degree of spatial-cognitive ability in order to understand how the individual pipe spools intersect in a 3D space.

This thesis builds on the foundation of previous findings from scholars who have researched methods of cognitive analyses. It is a recent phenomenon that the construction engineering and management (CEM) academic community has studied cognitive analyses. In the past decade, the CEM field has considered how craft worker abilities influence the interpretation of engineering drawings. However, a broader range of cognitive analyses have existed for many decades in the social sciences dating back to literature published in 1970s and before.

Crystal and Ellington (2004) discussed the history of modern task analysis models and their development. The main discussion evaluated the goals of certain techniques during past studies. Crystal and Ellington suggest that cognitive framework models have been "complex and fragmented" in the past. Their study discussed where research should head next, stating that cognitive analyses ought to clearly framed, created by researchers and not always from a complete practical standpoint.

Solis and O'Brien (2012) seemed to capture what Crystal and Ellington studied. They created models that provided more clarity than in the past. Solis and O'Brien (2012) examined construction superintendents' perspectives of what their work objectives were and how they were met. The study understood the ways in which superintendents used information to make each decision. They recorded all processes into a results model. The objective of the results model was to serve as a teaching guide for new professionals entering the role of superintendent, and benefit new trainees. Solis and O'Brien have since been developing cognitive design models in similar areas.

To accommodate the variance in levels of cognitive ability between workers, the information provided to them should be in formats that require the lowest possible cognitive demand. Current paper and digital devices lack the flexibility that may require workers to proceed without critical information they need or perform additional steps to change the workflow (O'Brien et al. 2011). This lack of flexibility increases the cognitive demand on the worker. Contextual information helps workers orient themselves and reduces the cognitive demand on workers.

2.5.1 Methods of Information Delivery and Cognitive Analysis

"Cognitive Workload Demands Using 2D and 3D Spatial Engineering Information Formats" (Dadi et al. 2014) analyzed 26 practitioners' ability to recreate a model design based on three types of information deliverables. The three information deliverables consisted of a two-dimensional drawing, a three-dimensional computer-aided drawing, and a three-dimensional physical model. The purpose of the research was to discover if mental workload and overall performance would differ between mediums during simple assemblies of a model. Use of mental workload evaluation has been used in the past, seen in aviation, occupational safety and transportation (Dadi et al. 2014). Dadi, Goodrum, Taylor and Carswell have since successfully applied this type of evaluation into the construction engineering management (CEM) realm. Its application in the CEM realm allows for evaluation of information perception.

The research methods required each subject to assemble the same design using all three spatial formats. However, this sequencing of mediums, one after another, allowed subject to gain familiarity with the design. After completion of the first sequence, the gained familiarity resulted in a learning curve. In attempt to control for the learning curve, the design was rotated between each medium. There were six different orientations implemented that one participant could have. Despite the learning curve the results yielded significance showing that performance differed by information type. Performance was measured by the percent of time that subjects spent on direct work, indirect work and rework. To capture mental loading on the subjects, a NASA Test Load Index (NASA-rTLX) was given to each subject to fill out per information format sequence upon completion. Lastly, the subjects were asked to fill out a background/experience questionnaire.

The research did have profound findings: (1) when subjects were first tested with the 3D Physical Model, the 2D and 3D drawings were easier to follow – the learning curve was greatest, (2) the 3D Physical Model had best results in its usability for less trained subjects (subjects with less experience in computer animated systems or two-dimensional engineering drawings), (3) by identifying different demographics of the subjects, results were able to discern that with greater "…age, construction experience, education and construction occupation" practitioners would perform better (Dadi et al. 2014), and (4) lower workload scores indicated better performance, thus concluding that information delivery must be clearly communicated and intuitive in order to maximize worker performance.

Limitations of the research are as follows: (1) there was no discussion of a relationship existing between the information types and cognitive ability of the workers, (2) sequencing the three information types caused a learning curve, therefore, no equal evaluation of each information type was achieved (due to limited sample size), and (3) the research did not account for differences in completion time of participants.

"Cognitive Demand for Engineering Information" (Sweany 2014) further analyzed the study performed by Dadi et al. by successfully breaking through limitations 1, 2 and 3. In addition, Sweany statistically proved that three-dimensional models enhance performance, information types affect different levels of cognitive abilities, and found several trends within the demographic surveys measured by performance. The most important trend found that training for all three formats is necessary and does improve performance. However, Sweany used different designs between subjects leading to an uneven comparison of results (also due to a limited sample size). This uneven comparison was statically controlled for.

This study serves as a continuation of the research performed in "Cognitive Workload Demands Using 2D and 3D Spatial Engineering Information Formats" by Dadi et al. (2014) and "Cognitive Demand for Engineering Information" by Sweany

(2014). This research adds other elements of relationships between cognitive abilities and performance by information types. The alliance of research provided by Dadi, the Folsom Experiments and the Industrial Experiments address the greater need for understanding how information delivery is perceived by the craft workers, how to best suit their needs in order to maximize productivity, and prove how critical utilizing the workforce considering all levels cognitive abilities can be.

CHAPTER III

METHODOLOGY

The methodology herein describes how the research hypothesis was tested – **whether or not cognitive demand is lowered and performance is enhanced during exercises that add visual or physical dimensions to isometric engineering drawings.** In order to find out what innovative methods would most effectively supplement the isometric drawings, a series of six focus group sessions were conducted. After selecting two methods of information delivery, they were field tested to understand their influence on isometric drawings.

3.1. Focus Groups

In order to find out what innovative methods of delivery would most effectively supplement isometric engineering drawings, a series of six focus group sessions were conducted. After selecting two methods of information delivery, they were field tested to understand their influence on isometric drawings (see 3.1. Field Trials).

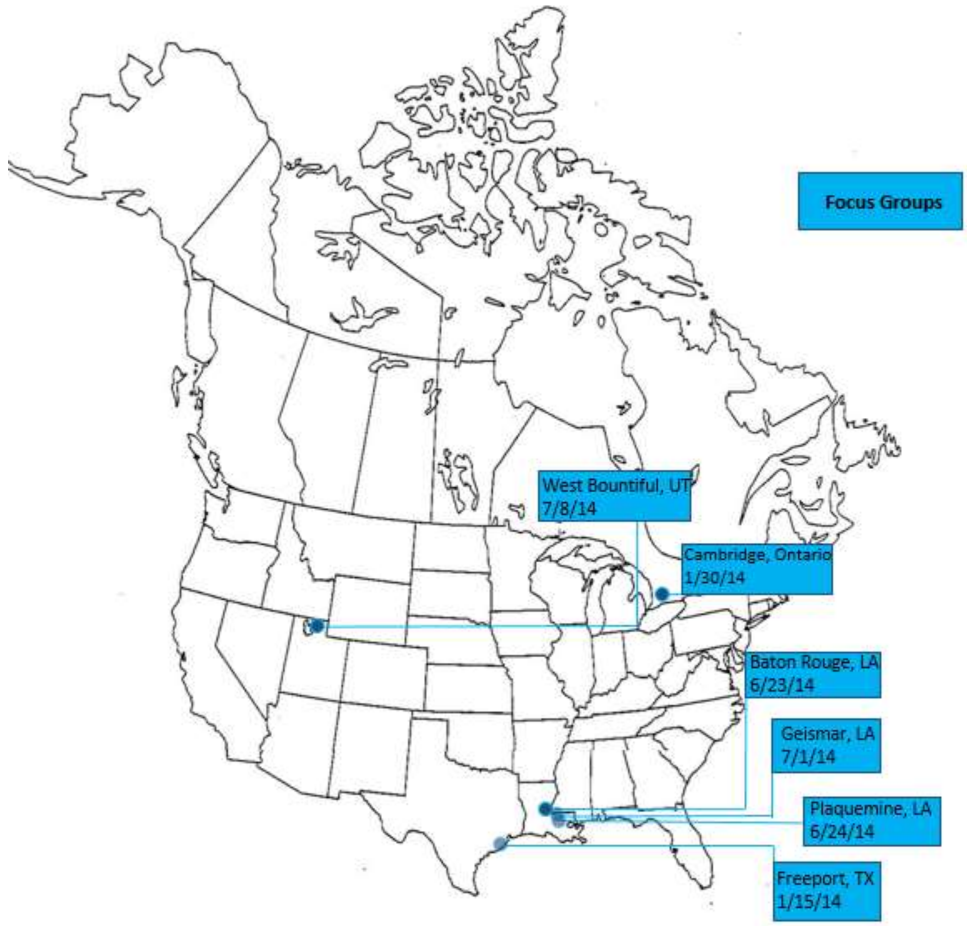

Figure 3.1. Focus Group Map

Research Team 327 collected information across six focus group sessions to identify craft workers' and supervisors' perceptions regarding how the delivery of engineering information does and can influence their performance. The locations of the sessions included:

- Freeport, Texas (January 15 2014)
- Cambridge, Ontario (January 30 2014)
- Baton Rouge, Louisiana (June 23 2014)
- Plaquemine, Louisiana (June 24 2014)
- Geismar, Louisiana (July 1 2014)
- West Bountiful, Utah (July 8 2014)

The focus groups predominantly consisted of pipefitters with at least one electrician. The sessions lasted 1.5 hours on average. Focus groups opened with introductions of all participants, the academics and the moderator. The moderator would then continue to deliver an open-forum presentation of current practices (included in Appendix F) and their common barriers, followed by ideas for innovative methods of delivery. The presentation would consequently evolve into a discussion. The purpose of this transition into discussion was to solicit feedback and reciprocate ideas back and forth covering innovative methods of delivery.

3.1.1. Focus Group Methodology

During the focus group sessions, three questions were targeted as the main points of discussion and represented the objectives of the focus groups:

- Q1 – How is the information (data and graphics) you need to do your job provided on a daily basis?
- Q2 – What is the biggest challenge you face in getting the information you need to do your job?
- Q3 – What are your ideas for improving installation and productivity at the jobsite?

Due to the open-ended nature of the focus groups, other discussion topics surfaced leading to dialogue deviating from the objectives of the focus groups. This ambiguity of responses led to a large pool of texts in the acquired transcriptions. The large text accumulation could no longer be simply broken up into three categories (as intended) that were in direct response to the three target questions.

Therefore, a more in depth content analysis became required. The content analysis that was performed took all data, or quoted responses and comments, from the transcriptions of focus groups 1 through 6 and broke it down into 16 categories each containing multiple subcategories to help further explain the responses within their respective category.

3.1.2. Categorical Analysis

Each of the sixteen categories were qualitatively and quantitatively described by coding that performed using NVivo (see Appendix E). A series of analyses were conducted in order to express how each of the target questions were addressed, what responses were made, the frequencies of responses and other correlations that were made to describe exactly what occurred during the focus group sessions. The categories include:

- Two-Sided Isometric Drawings
- Three-Dimensional Model Shots
- Three-Dimensional Physical Models
- Access to Digital Information (Hierarchy of Access)
- BIM (Building Information Modeling)
- Constructability Meetings
- Current Practices
- Exclusive Two-Dimensional Information Format
- Field Kiosks
- Virtual Heads-Up Display
- Information Delivery Issues
- Document Management
- Intrinsic Issues

- Tablets
- Need for Training
- Various Issues

The most frequent categories that came up in the focus groups were Interface Software, Current Practices, Tablets and Field Kiosks. Despite the frequency of occurrence during the focus groups, it does not exclusively indicate how critical the category of discussion is to this research. Frequency can often illustrate how important a matter is for individual participants in their daily work, how common something occurs in daily work or it can be a coincidence that the participants enjoyed commenting on a category of discussion.

The following table, Table 3.1.Composition of the 16 Categories of discussion, breaks down the sixteen categories, and essentially unitized them, that is, "…distinguished for inclusion in or exclusion from analysis, ideally in a way that acknowledges natural boundaries…" (Krippendorff 2004). Most of the categories are described as having data that contained either *perceived value* (green) or *negative responses* (red). The green-colored cells display the number of accounts which focus group participants agreed that the category of discussion was beneficial to construction, or that there was perceived value in the idea of the category of discussion. The red-colored cells display the number of times that the participants disagreed with the effectiveness or value in the category of discussion. The categories of discussion that could best be described by using red and green-colored subcategories were usually methods of delivery, rather than other issues (Access to

Digital Information, Constructability Meetings, Current Practices, Information Delivery Issues, Intrinsic Issues, Need for Training and Various Issues). These categories, subcategories which inlcuded neutral comments (light blue-colored cells) and future desires (yellow-colored cells) are also listed. Neutral comments/responses were comments that did not result positively or negatively, yet provided a subcategory that was meaningful to describing the category of discussion. Future desire comments/responses indicated a new idea or way to approach a method of delivery or construction function.

Table 3.1. Composition of the 16 Categories of Discussion

	Category	References	Subcategory$_1$	References	Subcategory $_2$	References	Subcategory$_3$	References
1	**Two-Sided Isometric Drawing**	17	Perceived Value	12				
2	**3D Model Shot**	9	Perceived Value	5	Negative Responses	4		
3	**3D Physical Model**	11	Perceived Value	7	Negative Responses	2		
4	**Access to Digital Information**	5						
5	**Building Information Modeling**	15	Perceived Value	9	Negative Responses	6		
6	**Constructability Meetings**	17	Integration of Technology	3				
7	**Current Practices**	48	Construction Operations	20	Electronic Information	15	Paper Information	13
8	**Exclusive 2D Information**	6	Perceived Value	2	Negative Responses	2		
9	**Field Kiosk**	22	Perceived Value	13	Negative Responses	8		
10	**Virtual Heads-Up Display**	10	Perceived Value	6	Negative Responses	4		
11	**Information Delivery Issues**	11	Communication Issues	5	Paper Delivery Issues	2	Software Delivery Pros	2
12	**Document Management**	51	Perceived Value	24	Negative Responses	1	SIC	4
13	**Intrinsic Issues**	6						
14	**Tablets**	48	Perceived Value	18	Negative Responses	12	FP	5
15	**Need for Training**	12	Generation Dependent Training	4				
16	**Various Issues**	7						

3.1.2. Word Analysis

Figure 3.2. Word Cloud

Figure 3.2. Word Cloud illustrates commonly occurring words in a visually pleasing format. This figure was produced by NVivo. The arrangement of words in the Word Cloud have no meaning, they are randomized. For example, a word being horizontal versus being vertical is irrelevant. The only significant formatting characteristics is the size of the word. Larger words indicate a higher frequency of occurrence in the transcriptions. Analyzing the frequency of words in the

transcription is a better way of understanding the content rather than analyzing the frequency of the categories. Word analysis yields a finer resolution of results than categorical analysis does.

The series of the 15 most frequently-occurring words, below, lends understanding to the motivation of conversation that took place during the feedback portions of the focus groups:

1. Change
2. Communication
3. Construction
4. Move
5. Make
6. Information
7. Tell
8. Think
9. Instrumentation
10. Knowledgeable
11. Organize
12. Hands
13. Drawings
14. Contractor
15. Leaders

"Change" occurred 1299 times and comprises 1.57% of the words used in the transcription (for every 100 words change would appear once). "Change" was the mission of the focus groups, so it does make sense that it would occur the most. The participants had many ideas of how to change the construction industry and were in favor of many presented innovative methods of delivery. The innovative methods of delivery are meant to change the way in which information is delivered. "Communication" was brought up over and over again when methods of delivery were discussed. For plans to be effective, communication, or delivery, must be performed in a way that is tailored to how the construction crews want to receive them. The ways in which construction crews want to receive information was discussed, preferred methods of communication arose. "Construction" is obviously a word that would occur frequently, because the participants of the focus groups were all construction workers, managers or engineers. Ways of improving construction was the broad topic of the focus groups.

3.1.3. Analysis of Categories

The following analysis was done via NVivo software that utilized a traditional "propositional distinction" method of analysis (Krippendorff 2004). Each category, resulted from a compilation of summarizing lines that can be viewed in Appendix E. The compilation of lines provides greater detail of what was discussed during the Focus Groups.

The 16 categories of discussion are outlined in the following format:

Paragraph A: Meaning of each category

Paragraph B: Results from analysis

Paragraph C: Common thematic responses that characterize the feedback

Category 1) Two-Sided Isometric Drawings

Figure 3.3. Two-Sided Isometric Drawing [Ford, Bacon & Davis]

Meaning

The two-sided isometric drawing is a printed delivery format of engineering drawings that offers unique perspective to the construction craft. The standard sized sheet, 8.5” x 11”, has an isometric detailed drawing on the front side of the paper, and a three-dimensional computer-model shot of the same detail on the back of the same sheet of paper. The front provides dimensions and details which include a list of materials. The backside provides a scaled image of the detailed drawing; this helps to lend better perspective of the actual size and shape of the assembly.

Results

The results from the focus groups were in uniform support of this product being put into practical use on the jobsite. The feedback from the discussions consisted of all positive responses (results displayed in Table 3.1.), there were 12 perceived values and 0 negative responses. This delivery format was easily the most favored among the innovative information delivery methods which Research Team 327 presented during the Focus Groups. The group participants had seen and heard of both Isometric drawings, and three-dimensional model shots, but they had never been exposed to a format where both were produced in sync with each other. This format was said to offer a better ability to visualize information than the standard two-dimensional construction plans that are used exclusively in current industrial construction practice.

Thematic Responses

The thematic responses that characterized the Two-Sided Isometric drawings aligned with each other, agreeing that the Two-Sided Isometric drawing would hold greatest value. Some adjectives and phrases that described the value included:

"strong," "game-changer," "perfect in the [fabrication] shop," and "the idea for job improvement." To further characterize the responses, it can be said that this format would improve information delivery of engineering drawings in the field to help installation productivity. This format would be especially beneficial in the piping construction industry, it would help to make piping assemblies more identifiable.

Category 2) Three-Dimensional Model Shots

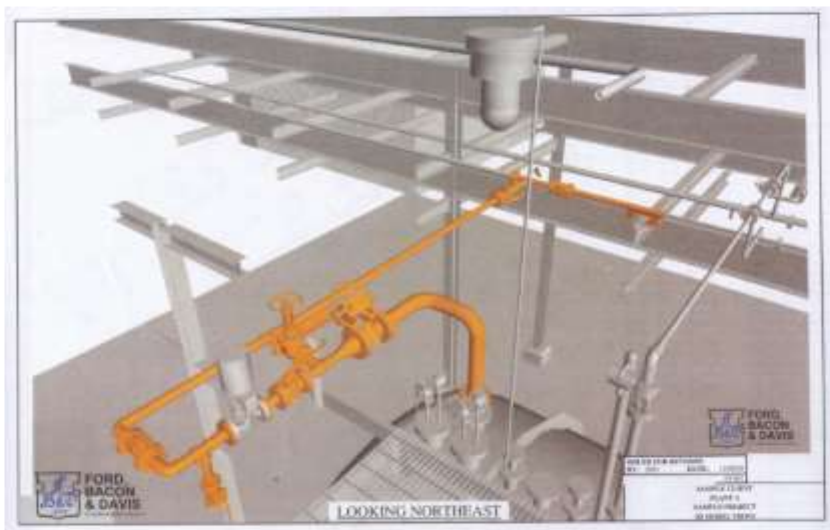

Figure 3.4. Three-Dimensional Model Shot [Ford, Bacon & Davis]

Meaning

This information delivery format is typically developed by an engineer who takes a screen-shot, or static picture, of a three-dimensional model (construction installation). The picture is a scaled, realistic adaptation of what is to be constructed onsite. The model shot can either be printed or viewed on a computer screen.

Results

Results from this category of discussion were nearly evenly distributed from positive to negative. The ratio of perceived values to negative responses was 5:4. Most of the negative responses were with regard to errors in producing the three-dimensional models. Thus, making it difficult to accurately understand the opinions that participants would hold on the affect that a correctly-produced three-dimensional model shot on construction performance.

Thematic Responses

The three-dimensional model shot was said to be useful for visualizing a certain view or perspective of a construction installation. Responses indicated that the model shots should not be used alone in construction, they would require the engineering drawing. The model shot should have another reference to help make dimensions identifiable, similar to how the Two-Sided Isometric drawing is produced. However, there was much value seen in showing the static model shots in a sequence of slides for easy-to-read and an understandable presentation of the construction production. Similar to the model shots themselves, it is important to note another conversation had spurred from this topic. Participants stated that viewing the static perspectives of the model from saved view-points would increase ease of navigation through a three-dimensional model on a computer interface.

Category 3) Three-Dimensional Physical Models

Figure 3.5. Three Dimensional Physical Model [Ford, Bacon & Davis]

Meaning

This format is printed, presented in a three-dimensional physical form. It is a plastic assembly model of a computer-model. Three-dimensional physical models make for a good presentation platform, they are meant to be physically grasped and utilized as an interactive learning tool.

Results

Results demonstrated that it was a mostly well-received topic. There were 7 perceived values and 2 negative responses. Most of the feedback was in discussion of how the models handle when being viewed.

Thematic Responses

The perceived values included agreement that the physical dimension of the information delivery is “one step ahead of three-dimensional computer models.” This illustrates the desire that construction workers have to hold something physical in order to visualize it. On the other hand, three-dimensional physical models were seen as fragile and limiting since pieces often break or are un-detachable (detachable pieces are desirable to have so that all spaces of the model can be taken apart and viewed). If these two negative aspects were able to be resolved, in a financially efficient way, this information delivery format would offer great conceptual aid to engineering drawings.

Category 4) Access to Digital Information – Hierarchy of Access

Meaning

This topic dove into discussion of how electronic information should be accessed and whom should have the power to access and/or manipulate the data. This topic is relative, because owner-companies often restrict access to information that contains updated specifications, standards and details as well as restricting crews from devices that could enhance worker productivity through better information delivery.

Results

This category did not yield positive or negative responses, yet offered a collection of ideas that were brainstormed during the group discussion. The responses included discussion of permitted accessibility, what level of management should have access to mobile devices, and how certain technologies could enhance communication between quality control and quality assurance, and the construction crews.

Thematic Responses

The participants commented that there should be at least permits instated to access higher levels of information so that the right people can access proper information. The level of management gaining access to mobile devices, such as field kiosks or tablets, was said to be the general foreman or foreman in most cases.

The way in which technology would allow for better communication is through updatable electronic information. Handheld electronic devices were perceived to be the best choice for mobile devices. The heads-up display was also mentioned as a great way to communicate construction issues, for quality control and quality assurance. This particular level of technology, especially, should only be in the hands of the general foreman and higher management.

Category 5) BIM – Building Information Modeling

Meaning

Building information modeling (BIM) is computer technology that contains a three-dimensional model of a construction installation, or the entire site. BIM contains information to help track materials, scheduling and other information pertinent to construction productivity.

Results

Results from BIM discussion yielded 9 perceived values and 6 negative responses. The perceived values mostly discussed benefits that BIM has to offer, which make upfront management much more effective. Upfront management refers to pre-project planning of construction phases and scheduling. The negative responses mostly concerned limited accessibility and costliness.

Thematic Responses

The positive themes of the building information modeling delivery were that it involved intensive planning and upfront integration of information that is available for both engineering and construction, to use for conflict resolution and constructing work packages. The negative themes addressed the expense restrictions and limitations. Often, owner-companies will not hire engineering companies to produce a building information model to be used on construction, because the owner-company sees it as an unnecessary fee. The fee, however, can most times return more money due to prevention of rework and expediting construction scheduling through intelligent, upfront planning.

Category 6) Constructability Meetings

Meaning

Constructability meetings are meant to be used for feedback and suggestion solicitation from construction workers to enhance construction performance, to save money and time, and to give the construction side of operations ability to communicate with the engineering and management side of operations. Constructability meetings are also used to communicate construction plans and tasks at-hand. Often constructability meetings use two-dimensional construction plans and whiteboards to present and review information. In this category of discussion, other means of technology were suggested to be used when presenting and reviewing information during meetings.

Results

There were no exclusive positive or negative comments, rather suggestions for implementing better constructability meetings. The suggestions involved ideas for better communication and integration of technology into the meetings. Construction crew members said they felt as if they have been on a "need to know basis" and only "get information when the time comes to adjust [construction installation]. [Engineering and management] don't view [construction crews] as value-added, integral team members that they can partner up with."

Thematic Responses

All too often construction craft workers are not offered any sort of constructability meeting on a jobsite. The craft professionals who participated in the discussions wanted to be involved in pre-project planning and constructability reviews more often. The information delivered for construction (i.e. construction work packages, engineering drawings, specifications or other information involved in the construction process) was often not "construction friendly," meaning that it was not accommodating for the ones actually performing construction, yet beneficial for engineering operations. Implementing technology into the construction reviews was viewed as a necessary change. The presentation of information (construction plans) is typically delivered on massive sheets of paper, which can be confusing and overwhelming. The use of model shots, two sided-isometric drawings and Three-Dimensional Physical Models would help to provide a more conceptually-friendly approach. Another technological approach, printing annotated model shots to be taken out to the field, would provide a visual aid the construction craft with specific notes and instructions annotated for a particular worker or skilled crew. The consensus was to (1) hold more meetings, (2) conduct meetings onsite so the craft involved in meetings are central to the crew's location, (3) integrate technology into construction reviews, and foremost (4) allow for construction crews to input meaningful suggestions that will actually impact change.

Category 7) Current Practices

Meaning

This category contains a broad array of data, or discussion feedback, which was tied with the Tablets category as being the second largest discussion category to Document Management. This implies that much of the focus group discussion was spent on this category. From the discussions three subcategories surfaced –

Construction Operation Activity, Electronic Information and Paper Copies. The purpose of categorizing the data as such was to describe how construction is currently practiced, and understanding what should be changed. Understanding current practices was important to this research since Research Team 327's goal was improve current construction practices by implementing new methods of delivering information.

Results

The results led the to many discussion topics that cannot all be covered, but can be seen in Appendix E. The subcategories were all neutral comments, generally speaking.

Thematic Responses

The following comments for each of the three subcategories were chosen due to their frequency, strong emphasis and re-emphasis of the same comment/response, and their clear impact on innovative delivery methods that were discussed.

a. Construction Operation Activity

    a. Standards, drawings, specification updates are paper based. They are not current or reliable. If the format were to transition from paper to electronic documentation, the flow of information would be much more effective; communication of updates could be accomplished more quickly; and questions and remarks could be fluently communicated about standards, drawings and specifications.

b. Material fabrication is done offsite and lacks substantial tracking and/or communication from the fabrication shop to the construction site. This loss of tracking, due to poor communication, causes materials and other items to be unaccounted for and delays in new orders to occur.

c. Cameras and other mobile devices that could be useful for tracking productivity and communicating field issues must go through a slow process of approval. Cameras and mobile devices cannot simply be brought out onto the jobsite to be utilized, they must have a permit for use.

d. Fast-tracking of construction scheduling and inefficient delivery of work packages causes rework. The fast pace delivery of orders and instruction tends to result in contractors receiving large work packages at once which are overwhelming – this can cause confusion and noise. Rework is regrettably often not documented, nor contributed in constructability meetings as “lessons-learned.”

b. Electronic Information

    a. Electronic drawings are typically delivered to project superintendents or general foremen in the form of email which include PDF files, or screen shots. These are saved on a shared drive, yet inaccessible to many craft workers.

    b. The use of three-dimensional models (both physical and computer-based) are utilized by upper management in construction presentations, however not utilized nearly as often with the craft.

    c. Equipment tracking would increase accountability by simply scanning barcodes on materials and construction equipment. It would greatly benefit both construction operations and quality control alike. This has been see before by the craft, but is not a common practice.

c. Paper Copies

    a. Drawing formats are typically distributed in the 11” by 17” format; the structural craft is in favor of this format – the mechanical and electrical and instrumentation crafts both prefer isometric drawings distributed in the 8.5” by 11” format.

    b. Work packages are typically distributed in a hard copy format and can be inadequate when navigating through large paper files to find information.

c. Material tracking is done manually by a field engineer on paper.

Category 8) Exclusive Two-Dimensional Information Format

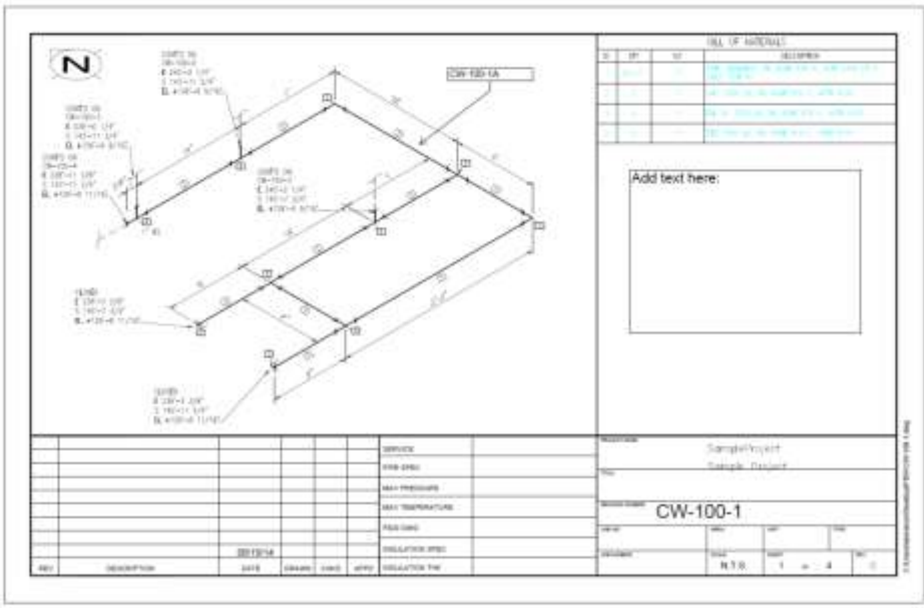

Figure 3.6. Construction Drawing [Ford, Bacon and Davis, LLC]

Meaning

Two-dimensional construction detail drawings are the most commonly used format on construction jobsites. This is the drawing format that is used in construction (constructability) reviews, piled up on tables, and inefficiently displayed. The participating members of the focus groups unanimously agreed that this format is used on all projects and does not provide the level of detail and conceptual understanding that is desired.

Results

This topic was not highly discussed since it was understood to be both outdated and exclusively the current method of information delivery. The results show that there was one neutral discussion, two perceived values and two negative responses. The ratio of positive to negative responses was 2:2.

Thematic Responses

The perceived values were: the two-dimensional format allows workers to mark up their sheet in the field, and two-dimensional construction plans are the method of information delivery that construction will never stray away from. The negative responses concerned the inefficiencies of the use of two-dimensional information (construction plans) in construction reviews, as it is unorganized and difficult to navigate through. Two-dimensional paper plans also lack locational reference of construction installations.

Category 9) Field Kiosks

Meaning

A field kiosk, also known as a "game box," is a work station that can be brought out into the construction field; it contains a large monitor, a printer, white boards and available space for a computer. The field kiosk is encased in a protective metal shell and is meant for presenting construction information to the construction crew, as well as quick, responsive communication between construction and engineering operations.

Results

The results from this category of discussion included 13 perceived values and 8 negative responses, illustrating that it was perceived as a mostly beneficial product during the discussions. The lower count of responses and comments may be due to its relatively new exposure to the construction industry.

Thematic Responses

The following perceived value comments portray the level of acceptance from the construction group-participants: "a real hit," "access information next to work," "keeps the foreman with the craft on the jobsite," and "cuts down on lag time." The participants liked the idea of having a piece of equipment on the jobsite that cuts down on “boot-time” (time that is wasted walking back and forth from the office to the jobsite) and is capable of communicating specifications, standards and solving problems from the jobsite via display monitor. Another perceived value was the capability of printing drawings or specifications; printed drawings can be annotated particular to one’s job description on the field kiosk. Negative responses concerned various issues such as not having a printer with color or two-sided printing capability, environmental issues (the equipment overheating or freezing) and limited availability of a controlled environment in which to use the field kiosk in case of bad weather or other threats – the industrial sector often does not have controlled environments that are conducive to using the field kiosk, whereas other sectors, like commercial, do.

Category 10) Heads-Up Display

Meaning

The heads-up display is another form of information delivery, it also can be used as platform for communicating construction installation issues between construction and engineering operations. This technology is a headset device that looks like a pair of safety goggles. The heads-up display allows for visual images to appear on the glass, and for audio-communication.

Results

Results from the focus groups concluded 6 perceived values and 4 negative responses. This category of discussion was not a high-value item in terms of frequency or acceptance amongst the construction group-participants.

Thematic Responses

This technology was said to save time by utilizing “real-time” visual and audio communication. Both communicating parties see exactly what the other is describing without having to send an email or meet in person (eliminating boot-time). This technology has already been developed and is readily accessible, however, the industrial sector would be slow to adopt since low-energy permits would be required for this technology to be on a jobsite. Negative responses also pointed out that heads-up display would require moderate to high levels of signal reception in the field. It was unanimously agreed that the heads-up display should not be put into the hands of craft, only general foreman and upper management.

Category 11) Information Delivery Issues

Meaning

This category of discussion covered issues that the construction participants saw as a hindrance to how software and hard-copy (i.e. paper) information are communicated. Many issues varied since there are so many different formats of information delivery. The results were categorized in a way to broadly organize the feedback for the discussion.

Results

The results were distributed into four categories: Communication Issues, Paper Delivery Issues, Software Delivery Pros and Software Delivery Cons. Communication issues included misrepresented data and unorganized data. The main entries of paper-documented information was said to be into work packaging and specifications. Software Pros and Cons mostly entered the topics of bills of materials and model-viewing software.

Thematic Responses

Re-occurring Communication Issues were that the engineering distribution of information to construction crews was last-minute and misleading. Drawings often were said to contain incorrectly numbered tie-points and line numbers, they did not represent the electrical and instrumentation craft well (drawings only included major components). Paper Delivery issues mostly led to the conclusion that specifications and work packages should be delivered and read off of electronic interfaces, allowing for easy updates, navigation and communication. Software Delivery Pros discussed the benefits of electronic documentation of bills of materials and how that applies to construction takeoff. If a bill of materials is updated and offers open-access for craft workers, the process of identifying missing equipment or materials is eliminated. Software Delivery Cons discussed current problems with work packaging, how standards are often not placed in the electronic file and are often pulled form older jobs. Likewise, three-dimensional model-viewing software is said to be too expensive, yet desired on construction jobs.

Category 12) Document Management

Meaning

Document Management is broken up into three categories to describe the positive and negative attributes of software further than Information Delivery Issues had done in the subcategories of Software Delivery Pros and Software Delivery Cons. The three categories are Software Interface Choice, Positive (or perceived values), and Negative (or negative responses).

Results

The results showed that this was the most highly discussed category of all. The results indicated 24 perceived values and 1 negative response. This vast difference from positive to negative responses indicated the desire to implement software technology in construction activity and that positive thinking behind interface software exists.

Thematic Responses

The Software Interface Choice subcategory demonstrated that common file viewing software includes both Bluebeam and Adobe, where Adobe is the more commonly used software product. More intelligent software that is used for building information model viewing and use consists of Navisworks and Smartplan. The mobile device to use this software did not seem to make much of a difference to the construction group-participants, there was no preference as long as the software could be made accessible and was moderately easy to navigate on. The Negative response that was discussed said there was no perceived difference in results from construction done using building information modeling, and construction without. This may be due to the fact that "big-picture" results are difficult to see when working intimately in construction. Some of the big-picture benefits of BIM include savings, reduced rework, well developed scheduling and clash detection. Positive comments that were made are described in these brief statements:

a. Specification software is helpful when it is easy to navigate within.
b. There is desire to implement mobile devices in the field capable of:
    a. Displaying the heads-up display technology on a handheld device.
    b. Identifying shoes, blocks and materials for checks and verification.
    c. Comparing progress to the building information model – "progress tracking."

d. Tracking daily meetings and communicating general updates.
e. Three dimensional model-viewing to help identify installations.
f. Annotating drawings to label location, elevation, line numbers, and other dimensional properties or updates.

Category 13) Intrinsic Issues

Meaning

Discussion involved safety hazards that technology possesses, permits that allow or deny certain technologies onto sites and how the implementation of delivery methods are delayed by company policies.

Results

This topic helped to describe limitations that have been seen on the implementation of innovative delivery methods.

Thematic Responses

Mobile devices are greatly devalued when faced with limiting policies. They are often not used due to the long process of obtaining a permit to bring them onto the jobsite, if they are even allowed at all. This problem is common within the industrial sector, because jobsites are often petro-chemical jobsites or contain other unstable and potentially harmful work areas. Some devices that are small, tablets and smart phones, may be used on sites by obtaining a low-energy permit. Larger technologies such as field kiosks and laser scanning technology may not be permitted at any cost, depending on site policy. Lastly, there was a comment made that stated site policies often mandate that technology does not interfere with localized transmitters.

Category 14) Tablets

Meaning

The tablet is a useful mobile device that typically can be taken onto the jobsite, connected to a wireless internet connection if available, and used as an interface for communication, documentation and other uses such as referencing information.

Results

The Tablet category of discussion was tied as the second-most highly discussed item during the focus group sessions. The Tablet category yielded mostly positive responses. There were 18 perceived values and 12 negative responses.

Thematic Responses

The tablet serves the user well when checking specifications, going through checklists, taking pictures, thumbing through pre-arranged model shots and reading through relevant construction documents. Unfortunately the tablet does seem to limit model-viewing, due to its small screen size and difficult use of navigation which could require training. Various perceived values, negative responses and a few future possibilities that were voiced are listed below:

a. Perceived Values
    a. Bar-code scanning is a capability for tracking parts and assemblies.
    b. Progress and labor tracking is a capability.
    c. Managing checklists and specifications is a capability.
    d. Work package management is a capability.
    e. There is a possibility to eliminate the need for the two-sided isometric drawings.
    f. This has perceived usefulness as a tool for training new craft workers.
b. Negative Responses
    a. It is a poor tool for reading drawings.
    b. It has a small screen that makes navigation difficult.
    c. Most of the capabilities require internet access.

d. There will be training required in order to implement this technology.

c. Future Possibilities

   a. Automated updates to notify the user (craft worker) when a task is complete or needs attention.

      i. Automated updates could also include attached verifiable pictures with completed task notifications.

   b. Ability to lock areas (i.e. installations) on the building information model once the installation is complete.

Category 15) Need for Training

Meaning

With the introduction of new technology into the construction workforce comes required training. Many discussions lead to this topic. Participants would sometimes declare that training was or was not required, and often discussed whether training should be gauged for particular demographic characteristics of construction workers (age and spoken-language).

Results

The only subcategory that the data resulted in was generation dependent training. Since this was a relatively small category of discussion, no other subcategories were required.

Thematic Responses

From the discussion it became evident that the participants were not experienced with three-dimensional modeling or model-viewing at any substantial rate. Because of this, instructions with pictures were said to be of great value, especially for the newer generation of craft workers. The two-sided isometric drawings and annotated model-shots both serve as good training tools since the picture provides a substantial level conceptual aid. Training was said to be both generationally dependent and non-generationally dependent on separate accounts. In either case, it was agreed that incorporating pictures into the construction drawings would be beneficial. Lastly, it should be noted that general training for mobile devices (i.e. tablets) would be required for foremen, general foreman and upper management. Training should involve formal model-viewing and navigation training, training that teaches documentation, training that covers necessary means of communication that are found on mobile devices and lastly training should involve free time to leisurely play with applications on the mobile devices to better grasp how the interface works.

Category 16) Various Issues – Common amongst Construction Technologies

Meaning

This last category of discussion was created to simply to cover trailing comments that couldn't appropriately fit into the other 15 categories of discussion. The issues that were discussed include transient employment and work package delivery issues.

Results

Transient employment was a discussion about management that shifts within a project's lifespan. If this happens it often results in management blaming others and not taking accountability for themselves. Another issue that was presented with transient employment would be the requirement to re-train crews upon changes in management. If management changes and new management wants to reinstate some new construction information technology (unfamiliar to the crew), time could be wasted retraining the crew.

Thematic Responses

Construction work package delivery issues currently are being shipped out to the construction crews from management and engineering operations as a whole civil package. Often, only a portion of the packet is necessary or required, when there is too much information thrown at the construction crew it can be overwhelming and cause documents to go missing. In the work packages, material accountability can be incorrect due to poor warehouse tracking or other challenges. If technology was implemented to document and communicate the material-tracking then this issue would be resolved.

3.1.4. Conclusions and Action Statement

The Two-Sided Isometric drawing offered a great solution and was unanimously voiced as the preferred method of information delivery by the focus group participants. Similarly, the Annotated 3D Model Shot was a close second since it offered similar capabilities for easy printing and reference. This printing and annotation production may be made possible with the field kiosk. The Field Kiosk is a large box unit that protectively encases a large monitor screen, space for a desktop or laptop computer, a printer and two white boards for sketching ideas. Not only can the craft workers use this to avoid "boot-time" between the office and jobsite, it also engages the crew with the field engineer to have better visibility of ongoing construction problems. The tablet was well-liked by some participants and not by others. It may serve as a good quick reference for various construction activities, yet is too small and difficult to use for viewing drawings and for navigating through 3D models. The 3D Physical Model and the heads-up display were not the most well-accepted amongst the focus group participants, but did seem to have much value. The physical models were said to be useful by one focus group if only the models could be taken apart and reassembled to handle and visualize inside components of the model. The biggest issue with physical models was fragility. The heads-up display is a desired product and would be valuable since it offers real-time communication and ability to view and resolve problems with the same viewing layout between the craft worker manager and engineer.

Intrinsic issues were a frustrating topic that were brought up constantly. Mobile computing devices, cameras or other electronic devices are often not allowed on the jobsite since they are often deemed intrinsically unsafe. If a device is deemed intrinsically unsafe then one may request for a permit to allow it onto the jobsite, yet can result in a lengthy, undesirable process. Other frequently discussed intrinsic issues were about protection of the devices themselves from the environment.

To answer the question of – who can operate and have access to digital information and electronic devices – was said to be the foreman, general foreman and higher management. Once these positions of authority have mastered the technological skills, they may begin to train and relay information the journeymen, laborers and other workers. If training were implemented efficiently then negative effects of transient management employment could be avoided so that continuity would be maintained. Another way in which continuity can be sustained is through constructability meetings. The constructability meetings were expressed as highly desired during the focus group sessions and were said to offer change and improvements, instead of facing the same problems time after time. Constructability meetings can take place before a project starts to present information via technological displays (field kiosk display, building information systems delivered from a projector and supplemented with printed model shots, or two-sided isometric drawings handed out to the crafts). Constructability meetings can also take place after a project to discuss what should be resolved and/or changed for the next project. In addition, constructability meetings give the crew members a feeling of ownership and can remove the craft worker stigma of being solely on a "need to know basis."

In conclusion, the (1) two-sided isometric drawing, the (2) annotated model shot, the (3) field kiosk, and the (4) 3D physical model are likely to benefit information delivery to construction. The findings from the six focus groups allowed the research to enter the next phase in conducting the Field Trials. Testing the influence of chosen information delivery methods.

By RT-327's reasoning, the Two-Sided Isometric drawing and the Three-Dimensional Physical Model were subjectively chosen to be tested. These delivery methods were perceived highly valuable and influential to improving installation and productivity at the jobsite. Other methods perceived as highly valuable were not readily deployable for field testing. Thus, the two-sided isometric and 3D Physical Models were employed as the best two options for field testing.

3.2. Field Trials

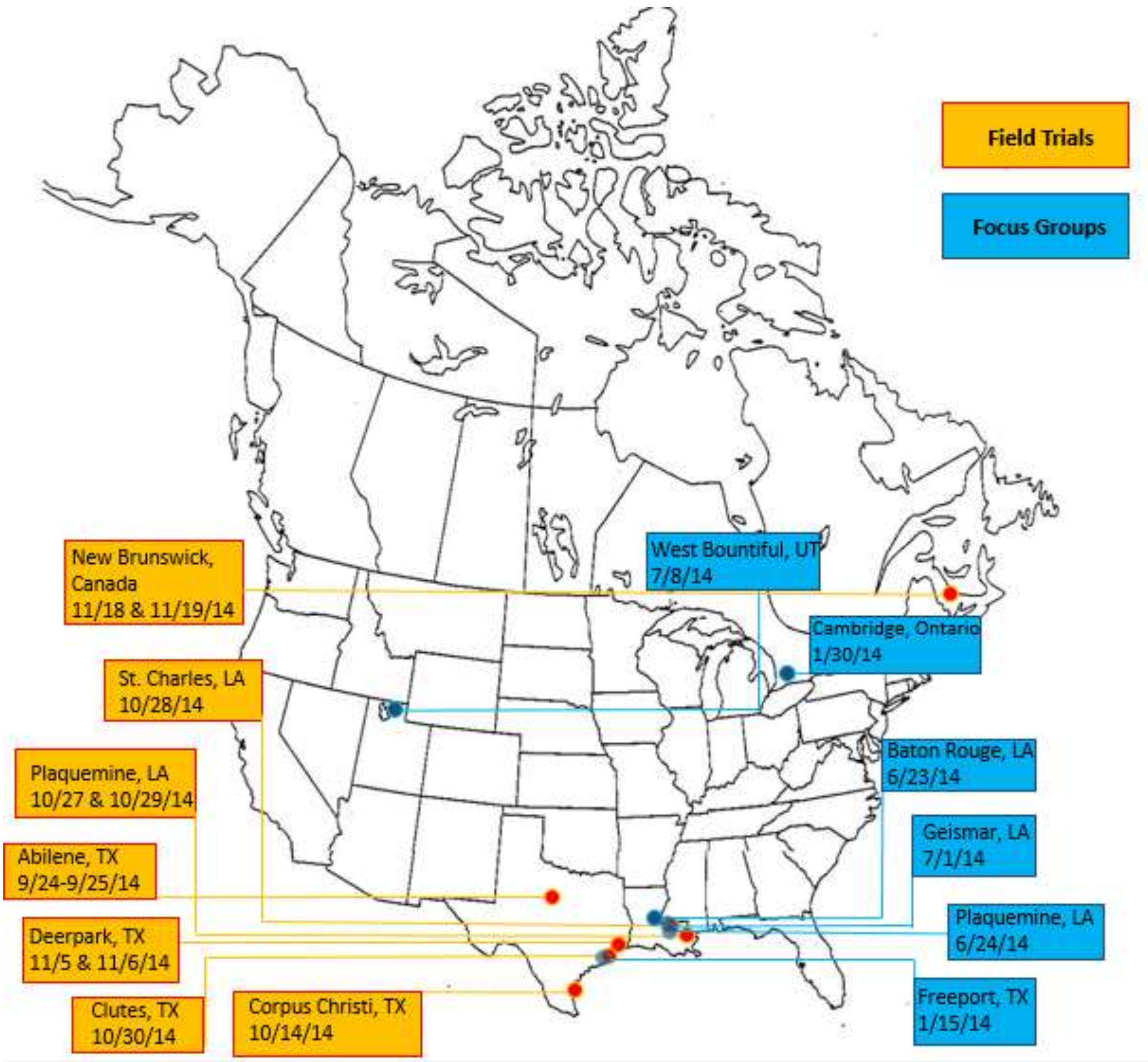

Figure 3.7. Field Trial Map

The influence of supplementing an isometric drawing with the Two-Sided Isometric drawing and the Three-Dimensional Physical Model was next measured during a series of experiments, or field trials. The investigator traveled to industrial petrochemical plants and conducted the field trials onsite (Figure 3.7. Field Trial Map), either in engineering trailers or pipefitting shops. The subjects were made of 54 pipefitters ranging from ages 26 to 65 with an average of 43, having anywhere from 1 to 47 years of experience with an average of 18.

Each trial involved one craft worker and lasted approximately 30 minutes. The objective was for each subject to assemble a model based off of one of three information formats. The following outline describes the steps involved:

1. Brief [5 Minutes]

   The investigator briefed the subject on what would take place and the purpose of the field trial.

2. Model Assembly [15 Minutes]

   Each subject assembled a small model kit made of ½" PVC pipe from one of three information formats used in the field trials: an Isometric drawing (n=24), a Two-Sided isometric drawing (model shot with an isometric drawing, n=21), and a Three-Dimensional Physical model with an isometric drawing (n=9). The Isometric drawing was used as the control of the experiment for the three formats. This allowed the investigator to realize how cognitive demand and performance would differ by supplementing a visual (the model shot on the backside of the Isometric drawing) or physical (the Three-Dimensional Physical model) dimension to the Isometric drawing.

By assembling a model, the participant would go through the information format and assemble the model kit performing similar tasks to that of pipefitting. The tasks included reading the plans (given information format), measuring the pipe lengths (PVC), joining pipe members by a variation of lengths and angles to create four spools, and finally assembling each of the four spools together. Each spool had its own engineering drawing sheet.

The three information formats are shown below:

a.

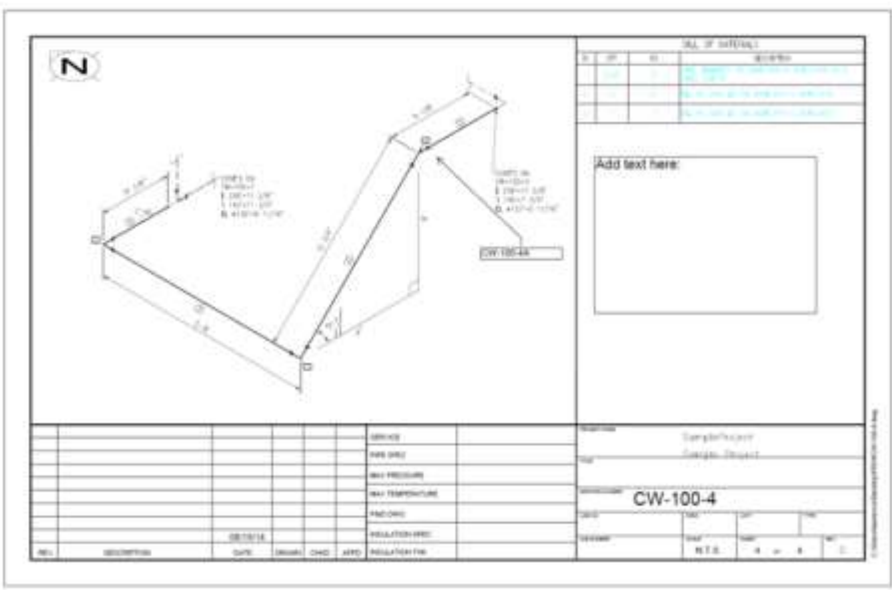

Figure 3.8. Isometric Drawing – Spool 1

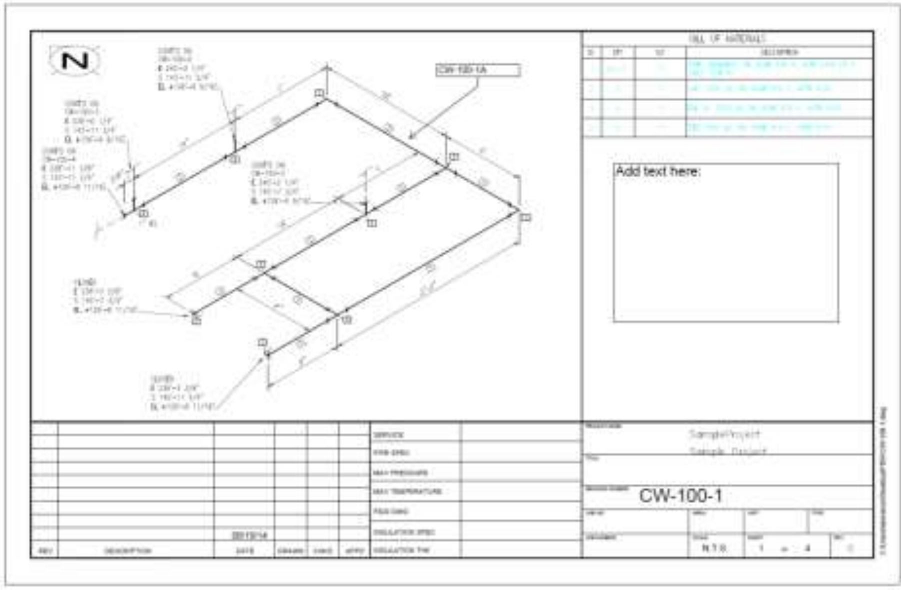

Figure 3.9. Isometric Drawing - Spool 2

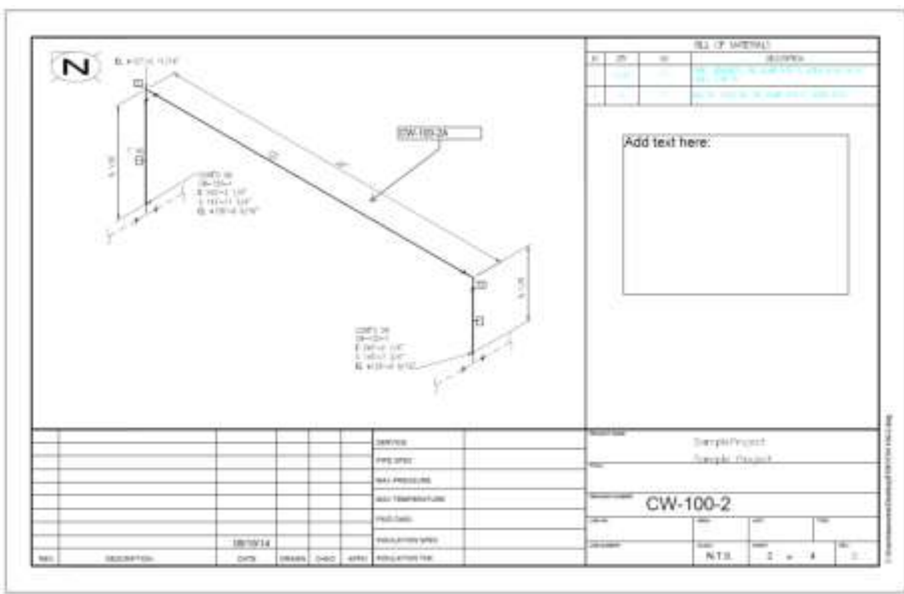

Figure 3.10. Isometric Drawing - Spool 3

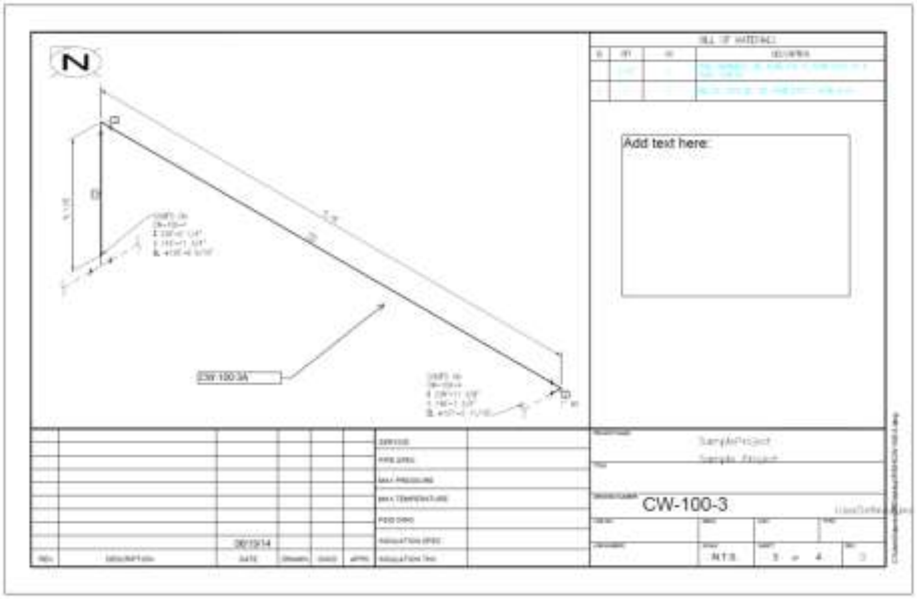

Figure 3.11. Isometric Drawing - Spool 4

b. Two-Sided Isometric Drawing

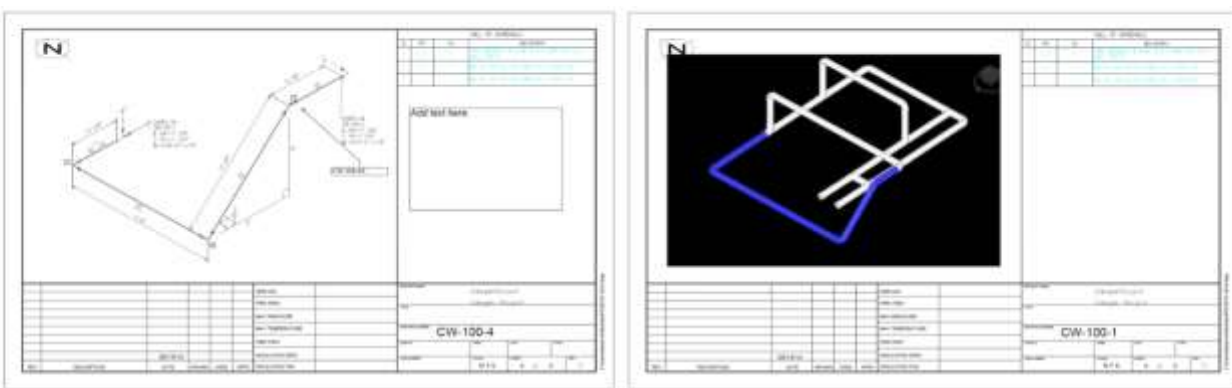

Figure 3.12. Two-Sided Isometric Drawing – Spool 1

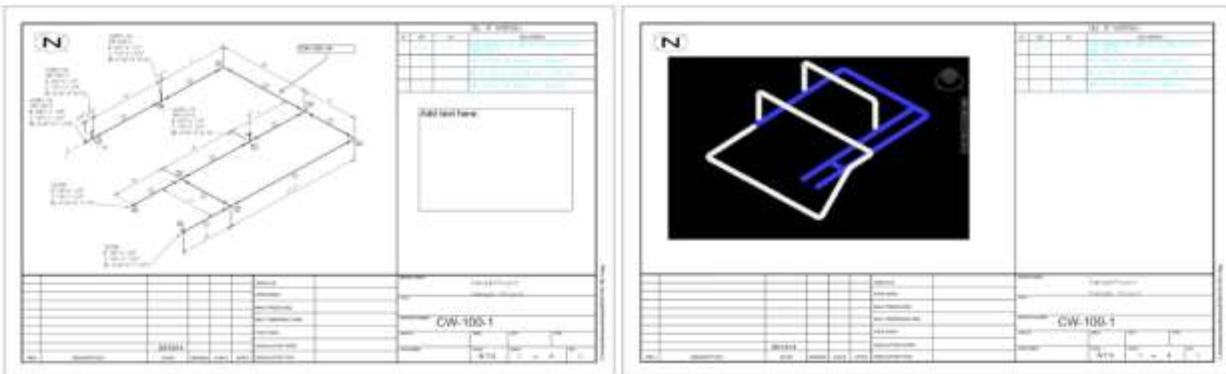

Figure 3.13. Two-Sided Isometric Drawing – Spool 2

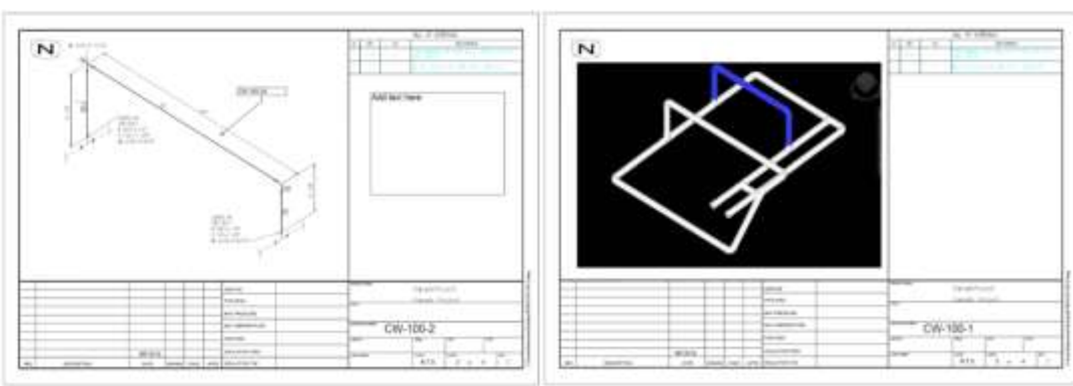

Figure 3.14. Two-Sided Isometric Drawing - Spool 3

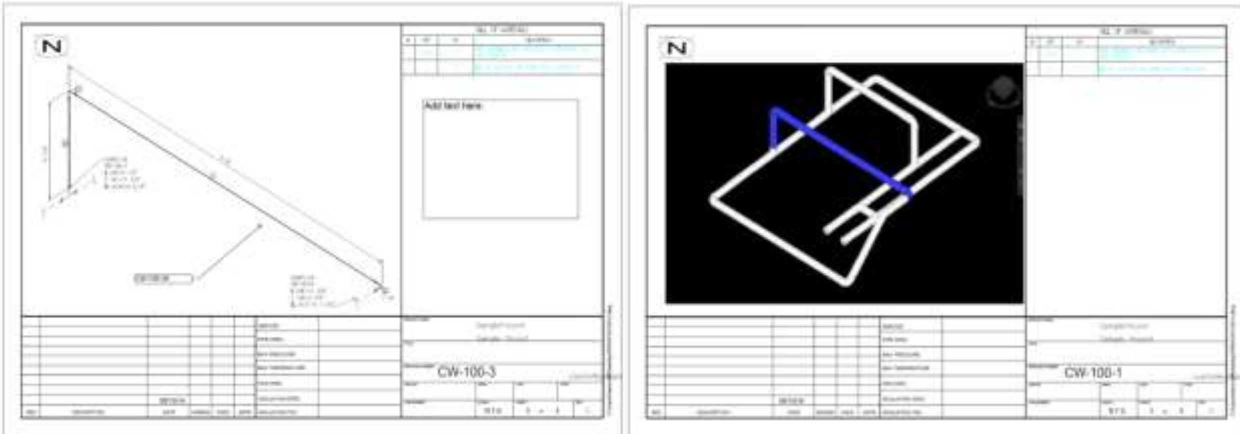

Figure 3.15. Two-Sided Isometric Drawing – Spool 4

c. 3D Physical Model plus Isometric Drawing

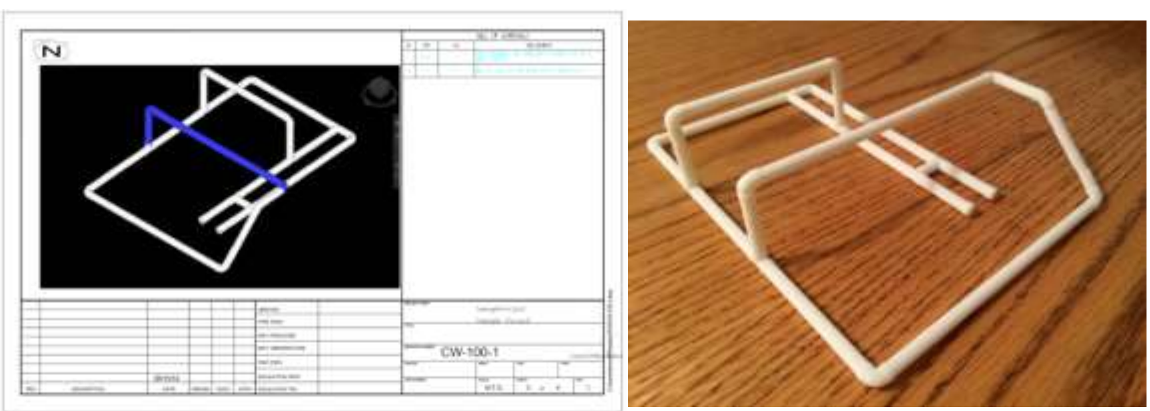

Figure 3.16. Three-Dimensional Physical Model – Spool 1

3. Cognitive Testing [10 minutes]

The cognitive ability of each participant was measured at the end of the model assembly. The participants were given a card rotation test and a cube comparison test. The card rotation and cube comparison tests were developed by the Educational Testing Service (ETS) to measure a subject's spatial relations ability (Ekstron et al. 1976). The card rotation tested a subject's ability to recognize two-dimensional shapes that have been manipulated. The cube comparison tested to a similar degree, but instead for three-dimensional cubes that had been manipulated (Ekstron et al. 1976). According to the research hypothesis, participants with lower cognitive ability should have performed better with information formats b and c. Cognitive demand should have eased with information formats b and c.

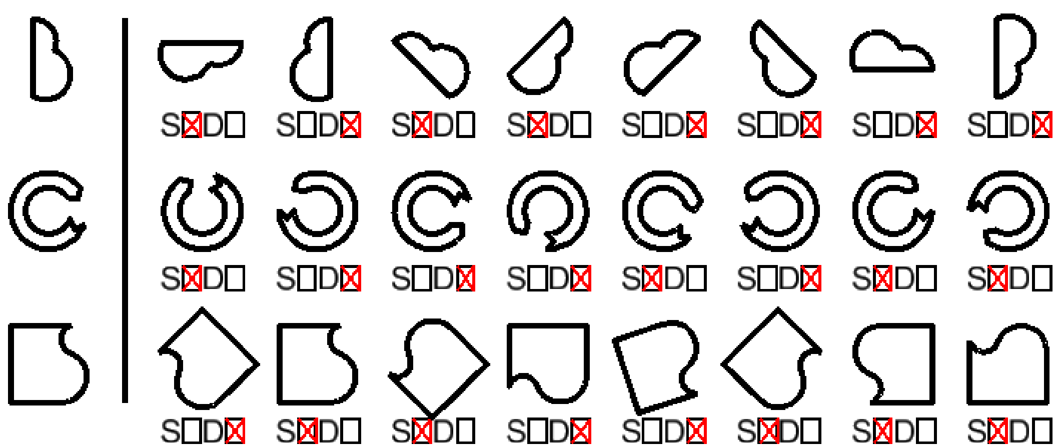

Figure 3.17. Card Rotation Test (Abbreviated)

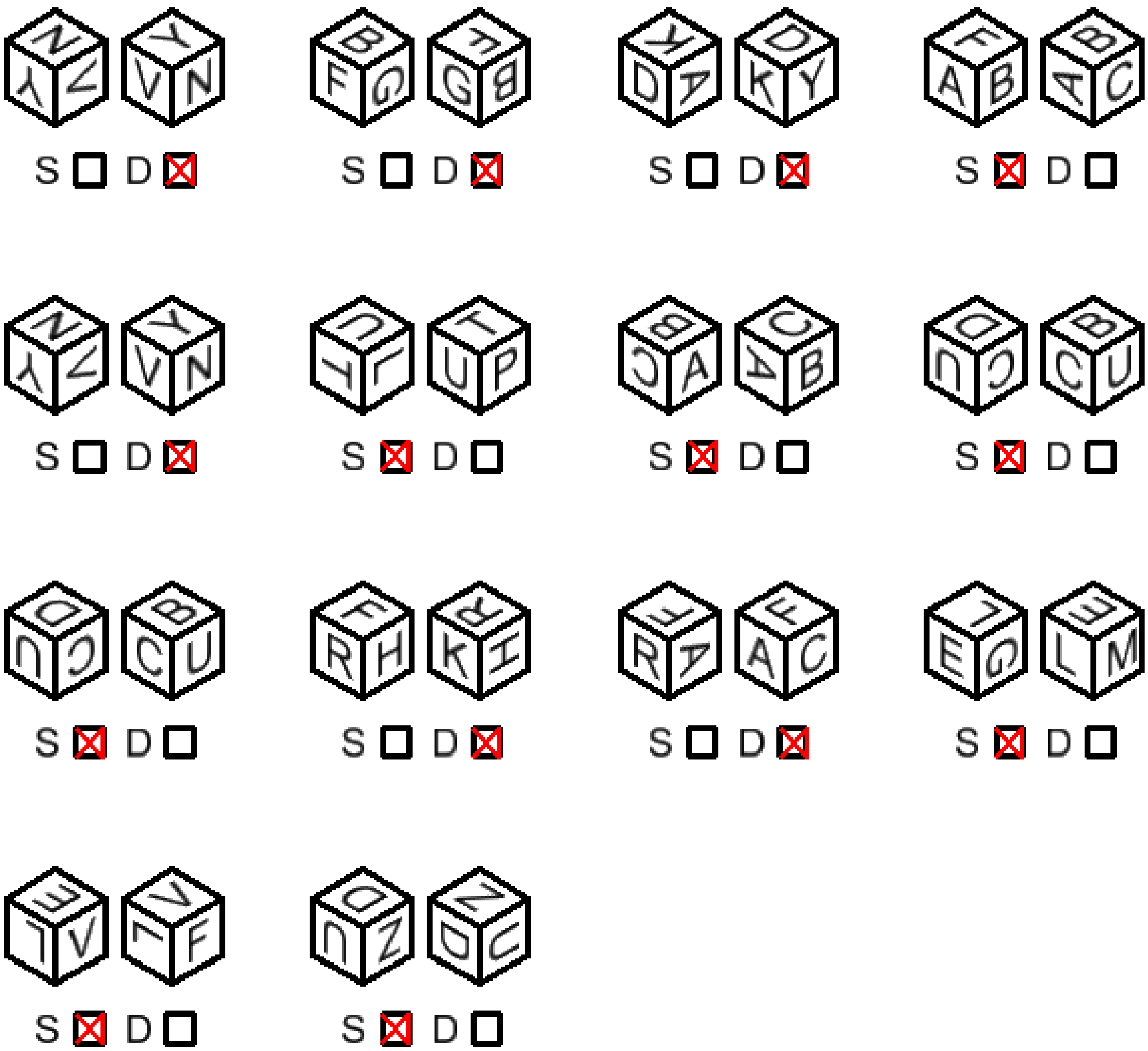

Figure 3.18. Cube Comparison Test (Abbreviated)

3.2.1 Field Trial Observations

Subjects were observed during the model assembly by a Five-Minute Rating. Five-minute ratings are meant for making general evaluations about an activity based upon a short amount of time, typically intended to make sense of a crew's efficiency (CII 2013). However, this analysis focused on one subject's performance over the span of approximately 15 minutes. The rating broke the workers' time up into a series of 30 seconds intervals to understand each interval in terms of either direct work, indirect work or rework. These intervals were summed over the span of the total length of assembly to analyze how the worker's time was being utilized. Optimal use of time would have low indirect work and rework time, and high direct work time. Direct work was considered assembling the model – handling the PVC pipe, measuring and attaching pieces together. Indirect work was considered reading the plans or idle time (mentally conceptualizing the model). Rework was considered any time utilized to disassemble model pieces and reassemble them. Below is the list of observations made during the model assembly:

1) Time to Completion: the total time in which a participant spends to complete the model assembly;

2) Error Occurrence: the likelihood that a participant would make one error;

3) Rework: the act of removing any piece that has already been assembled, or reinstalling a piece;

4) Direct Work: the physical act of installing pieces, or measuring pieces in order to assemble the model; and

5). Indirect Work: the act of reading plans, visualizing how the model is to be assembled, or any other act that is not Direct Work or Rework.

3.2.3. Contrasting Methods from Recent Studies

The two previous studies analyzed cognitive ability and performance with information formats similar to the research methods performed here. "Cognitive Workload Demands Using 2D and 3D Spatial Engineering Information Formats" by Dadi et al. (2014) and "Cognitive Demand of Engineering Information" by Sweany t al. (2014) both tested the Isometric drawing and the Three-Dimensional Physical Model, but did not use the Two-Sided Isometric drawing. Instead, Dadi and Sweany used a computer-aided drawing as their third information format.

Dadi et al. used the same design for each of the three information, allowing for a learning curve. Sweany did not use the same design, eliminating the possibility of a learning curve. However, Sweany's method compared different designs that each had different levels of difficulty. The methods from this research had a larger sample size than both Dadi and Sweany. This allowed each subject to have a different information format, eliminating the need for a subject to do more than one assembly and the learning curve. Also, each subject would be tested by the same level of difficulty by using the same design across information types.

Dadi and Sweany both used similar assembly model kits for their subjects. The model kits were plastic pieces that were laid out for the participant, the participant would snap the pieces together to create the model assembly based on the information format. The methods from this research were designed for one particular craft, instead of various construction workers, which is why the model kit resembled piping with members and joints similar to the shapes and obscure geometry seen in the pipefitting shop. The subjects had to measure and think more about which pipe members to choose and place into the assembly than subjects from Dadi et al. and the Folsom Experiment’s field trials.

Limitations with the model assembly in this research included the small scale of the model, and limited scope of work required to assemble the model, as compared to actual pipe fitting. Pipe used in the pipefitting industry is often 6 inches in diameter, 12 times larger than the ½” PVC pipe used in the model (Lauren Engineers and Constructors). Fitting pipe requires other tasks than measuring and assembling. However, the most important exercise (task) used in both the model assembly and pipefitting shops was erecting the pipe based on engineering drawings. This task demands mental focus and relies on the pipefitter’s cognitive abilities more than any other task in a pipefitter’s job description, such as: welding, material and equipment handling, and bolting (Lauren Engineers and Constructors). The research methods in this study focus on erecting/assembling pipe only.

CHAPTER IV

DATA ANALYSIS

Using the methodology described above, this research has been used to define the potential impact of new engineering deliverables to the field in craft labor performance. The analysis first examines the (1) performance of all subjects, then adds the relationship of spatial-cognitive ability to examine (2) cognitive abilities and performance.

4.1 Performance Metrics

The following table lists the demographics of the field testing population.

Table 4.1. Demographic Information of Field Trial Participants

Demographic	**Practitioner**
Current Occupation	Pipefitter
Number of participants	54
Age Range	22–65
Average Age	43 (SD = 11.5)
Years of Experience	1–47
Average Years of Experience	18 (SD = 10.7)

Table 4.2 lists the average measures of all five performance metrics by information type: time to completion, error occurrence, direct work, indirect work and rework. The sample sizes were 24, 21 and 9 for the Isometric, Two-Sided Isometric and the 3D Model, respectively. Due to limited sample size, the Isometric and Two-Sided Isometric formats were chosen to have larger sample sizes to test

the Two-Sided Isometric with greater significance, per request by the focus groups. In Table 4.2 the significance of each performance measures is described by the Score F and the P-Value. Score F is the variance of the group mean. The P-Value denotes the significance level of the mean score, to what degree of confidence that statistic holds. Where P-Values less than 0.15 yield a confidence level of 85% or greater, 0.10 yields confidence of 90% and values less than 0.05 yield confidence of 95% or greater.

Table 4.2. Performance Metrics by Information Type Analysis

Metric	Information Type	Sample Size	Mean	Overall Mean	F Iso vs 2-Sided Iso	P Iso vs 2-Sided Iso	F Iso vs 3D Model	P Iso vs 3D Model
Time to Completion	Isometric	24	12:06	11:01	4.79	0.034	0.02	0.88
	2-Sided Isometric	21	9:39					
	3D Model	9	11:18					
Error Occurrence	Isometric	24	0.58	0.37	1.51	0.230	3.96	0.06
	2-Sided Isometric	21	0.29					
	3D Model	9	0.00					
Direct Work	Isometric	24	63.0%	69.5%	4.43	0.04	7.36	0.01
	2-Sided Isometric	21	72.5%					
	3D Model	9	79.9%					
Indirect Work	Isometric	24	32.9%	26.9%	4.92	0.03	7.10	0.01
	2-Sided Isometric	21	23.7%					
	3D Model	9	18.3%					

Cells highlighted in red (Table 4.3) indicate that there is statistical significance among the mean performance scores. By examining the first metric, time to completion, the Two-Sided Isometric performed significantly better than the Isometric. The Two-Sided Isometric also performed significantly better than the Isometric in direct work. The 3D Model performed significantly better than the Isometric in error occurrence, direct work, indirect work and rework.

Trends were also found without statistical significance. Trends showed that the Two-Sided Isometric and 3D Model both performed better in all metrics than the Isometric. Also, trends showed that 3D Model performed even better than the Two-Sided Isometric in all metrics, except time to completion.

Overall, the Two-Sided Isometric was completed at the fastest rate, and had less errors, more direct work, less indirect work and rework than the Isometric supported by statistical significance. The 3D model had the least errors at zero, the highest direct work, lowest indirect work and rework among all three information types. Trends showed that the Two-Sided Isometric and 3D Model improve performance across all metrics when tested against the Isometric.

4.2 Cognitive Abilities and Performance

Testing each participant with the Card Rotation and Cube Comparison Tests allowed for discovery of a relationship between the spatial-orientation test scores and the performance of participants.

The following descriptive statistics analyzed significance and trends in the Card Rotation Test scores and Cube Comparison scores. Table 4.3 lists the descriptive statistics for the participants, with the exclusion of outliers (three outliers were omitted throughout the following graphs and charts in the Field Testing Analysis). Higher scores indicate a higher finite cognitive ability. Both cognitive tests tell us a story of a person's strengths and weaknesses in their spatial-relation ability.

Table 4.3. Cognitive Test Results

	Card Rotation Test	**Cube Comparison Test**
Maximum	40.0	14.0
Mean	28.2	4.9
Minimum	13.0	-4.0
Standard Deviation	6.5	4.1

The following plot Figure 4.1 is a pictorial representation of the spread these scores. The boxes show the center spread of 50% of the data, the vertical lines on either side each show the outer spread of 25% of the data both above and below the center spread. The black circle is the median of each Test.

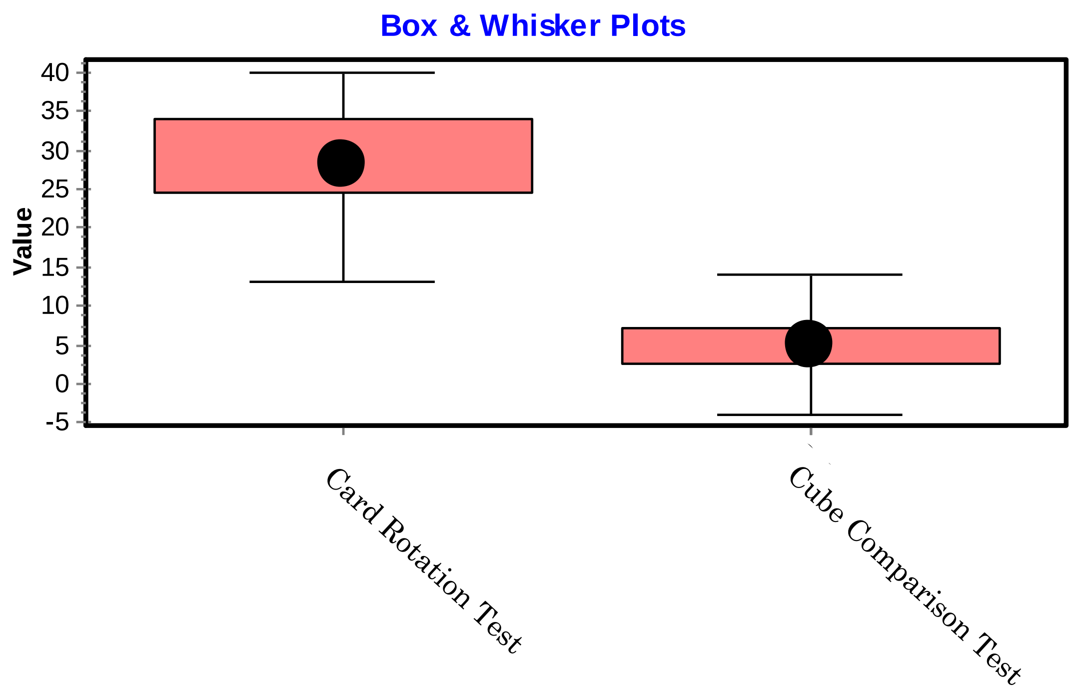

Figure 4.1. Cognitive Tests Box and Whisker Plot

Figures 4.2 and 4.3 are also pictorial representations of the spread of scores. The Natural Tolerances show a 6 standard deviation spread. The Card and Cube Comparison Tests both met normality. By cutting the spread down the middle, it discerned where to separate the data from High and Low categories. By categorizing the scores to High and Low, it allowed for an even analysis of results when comparing to performance metrics. The split for the Card Rotation was 28.2, the split for Cube Comparison was 4.9.

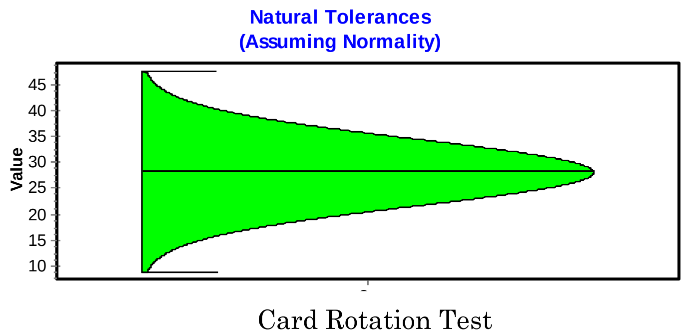

Figure 4.2. Card Rotation Test Normal Distribution

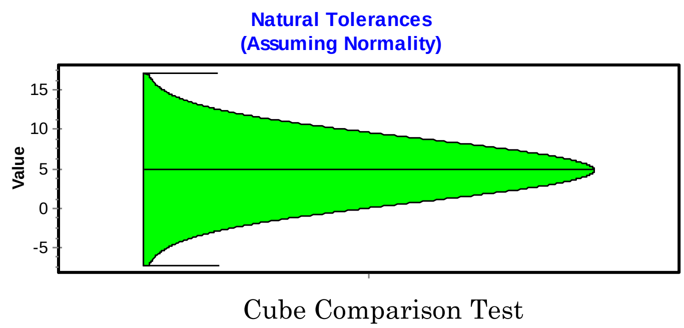

Figure 4.3. Cube Comparison Test Normal Distribution

A study conducted in 1963 and again in 1976 showed that Naval recruits, high school students and college students scored better on the Card Rotation Test, but lower on the Cube Comparison Test when compared to this study's data (Ekstrom et al. 1976). The average scores were 28.2 and 4.9 for the Card Rotation and Cube Comparison Tests, respectively, while Ekstrom found averages from his source to be around 21.5 to 24.6 and 5.1 to 9.4, respectively. It is important to consider other pools of data to understand what average population scores on the two tests would be.

Table 4.4. Previous Validation of Cognitive Tests

	1976 Data		**1963 Data**	
	Male Naval Recruits Source 1	Male Naval Recruits Source 2	High School Students	College Students
Card Rotation	24.6	24.6	22.5	22.7
Cube Comparison	5.2	5.1	6.6	9.4

The following table, Table 4.5 (p.81) compares the performance metrics between the Isometric and the Two-Sided Isometric similar to Table 4.2. However, Table 4.5 splits the participants into High Card Rotation and Low Card Rotation categories. These results offer several points: (1) the participants perform better on the Two-sided Isometric than the Isometric consistently; (2) the High Card Rotation participants score better than Low Card Rotation participants consistently – concluding that spatial-relation ability, or cognitive ability, does highly influence performance outcomes; (3) the difference of performance by metric between Isometric and Two-Sided Isometric is significantly greater with the Low Card Rotation, while the difference is insignificant and inconsistent with the High Card

Rotation – thus, concluding participants of Low Card Rotation scores are positively impacted when supplemented with the Two-Sided Isometric, while participants of High Card Rotation were not influenced by the supplement. The High Card Rotation means were so far insignificant that the expected consistent performance outcomes (seen in Table 4.2 where Card Rotation and Cube Comparison Test scores were not taken into account) were flipped, such as the error occurrence, direct work, and indirect work.

Table 4.5. Performance Metrics by Information Type (Card Rotation Analysis)

Metric	Information Type	High Card Rotation Score					Low Card Rotation Score				
		Sample Size	Mean	Overall Mean	F	p	Sample Size	Mean	Overall Mean	F	P
Time to Completion	Isometric	8	9:58	9:30	0.37	0.55	16	13:10	12:01	4.25	0.05
	Two-sided Iso.	11	9:10				10	10:10			
Number of Errors	Isometric	8	0.25	0.26	0.01	0.95	16	0.75	0.58	1.98	0.17
	Two-sided Iso.	11	0.27				10	0.30			
Direct Work	Isometric	8	73.6%	74.5%	0.03	0.86	16	57.7%	63.3%	5.73	0.02
	Two-sided Iso.	11	72.7%				10	72.3%			
Indirect Work	Isometric	8	23.3%	24.1%	0.06	0.81	16	37.7%	31.9%	7.86	0.01
	Two-sided Iso.	11	24.7%				10	22.6%			

Table 4.6. Performance Metrics by Information Type (Cube Comparison Analysis)

Metric	Information Type	High Cube Comparison Score					Low Cube Comparison Score				
		Sample Size	Mean	Overall Mean	F	P	Sample Size	Mean	Overall Mean	F	P
Time to Completion	Isometric	9	10:23	9:40	1.24	0.28	15	13:07	11:59	3.20	0.087
	Two-sided Iso.	11	9:05				10	10:16			
Number of Errors	Isometric	9	0.44	0.3	0.62	0.44	15	0.67	0.56	0.72	0.407
	Two-sided Iso.	11	0.18				10	0.4			
Direct Work	Isometric	9	73.60%	73.90%	0.01	0.928	15	56.60%	62.30%	5.08	0.034
	Two-sided Iso.	11	74.10%				10	70.70%			
Indirect Work	Isometric	9	23.90%	23.50%	0.05	0.827	15	38.40%	32.90%	6.24	0.020
	Two-sided Iso.	11	22.70%				10	24.80%			

Tables 4.7 offers the following results: (1) when the Isometric format was tested, there were significant increases in performance among High and Low Card Rotation scores in time to completion, error occurrence, direct work, and indirect work; (2) when the Two-Sided Isometric was tested, these increases in performance were much less, the same or worse and held no significance.

Table 4.7. Performance Metrics by Card Rotation

Metric	**Card Rotation Score**	**Isometric**				**Two-Sided Isometric**			
		Sample Size	**Mean**	**F**	**P**	**Sample Size**	**Mean**	**F**	**P**
Time to Completion	High	8	9:58	3.09	0.09	11	9:10	1.35	0.26
	Low	16	13:10			10	10:10		
Number of Errors	High	8	0.25	2.02	0.17	11	0.27	0.01	0.93
	Low	16	0.75			10	0.3		
Direct Work	High	8	73.60%	5.12	0.03	11	72.30%	0.01	0.94
	Low	16	57.70%			10	72.70%		
Indirect Work	High	8	23.30%	5.59	0.03	11	24.70%	0.19	0.67
	Low	16	37.70%			10	22.60%		

Table 4.8 offers the same results 1-3, as seen in Tables 4.5 and 4.6. When supplementing the Isometric with the Two-Sided Isometric, it eliminates the performance difference based on cognitive ability among the five performance Metric categories.

Table 4.8. Performance Metrics by Cube Comparison

Metric	Cube Rotation Score	Isometric				Two-Sided Isometric			
		Sample Size	Mean	F	P	Sample Size	Mean	F	P
Time to Completion	High	9	10:23	2.30	0.14	11	9:05	1.96	0.18
	Low	15	13:27			10	10:16		
Number of Errors	High	9	0.44	0.39	0.54	11	0.18	0.59	0.45
	Low	15	0.67			10	0.4		
Direct Work	High	9	73.63%	6.44	0.02	11	74.10%	0.56	0.46
	Low	15	56.64%			10	70.66%		
Indirect Work	High	9	23.86%	5.59	0.02	11	22.70%	0.19	0.67
	Low	15	38.35%			10	24.78%		

4.3 Age, Experience and Performance

The following Table 4.9 extracts data from the demographic questionnaire to exam whether or not (1) work experience would influence performance, and if (2) craft having lower experience would benefit more from the Two-Sided Isometric than craft with high experience. To answer the first (1), more work experience did indeed cause greater performance. However, this does not hold true for direct work for the Two-Sided Isometric, leading into the second hypothesis (2). When workers of lower experience were supplemented with the Two-Sided Isometric their performance exceeded those with greater experience. Anecdotally speaking, this is attributed to younger, less experienced craft having more familiarity with graphics, producing a greater response to the influence of graphical supplementation (anecdote originated in the Focus Groups). When Isometric means are compared to the Two-Sided Isometric means, the low-experienced craft rendered a 16% increase in direct work, the high-experienced worker only rendered a 3% increase.

Table 4.9. Performance Metrics by Work Experience

		Iso.				2-Sided Iso.			
Metric	**Experience**	**Sample Size**	**Mean**	**F**	**P**	**Sample Size**	**Mean**	**F**	**P**
Time to Completion	High	10	12:16	0.85	0.37	12	9:58	0.70	0.41
	Low	13	10:56			9	9:14		
Direct Work	High	10	63.19%	0.00	0.97	12	66.18%	20.11	0.00
	Low	13	62.85%			9	88.84%		
Number of Errors	High	10	0.60	0.03	0.87	12	0.33	0.15	0.71
	Low	13	0.54			9	0.22		

4.3.1 Age, Experience and Cognitive Ability

Table 4.10 shows that shows that craft of lower age scored better on the Rotation Tests significantly. This is finding is relevant, because it shows that older craft have lower cognitive spatial-relation ability, and should, in theory, benefit from supplementation of graphics just as younger craft would. However, due to older, more experienced workers settling into their ways of isometric drawings, they are more resistant to change. Younger workers regardless of cognitive abilities will benefit from the graphic supplement.

Table 4.10. Age and Experience by Cognitive Ability

Metric	**Card Rotat.**	**Sample Size**	**Mean (Year)**	**F**	**P**	**Cube Rotat.**	**Sample Size**	**Mean (Year)**	**F**	**P**
Age of Worker	High	28	39	6.61	0.01	High	28	41	2.24	0.14
	Low	28	46			Low	28	45		
Experience of Worker	High	28	15	4.12	0.05	High	28	16	1.50	0.23
	Low	28	20			Low	28	19		

In summary, younger workers prove to benefit from graphic supplement due to their lack of experience and willingness to accept change. Older, more experienced workers may not benefit from the graphic supplementation due to resistance to change. Older workers have lower spatial-relation cognitive abilities, therefore, should respond well to the graphic supplementation, this logic is supported statistically in hypothesis (3) p.79, of Table 4.5 p.81.

4.4 Key Findings

4.4.1 Performance by Information Type

Using the methodology described above, this research defined the potential impact of new engineering deliverables to the field on craft labor performance. It was discovered that a statistically significant difference in pipe fabrication/installation speed can be made if pipefitting crews are given two-sided isometric drawings in comparison to using conventional isometric drawing. A **16% improvement in installation speed was observed** (Table 4.2. Performance Metrics by Information Type Analysis, p.74), with the piping model requiring an average of 11 minutes and 31 seconds to complete using an isometric drawing versus 9 minutes and 39 seconds using a two-sided isometric drawing. This research also indicated a directionally positive reduction in the error occurrences observed, although this finding lacked a strong statistical significance. **Direct work (time**

on tools) improved 9%, with strong statistical significance (Table 4.2. Performance Metrics by Information Type Analysis, p.74). The improvement in direct work was mirrored by similar improvement in indirect work.

When the pipefitters were given a 3D Physical Model in addition to a conventional Isometric drawing, there was little reduction in fabrication time, but the **error rate dropped to 0% and an overall improvement of 17% in direct work was experienced**. Furthermore, the **indirect work decreased by approximately 14%** (Table 4.2. Performance Metrics by Information Type Analysis, p.74).

4.4.2 Performance Linked to Spatial Ability

Perhaps the most significant discovery was found when the performance metrics were compared by deliverable for differences in spatial ability among the participating pipefitters. **When using the two-sided drawings, pipefitters with lower spatial ability, as measured by the card rotation and cube comparison tests, performed with greater efficiency and effectiveness** (Table 4.5. Performance Metrics by Information Type (Card Rotation Analysis), p.81; Table 4.6. Performance Metrics by Information Type (Cube Comparison Analysis), p.82). When using the Isometric drawings only, their overall performance was significantly degraded. Utilization of a Two-Sided Isometric drawings allows construction to close the gap between less and higher skilled craft.

The difference in performance metrics between Isometric and Two-Sided Isometric will be called "delta." The delta between High Card Rotation Scores is much lower than the delta between Low Card Rotation Scores, significantly, in Time to Completion and Direct Work seen in Table 4.5. Performance Metrics by Information Type (Card Rotation Analysis) p.81. The delta between High Cube Comparison Scores is much lower than the delta between Low Cube Comparison Scores, significantly, in Direct Work and Indirect Work seen in Table 4.6. Performance Metrics by Information Type (Cube Comparison Analysis) p.82. The performance delta is larger in low card rotation and low cube comparison tests, because the 3D model shot on the back of the Two-Sided Isometric improves performance drastically, where high scoring subjects did not perform significantly better since their ability to recognize 3D shapes in space did not need the added visual aid. Though high scoring subjects did improve slightly with the use of Two-Sided Isometric in most performance metrics, there was no statistical significance. This absence of significance in high scoring subjects versus strong significance in low scoring subjects supports the original research hypothesis – by supplementing visual aid, performance is improved, creating the delta in low scoring subjects. By giving the spatially-challenged a 3D graphic it allowed participants to find their way in the space quickly, improving performance.

4.5 Return on Investment Analysis

As field trials reached the desired sample size, it was obvious that favorable results using the Two-Sided Isometric drawing compared to conventional Isometric drawings could have a significant impact on the overall field installation costs on construction sites. To address the question of how much difference the use Two-Sided Isometric drawings could make to the bottom line of a project, RT-327 first determined that it needed to scale up the size of our model. The scaling of the pipe diameter and length would need to be comparable to what would typically find on a project job site. Factoring the model used in our field testing, at twenty two feet in length, we scaled up from the one-half inch diameter to six inch diameter, which gave us an equivalent length of two hundred and sixty four feet of total installed pipe.

To examine the potential return on investment (ROI) of using Two-Sided Isometric compared to conventional Isometric drawings, the research team first identified expected unit rates (man-hour per linear foot) for the installation of 6” diameter carbon steel pipe, a common pipe commodity installed on many industrial projects. Based on productivity data from the CII Benchmarking and Metrics Data (CII 2011), the average pipe installation rate was found to be 2.6 man-hours per linear foot, which will be referred to as the academic rate (Equation 4-1).

$Academic\ Unit\ Rate\ (Pipefitting) = 2.61\ hr/LF$ [Equation 4-1]

This was validated by one of RT-327's industry member own internal rate of 2.5 man-hours per linear foot of six inch piping installed, which will be referred to as the industry rate (Equation 4-2).

$Industry\ Unit\ Rate\ (Pipefitting) = 2.50\ hr/LF$ [Equation 4-2]

Considering that the composite rate reflects welding, bolting, and other pipefitting tasks, RT-327 felt the most practical analysis was to break down the unit rate by excluding time for activities that are not directly impacted by the benefit of the Two-Sided Isometric by focusing on just the hours involved in the erection tasks for pipe installation. Using available industry knowledge estimating tables, .44 man-hours per linear foot was the standard unit rate for erection for 6" standard wall carbon steel piping based on the industry rate (Equation 4-3).

$Industry\ Unit\ Rate\ (Erection\ Only) =\ 0.44\ hr/LF$ [Equation 4-3]

Assuming the same ratio from the composite academic rate, RT-327 determined a similar rate of .46 man-hours per linear foot to be applicable to the academic rate (Equation 4-4).

$$Academic\ Unit\ Rate\ (Erection\ Only) \cong \left(\frac{0.44\ hr/LF}{2.50\ hr/LF}\right) = \left(\frac{x}{2.61\ hr/LF}\right)\ ;\ x = 0.46\ \text{hr/LF}$$

[Equation 4-4]

Next, the average unit rate, considering erection only was calculated based on both the industry rate (Equation 4-3) and the academic rate (Equation 4-4) as shown in Equation 4-5, referred to as the Isometric Unit Rate.

$$Isometric\ Unit\ Rate = \frac{\frac{0.44hr}{LF}+\frac{0.46hr}{LF}}{2} = 0.45\frac{hr}{LF}$$ [Equation 4-5]

The final "time to completion" results from the RT-327 field trials showed that those individuals working with the Two-Sided Isometric drawing completed the erection/assembly by a margin of 16% faster than individuals working with conventional Isometric drawings (Equation 4-6).

$$Percent\ Improvement = \frac{11{:}31 - 9{:}39}{11{:}31} = 16\%$$ [Equation 4-6]

This 16% time savings was applied to the average unit rate for erection only (Equation 4-5) to derive a Two-Sided Isometric unit rate of 0.38 man-hours per linear foot (Equation 4-7).

$$Two\ Sided\ Isometric\ Unit\ Rate = 0.16 * \ \ 0.45\frac{hr}{LF} = 0.38\frac{hr}{lf} \qquad \text{[Equation 4-7]}$$

Using available costing data from RSMeans for the expense of a pipe installation crew at a value of $2,331.73 per day (assuming eight hour days) or $291.47 per hour, RT-327 accurately estimated the cost of installation at both the conventional Isometric drawing unit rate (0.45 hr/lf) and the improved Two-Sided Isometric unit rate (0.38 hr/lf).

When utilizing all factors, the cost for installation of one hundred linear feet of pipe using an Isometric cost of $13,116.15 (Equation 4-8) compared to a Two-Sided Isometric cost of $11,235.86 (Equation 4-9), revealed an overall field savings of 14.34%, equaling $1,986.89 (13,116.15 – 11,129.26).

$$Crew\ Cost\ with\ Isometric = \left(\frac{\$291.47}{hr}\right) * \left(\frac{0.45\ hr}{LF}\right) * \left(100\ LF\right) = \$13{,}116.15$$

[Equation 4-8]

$$Crew\ Cost\ with\ Two - Sided\ Isometric = \left(\frac{\$291.47}{hr}\right) * \left(\frac{0.38\ hr}{LF}\right) * \left(100\ LF\right) = \$11{,}075.86$$

[Equation 4-9]

The final factor to determine as part of the ROI was the "cost of investment" required to generate the Two-Sided Isometric drawing. Based on RT-327 own experience in developing the Two-Sided Isometric drawings, the additional time to include a model shot of the piping isometric to each individual isometric drawing is equivalent to .33 engineering hours. The final assumption/determination needed was the number of isometrics per linear foot of pipe. The team recognized a typical industry practice that 50 feet of pipe is typically represented on each Isometric drawing as a fairly conservative standard to use in the determination of its cost of investment. Assuming a designer cost of $80/hr, the added cost of developing Two-Sided Isometric drawings for 100 feet of pipe was determined to be $53.40/hr (Equations 4-10 and 4-11).

$$Additional\ Engineering\ Time\ for\ 100\ LF\ = 2\ drawings * 20\frac{min}{drawing}$$

$$= 40\min = 0.667\ hrs$$

[Equation 4-10]

$$Additional\ Engineering\ Cost\ for\ 100\ LF = (\$80/hr) * (0.667\ hrs) = \$53.40$$

[Equation 4-11]

Based on the savings and added engineering cost, an ROI of 3,620% was estimated (Equation 4-12).

$$ROI = \left(\frac{Savings - Cost}{Cost}\right) = \left(\frac{\$1,986.89 - \$53.40}{\$53.40}\right) = 3620\% \quad \text{[Equation 4-12]}$$

Another way of describing the ROI estimation is that for every $1 investment (cost) a return of $36.20 (Savings – Cost) is expected.

CHAPTER V

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This research offers a new approach to information delivery and unique considerations for the skilled labor-force; with respect to their desires for jobsite improvements and individual spatial-cognitive ability levels. These findings contribute both innovation and validation for the Construction Engineering Management body of knowledge - implementable in industry. Both the two-sided isometric drawing and the three-dimensional physical model prototypes were validated by practical experiments exercised in a controlled environment which replicated industry practices.

Dadi (2014) and Sweany (2014) set the framework for measuring productivity by cognitive demand and spatial-cognitive ability. Dadi tested three formats of information by one design utilizing a variation of craft (carpentars, electricians, mechanical workers and engineers), but was limited when each participant assembled the same design using the three formats. Dadi's major finding was in cognitive workload demands. When subjects use formats with three-dimensional visual aid workload decreases, when workload is decreased productivity improves. Dadi proved that intuitive information leads to better performance. Sweany tested three formats of information by three designs utilizing workers and engineers who specialized in ironwork, but was limited in design differences in usability. Sweany's major finding was in productivity metrics. When subjects used the three-dimensional visual aids all productivity metrics improved. Improvements from the 2D Plans were realized for 3D CAD and increasingly more for the 3D Physical Model.

While Dadi and Sweany used the 2D Plans, 3D CAD and the 3D Physical Model, this research used different formats: Isometric Drawing (similar to the 2D Plans), Two-Sided Isometric (similar perspective to the 3D CAD) and 3D Physical Model (similar to the 3D Physical Model, but monolithic and not attachable pieces). This research focused on one trade and only one job only, pipefitters. The major breakthrough this research provides is the significant finding in spatial-cognitive ability. When subjects of lower spatial-cognitive ability are provided a 3D visual enhancement their performance improves to match subjects of higher spatial-cognitive ability, leveling the playing field.

Limitations in this research included a relatively small sample size and mild complexity. The 3D Printed Model had a sample size of 9 (N=9). Complexity of the design was simplified to meet time demands. Increasing the number of spools and variation in the design to match real complexity field trials could have taken hours. Finally, the mock assembly did not replicate welding, it only replicated the "fitting" or erection of pipe spools, which does not make up the entirety of a pipefitter's duties.

The analysis for validating both innovative technologies was endorsed by rich statistical significance over a strong demographic of industry pipefitters. Perspectives of the construction skilled labor for jobsite improvements can be found in 3.1 Focus Groups. Here, ideas for innovation and improvements in communication are presented in a convenient schematic for viewing and use in future literature. Perspectives of the construction skilled labor was further considered by realizing individual spatial-cognitive abilities 4.2. Cognitive Abilities and Performance, while data was gathered from the cognitive testing during the field trials. Finally, opportunity for industry economic gains from this research was described in 4.5 Return on Investment Analysis.

5.2 Recommendation

Due to the delayed adoption of three-dimensional rapid printing, and its fragility and cost, it is recommended that owners utilize this technology when presenting information within the constraints of controlled environments; i.e. jobsite trailers during constructability meetings. However, the two-sided isometric drawing is recommended to be utilized by owners, providing two-sided isometric drawings at the face of the work, printed by field kiosks onsite or in the office and brought to the jobsite. Fortunately, technology advancements over the past decade have made it possible to create, store, transfer and consume information in ways never imagined, improving the speed at which we learn, understand and react to information. These advancements have the potential to significantly improve an individual craft worker's performance as demonstrated in this research.

The contribution this research provides to academia in construction engineering management is the validation that greater accommodation for lower spatial-cognitive is necessary. If management wants to see improvements across all individual skilled craft, management must aid workers with 3D visual enhancements that are meaningful to the craft. Furthermore, testing for spatial-cognitive ability should be considered to understand where implementing 3D visual enhancements are appropriate. In addition to the current workforce, accommodations for spatial-cognitive ability should be considered in training. Associated Builder and Contractors (ABC) trade schools can help new trainees adopt blueprint reading skills more efficiently. When training programs assist those with low spatial-cognitive abilities, their learning curve can match efficiencies of those with higher spatial-cognitive abilities. Improvements of this nature are especially important for the construction industry when workforce shortages are eminent (Albattah et al. 2015).

How the individual craft worker accesses, views and interprets information relevant to perform their tasks is a critical area for further research. Further examination of the innovations presented in this thesis, and other technologies should be examined that are practical for use in the field. To better understand the influence of three-dimensional perspectives and spatial-cognitive ability, other designs should be tested using the same two formats: the two-sided isometric drawing and the three-dimensional physical model. These designs should vary in complexity to test if (1) 3D perspectives enhance productivity respective to increasing complexity, and (2) how productivity gaps are reflected from high to low spatial-cognitive ability groups when complexity increases.

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APPENDIX

A. Five-Minute Rating Form

Date	PIN
9/24/2014	001

Totals	
Units	24
Direct	11
Indirect	11
Rework	2
Delay	0

Percentage	
Units	24
Direct	45.83%
Indirect	45.83%
Rework	8.33%
Delay	0.00%

Info Type: Isometric

Errors: 2

Uninstalled: 0

% Complete: 100%

Card Rotation: 22

Cube Comparison: 4

NASA-TLX

Mental: 11

Physical: 7

Temporal: 9

Performance: 20

Effort: 10

Frustration: 2

Time	Direct Work	Indirect Work	Rework	Delay due to rework
0:30	X			
1:00			X	
1:30		X		
2:00			X	
2:30	X			
3:00		X		
3:30	X			
4:00		X		
4:30	X			
5:00	X			
5:30	X			
6:00		X		
6:30		X		
7:00	X			
7:30		X		
8:00	X			
8:30		X		
9:00	X			
9:30		X		
10:00		X		
10:30	X			
11:00		X		
11:30		X		
12:00	X			
12:30				
13:00				
13:30				
14:00				
14:30				
15:00				
Total	11	11	2	0

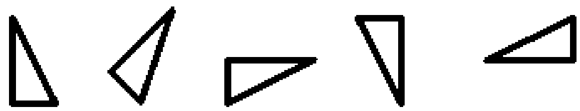
Total Time: 12:15

Rework Instances: 5

B. Card Rotation Answers

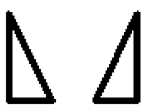
Card Rotation Test (Answers)

This is a test of your ability to see difference in figures. Look at the 5 triangle-shaped cards drawn below.



All of these drawings are of the **same** card, which has been slid around into different positions on the page.

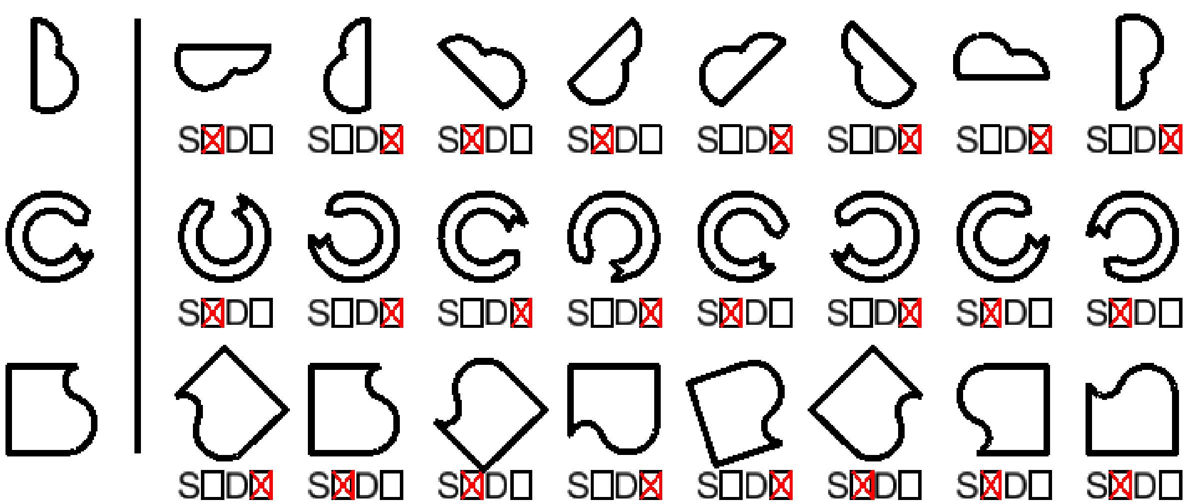
Now look at the 2 cards below:



These two cards are **not alike**. The first cannot be made to look like the second by sliding it around on the page. It would have to be **flipped over** or **made differently**.

Each problem in this test consists of one card on the left of a vertical line and eight cards on the right. You are to decide wether each of the eight cards on the right is the **same as** or **different from** the card at the left. Mark the box besides the S if it the **same as** the one at the beginning of the row. Mark the box beside the D if it is **different from** the one at the beginning of the row.

Practice on the following rows. The first row has been correctly marked for you.



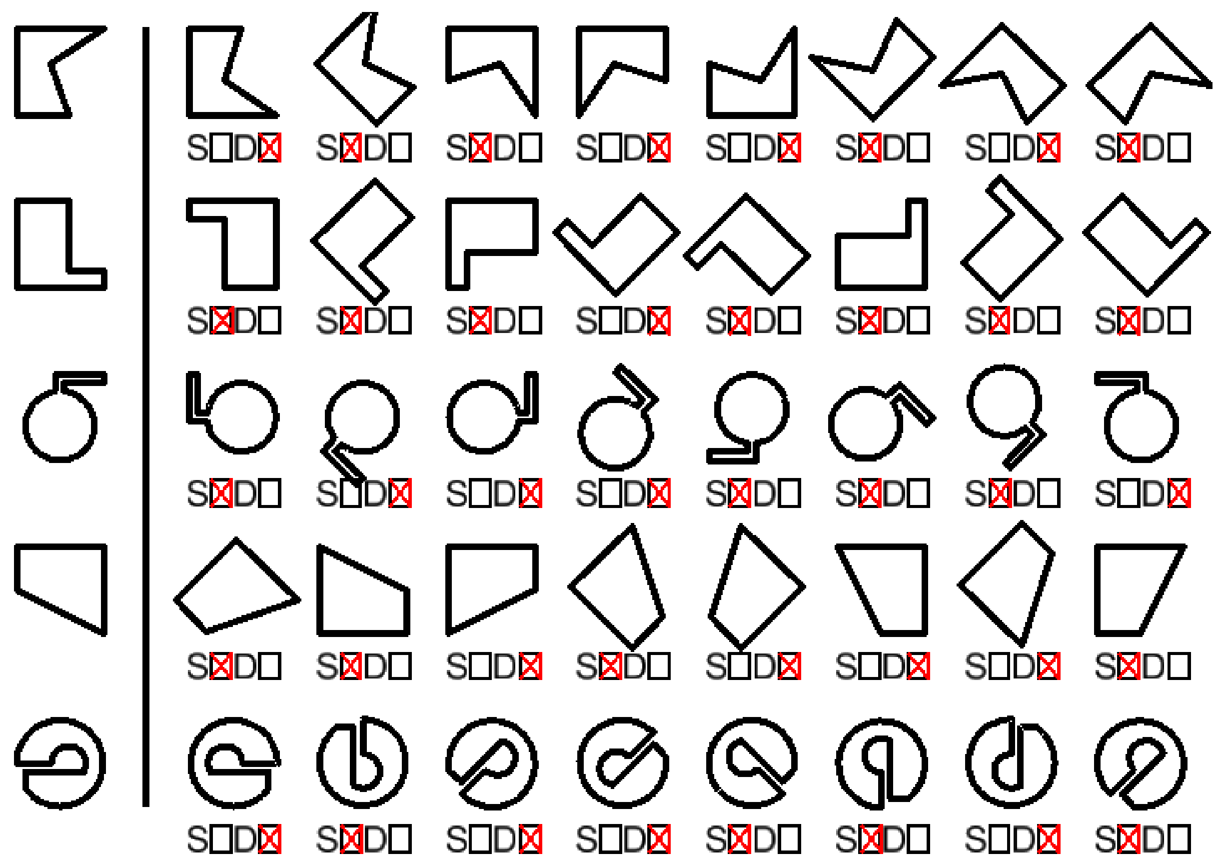
Your score on this test will be the number of items answered correctly minus the number answered incorrectly. Therefore, it will **not** be to your advantage to guess, unless you have some idea whether the card is the same of different. Work as quickly as you can without sacrificing accuracy.

You will have **1.5 minutes** for this test. When you have finished this test, STOP

Card Rotation Test (1.5 minutes)

S = same (only rotated)

D = different (flipped and/or rotated)



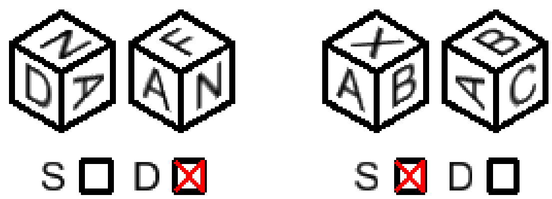
_____________ – _______________ = __________ / 40

Correct Answers – Incorrect Answers = Total Score

C. Cube Comparison Test Answers

Cube Comparisons

Wooden blocks such as children play with are often cubical with a different letter, number, or symbol on each of the six faces (top, bottom, four sides). Each problem in this test consists of a drawing of pairs of cubes or blocks of this kind. Remember, there is a different design, number, or letter on each face of a given cube or block. Compare the two cubes in each pair below.

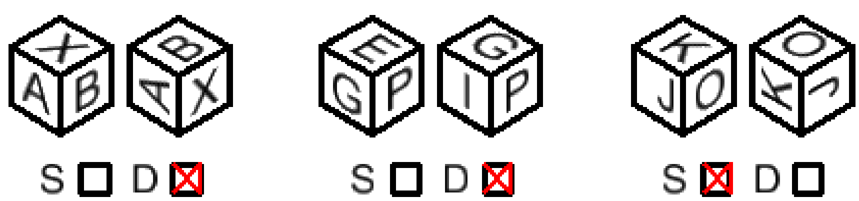


The first pair is maked D because they must be drawings of **different** cubes. If the left cube is turned so that the A is upright and facing you, the N would be to the left of the A and hidden, not to the right of the A as is shown on the right hand member of the pair. Thus, the drawings must be of different cubes.

The second pair is marked S because they could be drawings of the **same** cube. That is, if the A is turned on its side the X becomes hidden, the B is not on top, and the C (which was hidden) now appears. Thus the two drawings could be of the same cube.

Note: No letters appear on more than one face of a given cube. Except for that, any letter can be on the hidden faces of a cube.

Work the three examples below.



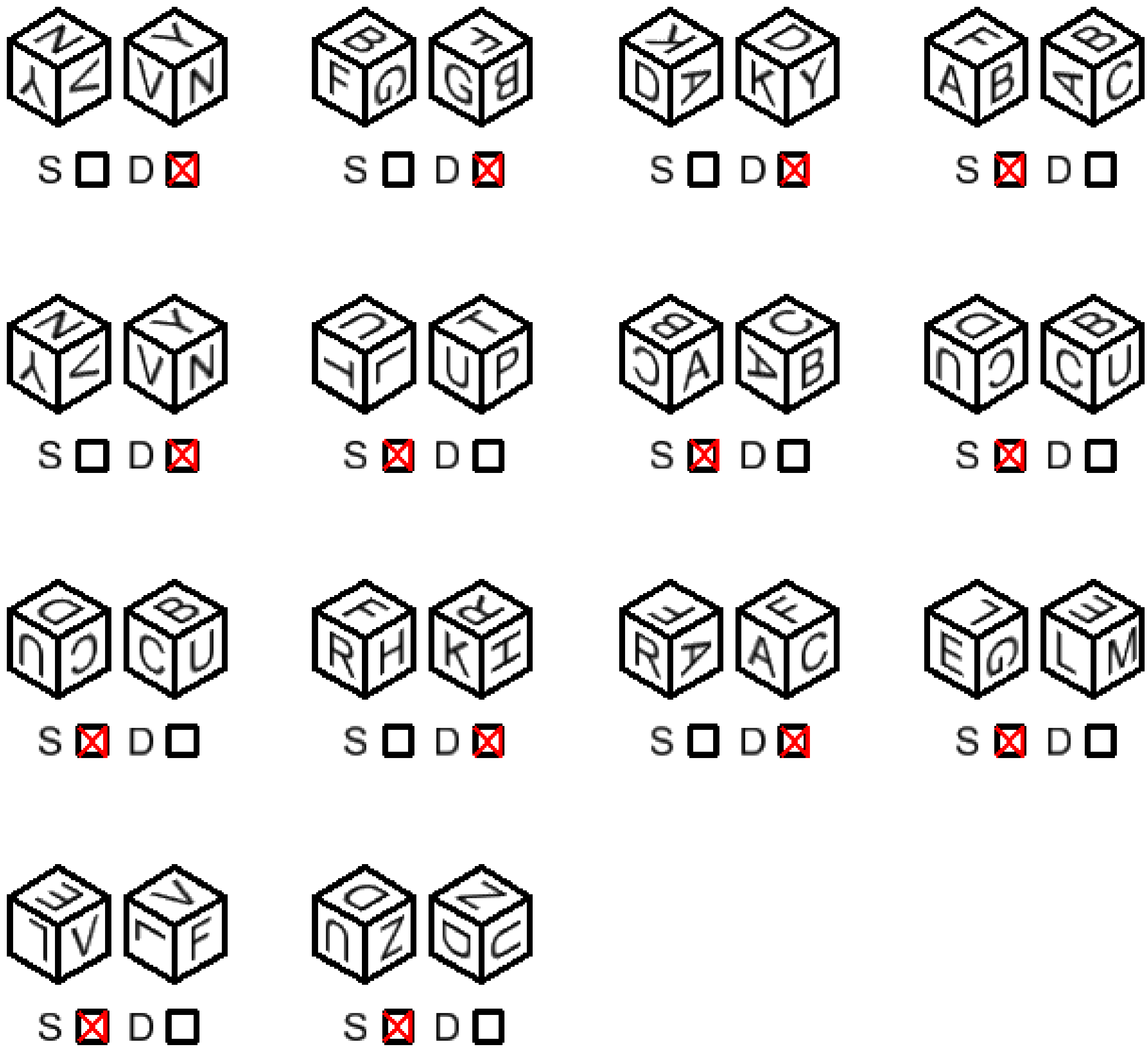
The first pair immediately above should be marked D because the X cannon be at the peal of the A on the left hand drawing and at the base of the A on the right hand drawing. The second pair is “different” because P has its side next to G on the left hand cube but its top next to G on the right hand cube. The blocks in the third pair are the same, the J and K are just turned on their side, moving the O to the top.Your score on this test will be the number marked correctly minus the number marked incorrectly. Therefore, it will **not** be to your advantage to guess unless you have some idea which choice is correct. Work as quickly as you can without sacrificing accuracy.

You will have **2 minutes** for this test. When you have finished this test, STOP.

Cube Comparison Test (2 minutes)

S = same (same cube)

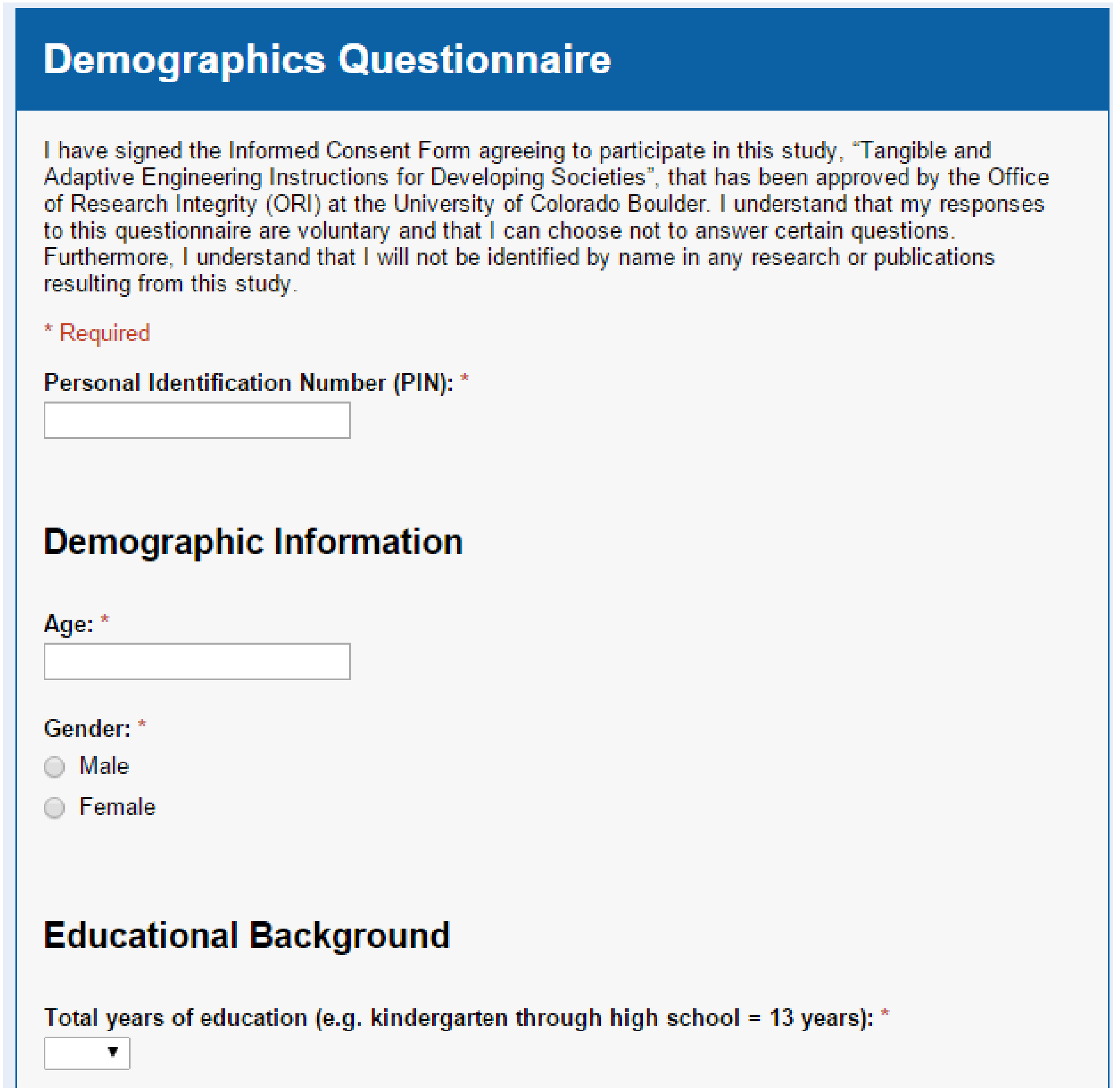
D = different (different cubes)



____________ – ______________ = _________ / 14

Correct Answers – Incorrect Answers = Total Score

D. Demographic Questionnaire



Demographics Questionnaire

I have signed the Informed Consent Form agreeing to participate in this study, "Tangible and Adaptive Engineering Instructions for Developing Societies", that has been approved by the Office of Research Integrity (ORI) at the University of Colorado Boulder. I understand that my responses to this questionnaire are voluntary and that I can choose not to answer certain questions. Furthermore, I understand that I will not be identified by name in any research or publications resulting from this study.

* Required

Personal Identification Number (PIN): *

Demographic Information

Age: *

Gender: *

- Male
- Female

Educational Background

Total years of education (e.g. kindergarten through high school = 13 years): *

Please select your highest level of education: *

Have you had any formal training in engineering drawings/blueprint reading? *

- Yes
- No

Work Experience

Current Occupation: *

Years of Engineering Industry Work Experience: *

Type of Engineering Industry Work Experience *
check all that apply

- None
- Design
- Construction
- Internship or Co-op
- Field Inspector
- Estimator
- Project Engineer
- Project Manager
- Craft Worker
- Foreman
- Superintendent
- Owner's Representative
- Other:

E. Propositional Distinctions

The lines from the focus group transcriptions were methodically decomposed to a form that describes the most basic meaning of each response or comment as shown:

Subject or Object////Evaluative Meaning
Subject or Object//Dependent Connector////Evaluative Meaning

For example, the first line under Two-Sided Isometric Drawings is saying: two-sided isometric drawings provide strong document management. The second line is saying: if model shots within the two-sided isometric drawings are correct, two-sided isometric drawings are valuable.

Two-Sided Isometric Drawings

- Positive

Document management system////Strong
Model shots//IF correct////Valuable
Model shots, two-sided isos////that's a game-changer
2 sided iso////No Explanation Needed
2 sided iso////Valuable
2 sided iso////See more in the field
2 sided iso////Perfect in the shop too
2 sided iso////Would help a lot
2 sided iso//From a mechanical standpoint////A lot
2 sided iso//Iso and the model shot at the same time////just an extra click of the button
2 sided iso//Limit as much information as possible////so wouldn't miss something important
2 sided iso////The idea for job improvement

- Neutral

2 sided iso//IF it's up-to-date////Fine

Annotated model shots////Piping must be identifiable

Projects now…usual format…one sided////2 sided iso not given

Model shot... 2 sided iso////Never seen before

Out of date documents////Useless

<u>3D Model Shots</u>

- Positive

Static 3D Model Shots//IF sequence of Slides in 3D////Useful as animation easier to read

Model Shots////They did seem to like

Model Shots//IF correct////Good

Model Shots//IF correct////Valuable

Model Shots//IF not on the job////Create a mess of guessing the situation [orientation]

- Negative

Model Shots////Problems showing correct placement of piping rack

Model Shots////Not where it should

Model Shots////Not labeled correctly

Model Shots//Sometimes////Not reliable

3D Physical Models

- Positive

3D Model////Replaces higher costing method [scale wire models]
3D Model////Valuable to operators
3D Model////Can sit out for all to see
3D Model////One step ahead of 3D computer models3D Model////Perceived Value
3D Model////Helpful
Physical objects//Better than PowerPoint presentations////Crafts seems to respond
Detachable 3D Model////Perceived Value

- Negative

3D Model////Pieces break
3D Model//IF pieces are not detachable////Can't see interior

- Neutral

Increase of projects using 3D models////No increased use
3D Model////Must be interactive for perceived value

Access to Digital Information

- Neutral

Digital Information////Should Require Permit to Access Certain Levels
HUD////Access Will Help QA & QC Communication
HUD////Should not be in Hands of Craft
Mobile Devices//Field Kiosk, Tablet////Foreman Should Have Access

Restriction of Access////Denies Ability to Have Latest Standards & Specs

BIM – Building Information Modeling

- Positive

BIM//look at problems////easy
BIM//pipe referencing////useful
BIM////gets the contractor involved upfront
BIM//integration upfront////useful
BIM//updating drawings & construction packages////helpful
BIM//work package management and updates////helpful
BIM//engineering and conflict resolution////great
BIM////perceived value - layer viewing
BIM////perceived value - picture isolation

- Negative

BIM//sometimes////expensive
BIM////cannot tell which piping line is referenced
BIM////only accessible at the superintendent level
BIM////cannot be taken to craftsmen
BIM//electrical installations////not shown
BIM////not seen in industry

Constructability Meetings

- Neutral

Const. Meetings////not done with craft before drawings come out
Const. Meetings////beneficial

Const. Meetings////get a lot of information

Const. Meetings////no longer occurring

Const. Meetings////would help to get information quicker

Const. Meetings////not occurring when requested

Const. Meetings//cannot be in-house people////opinions not voiced

Const. Meetings//on-site meetings////positive impact

Const. Meetings//on-site meetings////control a lot more

Const. Meetings////eliminates being on a “need-to-know basis”

Const. Meetings//eliminates broken information///gives big picture

Const. Meetings//follow-up meetings////provides lessons learned continuity

Const. Meetings////model reviews////desire construction crew involvement

Const. Meetings////don’t have time

- Integration of Technology (into Constructability Meetings)

Face-to-Face Meetings////track communication

Automated Integration of Changes////track communication

Const. Meetings//IFA reviews////desired

<u>Current Practices</u>

- Construction Operation Activity

Updated standard details or specs////very difficult to obtain

Available standard details or specs////old versions

Field Verifiers////holding field workers accountable for engineering faults

Fabrication////done offsite

Cameras in Field////must be approved to use

Cameras in Field////used to track progress

3D Laser Scanning////done on big turn-around jobs

Fast-tracking projects//install I&E prior to piping////causes rework
Fast-tracking projects////commonly done
Drawings////poor reference for locating items
Drawings////distributed from owner-company to contractors
Drawings Delivery////electronic and hard copy
Drawing//Revisions////month and half delay
Drawing Revisions//distributed in field////come through document control
Industry Organization//compared to Commercial////less direct, spread out, communication issues
RFIs////couple hundred on a project
Annotative Document Capabilities////conflict resolution, understood communication
Information, Feedback////engineers soliciting more from construction
Bill of Materials////generated from isometric drawings
Bill of Materials////generated on site post purchase

- Electronic Information

Electronic Drawing Format//email link////PDF, screenshot
Electronic Drawing Format//email link////PDF
Electronic Drawing Copies////shared on saved drive
Drawing Delivery////normally get electronic copy
Drawing Process////from engineering, to QC, to proj Sup, Sup sends RFI for revisions
3D Model////contractors have experienced on project
3D Model////contractors have experienced with superintendent
3D Model Model Review////desired from engineering & construction
3D Model on Project////no perceived difference from deliverable standpoint
IFA Delivery//issued upon request////after IFC is in place
IFA, IFC Delivery////material issues occur
IFA, IFC Delivery//bill of materials////can be good or bad
Mobile Applications//installation conflict////take picture, mark & labeling, send off

Mobile Applications//drawings////scaling isn’t accurate
Equipment Tracking////QC scans barcode for equipment accountability

- Paper Copies

Drawing Format//typically////11x17”
Drawing Format//11”x17”////desired only by structural industry
Drawing Format//isometrics////desired by mechanical & E&I industry
Drawing Format////foreman have paper copies, sup has electronic & hard copies
Isometric Drawings////printed off to include in work package
Isometric Drawings////given without plans and sections
Isometric Drawings////one-sided only on jobsites
Isometric Drawings////paper copies will always be needed
Isometric Drawings//IF given with plans////adequate
Model Shots////high value
Model Shots//uncommonly////given in work package
Material Tracking////field engineer manually track on paper
Bill of Materials//onsite fabrication////manually produced

Exclusive 2D Information Format

- Positive

2D Format////won’t get away from paper copies
2D Drawings////allows workers to mark up in the field

- Negative

2D Drawings//stacks of drawings in construction review////inefficient

2D Format////not detailed

- Neutral

2D Drawings////used on all projects

Field Kiosks

- Positive

Field Kiosks//group unanimous agreement////real hit
Field Kiosks////can access information next to work
Field Kiosks//access////model, specs, vendor data, standards
Field Kiosks//printing capability////craft wants paper on scaffold
Field Kiosks////keeps foreman with craft on jobsite
Field Kiosks////can prevent machine from freezing by warming inside
Field Kiosks//fork lift capability////can bring into controlled environment
Field Kiosks//access////RFIs, model shots – printable for crew takeoff
Field Kiosks//capability////annotate drawings particular to contractors work & safety
Field Kiosks//capability////transmit corrections directly to engineer of records
Field Kiosks////cut down lag time
Field Kiosks//model viewing////help right away
Field Kiosks////engineer onsite//// motivated, no filter, highly responsive

- Negative

Field Kiosks////no color printing
Field Kiosks////requires training
Field Kiosks////workers would take home and sell
Field Kiosks////not ready for field use

Field Kiosks//controlled environment////better for commercial than industrial area

Field Kiosks//90% of work is outside////can freeze or overheat

Field Kiosks//IF affective////must have multiple kiosks onsite

Field Kiosks////limited availability of controlled environment

Heads-Up Display

- Positive

HUD//checking interfaces, layouts////great for QA & QC

HUD//capability////real-time access to video & picture communication

HUD//IF in turnaround situations, fast-paced jobs////beneficial

HUD////eliminates travel time, measure and converse out of office

HUD////saves time in the field

HUD////technology is already developed

- **Negative**

HUD////do not put in hands of craft

HUD////both engineer & construction must be readily available

HUD//may be low-energy////not intrinsically safe

HUD////signal must be available in field

Information Delivery Issues

- Communication Issues

Drawing Standards////not in job files

Issued Drawings//last minute access////issued when owner-company is ready
Issued Drawings//last minute access////engineering doesn't coordinate with construction
Issued Drawings////issued all at once – undesired
Drawing Errors////incorrectly-numbered tie points or line numbers
Drawing Errors////E&I is not represented well, only major components

- Paper Delivery Issues

Specifications//paper books////problematic
Specifications//printed copies////problematic

- Software Delivery Pros

Models//planning field routing////useful
IPIMS////speed up bill of materials and construction takeoff

- Software Delivery Cons

Standards////not issued in electronic work packages
3D Modeling////too expensive to purchase model-viewing software

<u>Interface Software</u>

- Positive

Software//IF access to specs, instructions exist////easy navigation
Software//IF full integration, no need for off-screen info exists////positive attribute
Software//IF weld mapping exists////positive attribute

Software//mobile app desire////HUD viewer on handheld via gps technology
Software//mobile app desire////help to identify shoes, blocks, material inventory check
Software//mobile app desire////reflect model to accurately evaluate installations
Software//mobile app desire////bill of materials available onsite
Software//accessibility of interface////must be two or three clicks
Software//mobile app desire////annotated & shared documentation
Communication Tracking//ability////track daily meetings
Communication Tracking//integrated in field (superintendent)////keeps craft properly informed
Automated Checks//capability////access to training records & qualifications
Automated Checks//capability////pop-ups for QA & QC
Automated Checks//capability////notifications for material & equip. availability
IPIMS//IF in construction////would solve issues, fantastic
IPIMS//give access to owner-company and contractors////valuable
IPIMS////provide latest revisions & re-issues
Field Updates//updating status, productivity////occur with mobile devices
3D Model////puts piping configurations into context
3D model////must identify field welds and line numbers
3D Model////better, faster, cheaper than 2D information format
Annotated Drawings//most critical aspect////location and elevation
Annotated Drawings//most critical aspect////line numbers
Mobile App - Bill of Materials Onsite//IF done with discipline////nice

- Negative

3D Model//perceived difference of deliverables than without 3D////non-existent

- Software Interface Choice

Software//Bluebeam or adobe////adobe
Software//switched from Navisworks////currently in Smartplan
Software//current use////Navisworks
Mobile Device Choice//IF it's a web-device////no preference of device type

Intrinsic Issues

Mobile Devices//due to safety////not used
Mobile Devices//due to safety delay////devalued
Mobile Devices//due to safety delay////not ready for a few years
Mobile Devices//on petro-chemical sites////not intrinsically safe
Mobile Devices////not allowed into work area
Mobile Devices//Tablets, smartphones////can use if low energy permit is used
Tablet//IF permitted & inner-company mandated////can use on project
Site Policy//deemed safe IF////frequency does not interfere with localized transmitters

Tablets

- **Positive**

Tablets//capability-barcode scanner////parts/assemblies
Tablets //capability-barcode scanner////assembly instruction videos, specifications
Tablets //capability////track labor hours
Tablets //capability////progress tracking
Tablets//capability////update revisions, drawings
Tablets//capability////general foreman use illustrations to give guidance
Tablets//accessibility////full integration of specs, instructions

Tablets//checklists, specs////good

Tablets//quick reference////desired by Foremen

Tablets//will require change in the industry////useful

Tablets//work packages////model shots available to thumb through

Tablets//possible distraction////eliminate by blocking games, media

Tablets//useful tool////time sheets, RFIs, drawings, quantity ledger, daily reports

Tablets////useful training tool

Tablets////eliminates need for two sided isometric drawings

Tablets//versus traditional paper format////better approach

Tablets//use for training and implementation////cannot go below gen. foreman

Tablets//possible distraction////foremen on project had access to all documents, no outside media

- **Negative**

Tablets////poor for drawings

Tablets////crafts sees no need

Tablets////small screen

Tablets////small screen, requires monitor

Tablets////small screen, require zooming and adjusting

Tablets////small screen, required zooming and turning

Tablets//often left in office////hassle to carry around

Tablets////require internet to access documents

Tablets//training////takes time

Tablets//training////would be struggle

Tablets////not as intuitive as they should be

Tablets//before going into industrial area////must satisfy environmental issues

- **Future Possibilities**

Tablets//automated updates////notify user when task is ready or complete

Tablets//automated updates////attach picture with completed tasks

Tablets//3D model////lock areas that have completed installations

Tablets//RFIs////foremen desire photo capability to send in problems

Tablets//scan-able technology////verify %complete sections of rack, piping – progress tracking

Need for Training

Installation Instructions//vs. conventional drawings, isos////concept not understood

3D Model Experience//craft workers////none

IDF Files Experience//craft workers////none

Two Sided Isometric Drawings//vs. standard isos////much easier to train

Two Sided Isometric Drawings////good training tool

Two Sided Isometric Drawings////better understanding of the drawing

Two Sided Isometric Drawings////a picture is work a thousand words

Mobile Devices////take time to train

Mobile Devices////there would be struggle

Mobile Devices// Tablets, Kiosks////trained management must relay to lower craft workers

- Generation Dependent Training

Older Generation////challenged to even complete timesheets

Non-Generation Dependent////surprising at who adapts to it

Younger Generation//visualization////needs a picture to understand drawing concepts

Younger Generation//Two Sided Isometric Drawings////less confusion

Various Issues Common Amongst Construction Technologies

Transient Employment////management not willing take accountability for work

Transient Employment////workers switch from company to company

Communication//materials////warehouse lacks tracking, accountability

Communication//challenges met////knowledge and upfront planning

BIM////management not willing to pay for engineering requirements

BIM//communication of cost savings////PMs not communicating with engineers

Work Packages//shipped as a whole civil package, not requested portion////rough

F. Focus Group Presentation Slides

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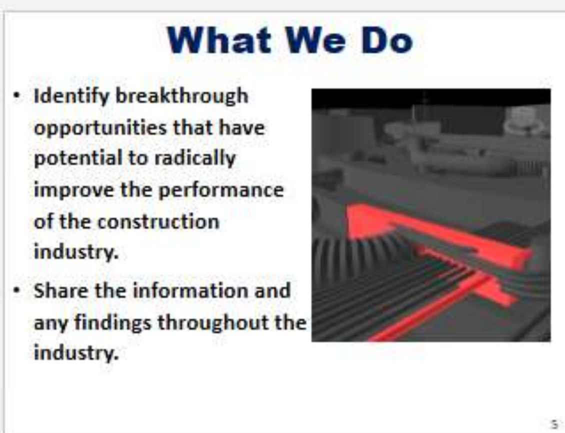

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WE NEED:

Breakthrough: a *leap*—an opportunity for a step change improvement in the industry!

Includes a very broad spectrum of:

- Practices
- Mindset/culture
- Truly effective implementation
- Technology
- Information
- Materials,
- Tools,
- People
- Processes

7

Innovative Installation Instructions

OUR MISSION TODAY:

Identify more innovative installation instructions and information to craft to improve performance

OBJECTIVE:

1. **Easy to understand and follow**
2. **Improve craft productivity**
3. **Keep the foremen with the crew**

8

Rethinking Craft Needs

Deliverables

Automation

Fabrication & Erection ISOs

Advanced Work Packaging

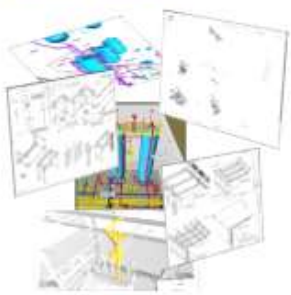
Installation Work Packaging

Youtube videos How To's

Leveraging 3D Models

Communication & Control

Mobil IT at the WORKSITE
NOT in the Construction Shack



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CII RT-327 PREMISE

Get the right information
to the right person
in the right format
at the right time
to support
a decision or process.

10

Typical Barriers

- Industry Standards & Perceptions – *Dry Wall 1916 (10 to 1)*
- Outdated Codes– *Name Plate Rubbings*
- Outdated Procedures -
- Organization Charts
  - Department Managers
  - Work Split – Divisions (not my job!)
  - Departmental Segregation (Turf)
- Misaligned Rewards/Recognition
- Profit & Loss Responsibilities – pushing costs downstream
- Silos of Excellence
- That's NOT the Way We Do IT!!!

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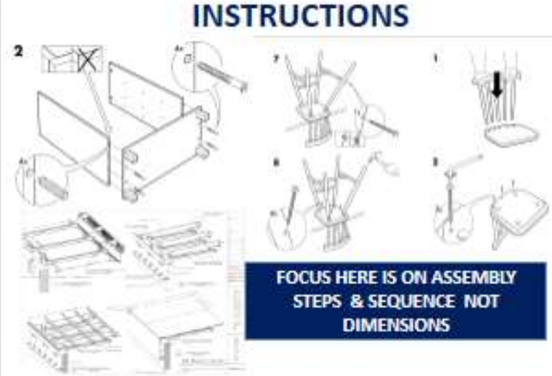
EXAMPLES of INSTALLATION INSTRUCTIONS



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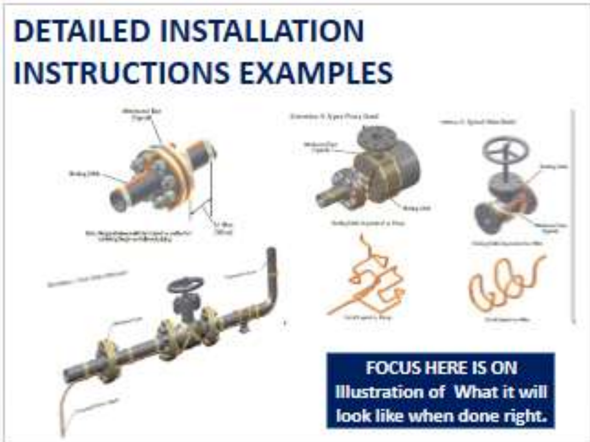

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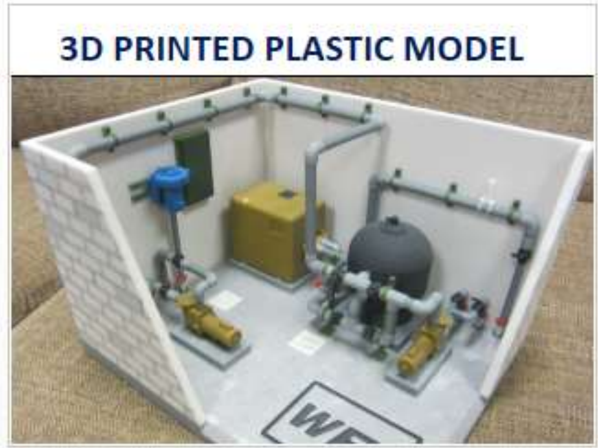

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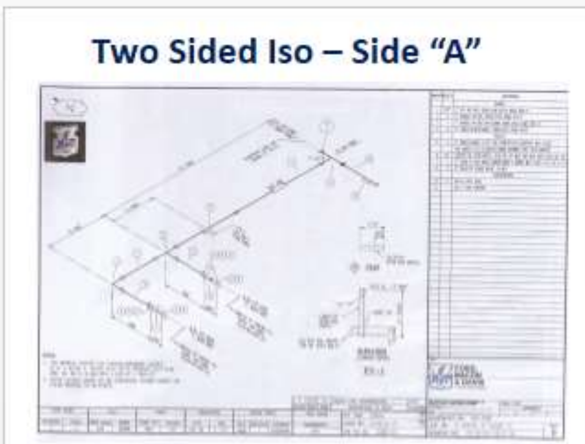

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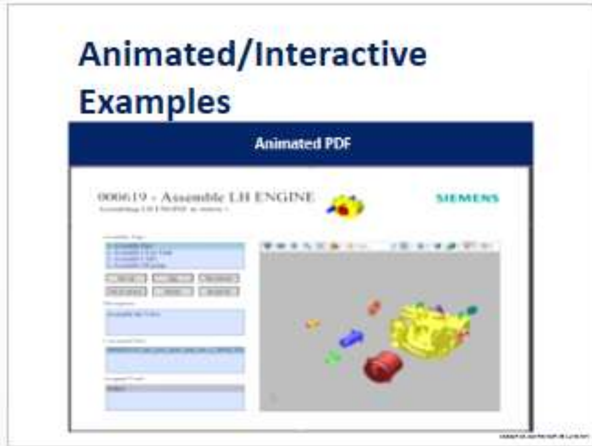

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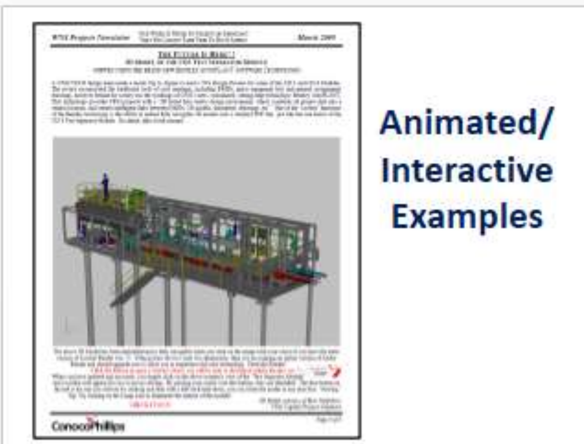

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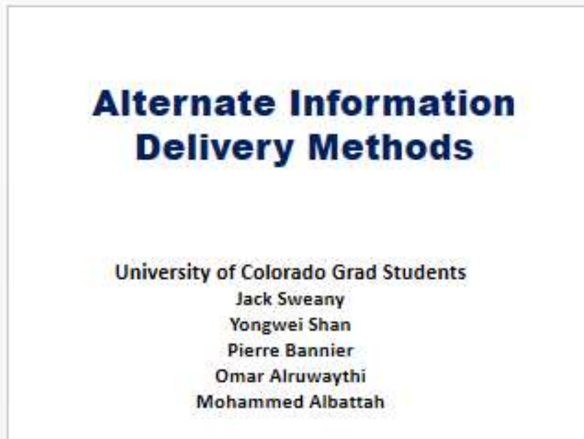

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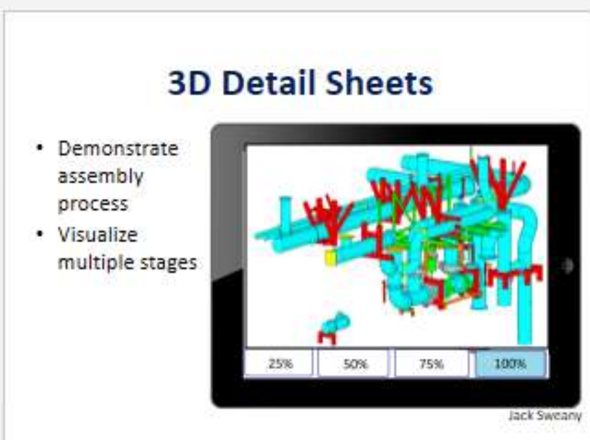

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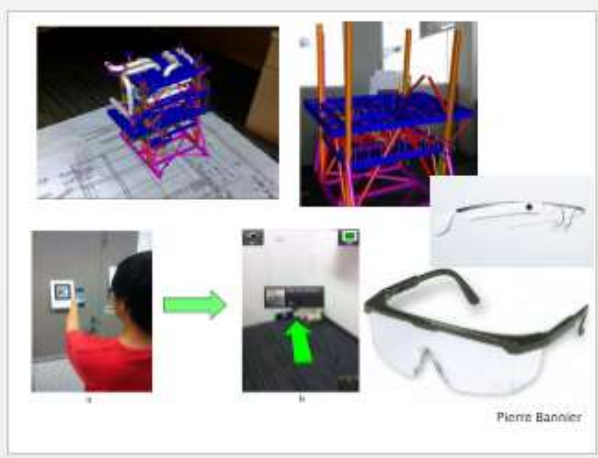

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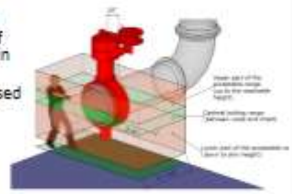
Means & Methods Modeling –

- How to Apply it:
  - Built on BIM model (Bentley/Rivet).
  - Do detailed Animation video showing step by step for each trade separately (same idea of Discrete Event Modeling, but in 3D).
  - It could be multiple videos based on weekly bases (from work packaging), and we can add status visualization to it.
  - Add vocal media based on worker language (i.e. English, Spanish … etc.).



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Mobile IT At The Jobsite

- Instant access to specs, documents, emails, RFI's, Material Status, etc.
- Take pictures of issues/problems and send to office for help
- Forms – completion, QA/QC, Non-Conformance, Changes, etc
- Primarily used by the foreman
- Can be a tablet with camera

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Jobsite Field Kiosk

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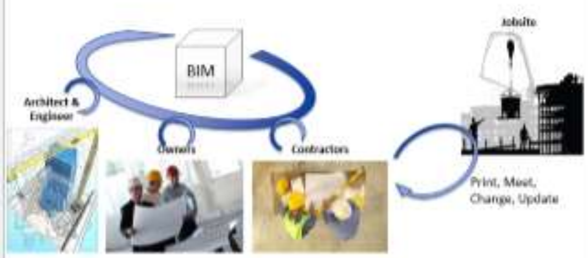
CAPABILITIES of SITE KIOSK



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BENEFITS of SITE KIOSK

- Eliminate Time between Jobsite and Office
- Access to all Documents/drawings/Files
- View Drawings FULL SIZE at work site
- Annotate & Print Instructions for Craft
- Access RFI's – Create RFI's
- Ensure LATEST Revision is being used
- View Vendor Information
- 3D Model Views - Predefined
- Check the Weather reports

30

DISCUSSION and IDEA COLLECTION

We need YOUR thoughts and ideas on deliverables or instructions at the job site that will improve productivity?

1. To understand and communicate to the foreman for the work to be accomplished?
2. To understand and communicate from the foreman to the craft

31

Discussion: Current Practices

How is the information (data and graphics) you need to do your job provided on a daily basis?

32

Discussion:

What are your ideas for improving installation and productivity at the jobsite?

33

- Identify innovate ways to communicate information
- Provide Pilot for Proof of Concepts
- Collect craft/foreman feedback on value
- Capture Metrics to prove productivity improvement
- Develop an Implementation (How-to) Guide to help others blast through implementation barriers.

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G. Protocol

University of Colorado
Boulder

TITLE: Tangible and Adaptive Engineering Instructions for Developing Societies

PROTOCOL VERSION DATE: October 22, 2014October 22, 2014

VERSION: 3.0

PRINCIPAL INVESTIGATOR (PI):

Name: John Sweany

Address: 1111 Engineering Drive ECCE 153 UCB 428, Boulder, CO 80309

Telephone: 773-663-5652

Email**: john.sweany@colorado.edu**

KEY PERSONNEL

Name: Dr. Paul Goodrum

Role in project: Faculty Advisor

1. OBJECTIVES

- Describe the purpose of the study, including identification of specific primary objectives/hypotheses. Describe secondary objectives/hypotheses, if there are any.

This study is a proof of concept on the effectiveness of tangible engineering instructions compared to 3D computer instructions and traditional 2D plans. The main hypothesis is that tangible engineering instructions are more accurate, efficient, and less cognitively demanding especially for people with low literacy and no experience in engineering drawings.

2. BACKGROUND AND SIGNIFICANCE

The construction industry is a major contributor to the health of the United States economy. The industry's annual spending is consistently over $800 billion dollars, $893 billion in 2012 (United States Cencus Bureau, 2013). The 2012 spending levels accounted for 3.6% of the U.S. GDP making construction the 8th largest economic sector analyzed by the Bureau of Economic Analysis (Bureau of Economic Analysis, NAICS Data, 2012). The construction industry's performance is critical to the success of the country's economy and crucial to the nearly 6 million individuals it employs (Bureau of Labor Statistics, 2013). Oglesby et al. (1989) divides construction performance into four categories: productivity, safety, timeliness, and quality. Construction productivity has historically lagged behind the manufacturing industry making it a continuous focus of academic studies.

A construction project's productivity ultimately relies on the craft worker practices. They need to be supplied with the proper training, tools, materials, and information to effectively complete their job. Many craft workers feel that information delivery, and further design or construction drawing management, is a significant factor to efficiently performing their job (Construction Industry Institute, 2006; Dai et al., 2009a; Dai et al., 2009b; Mourgues and Fischer, 2008; Rojas, 2008; and Schwartzkopf, 2004). Information delivery has the ability to positively or negatively impact numerous aspects of a project. Rojas (2008) and Schwartzkopf (2004) discuss inefficiencies from design drawings ultimately leading to increased rework on the project. Supervisors and foremen then become focused on correcting engineering errors and rework instead of planning future work and focusing on crew performance.

The need for successful information delivery systems is even more prevalent in developing communities. Serpell and Ferrada (2007) determined that the lack of construction education and formal training in developing countries results in a lack of professionalism in workplace decision-making. The lack of education makes interpreting engineering information a challenge for craft workers. Workers become frustrated and cannot cope with new technologies that are being made available (Datta, 2010). Any new information delivery system must have a low cognitive demand to be easily implemented and accepted by the craft workers. Advances in three dimensional modeling and printing provide opportunities to improve the traditional methods of supplying craft workers with the information they need to complete a job.

3. PRELIMINARY STUDIES

A similar study "Performance of 3D Printed Models as a Means for Spatial Engineering Information Visualization" was performed by Dadi et al. (2013). The study design required subjects to assemble a model column and beam building frame. Subjects were given the assembly information in 2D plans, 3D computer instructions (CAD), or a 3D tangible model. The test subjects were University of Kentucky students and construction professionals from Lexington, KY. The researcher hypothesized that the college students would be more comfortable using new technology such as CAD and 3D printed models, and the construction professionals would be more comfortable with the 2D plans that they use daily at work. The assembly was measured for time to completion, a five minute rating, and the NASA Task Loading Index (NASA-TLX). The five minute rating is used to determine how much time was spent on direct work, assembling the model, and rework, fixing errors. The NASA-TLX is a measurement method used by NASA to assess the mental demand of an activity. This measurement tool provided minimal results. The study found that the 3D tangible instructions lead to the quickest completion time, highest direct work rate, lowest rework rate, and the lowest mental workload. The 2D plans were found to be second with the 3D computer model in third. This study established the baseline that 3D tangible engineering instructions are a promising alternative to 2D plans and 3D computer models. No results were listed regarding the hypothesis on the subjects groups' preferred information medium.

4. RESEARCH STUDY DESIGN

Two differing groups will be included in this study. Once consists of students, both University of Colorado Boulder students and high school students at engineering career fair days. The second is actual construction and craft workers. Workers in developing communities have two identifying characteristics: low-literacy and no experience in engineering drawings. Thus, we will adopt inclusion/exclusion criteria to approximate these two characteristics. For low-literacy, students will be native English speakers and monolingual. They will be tested with engineering instructions written in a foreign language (e.g., Russian), which simulates a low-literacy condition. For no engineering experience, students will be non-engineering majors. The second group of construction professionals will be an exact simulation of our other target group of construction workers in the U.S.

The study will use a between-subject design with 30 subjects in each group (N=90). In the first group, subjects will be given engineering instructions in traditional 2D plans (text and drawings). In the second group, subjects will be given 3D computer instructions (CAD). In the experimental group, subjects will be given tangible engineering instructions. Subjects in all groups will be asked to assemble a miniature shelter following the given instruction. Subjects will be provided with a construction kit consisting of necessary parts to assemble the shelter. The shelter being modeled was originally designed and used for post-disaster reconstruction after Katrina.

We will take quantitative and qualitative observations on efficiency, accuracy, and cognitive ability. Efficiency will be measured as the time each subject takes to complete the assembly and by typical construction productivity analyses techniques, including work sampling and five-minute ratings (Oglesby et al 1988). Each subject is given unlimited amount of time, but we do not anticipate the assembly will take more than 1.5 hours. Accuracy will be measured as the number of errors in the final assembly.

Cognitive ability will be measured using a card rotation test. Qualitative data will be gathered through post-assembly questionnaires.

5. ABOUT THE SUBJECTS

Subject Population(s)	*Number to be enrolled in each group*
CU Students	**40**
High School Students	**15**
Construction Workers	**45**

With a subject population size of 100, we expect that a minimum of 90 will be able to complete the study. Each type of engineering instructions (2D plans, 3D BIM model, and physical model) will have the desired 30 subjects. The population will be 18-30 year old University of Colorado students, 17-19 year old high school students, and 18+ year old construction workers. The gender and ethnic distribution will not be monitored or controlled. Inclusion criteria include being a native English speaker and monolingual. The inclusion criteria serve to simulate the low-literacy found in developing communities as the engineering instructions will be written in a foreign language (e.g. Russian). Students with varying levels of engineering background and experience will be recruited. This will serve to simulate the difference between formally trained craft workers of a developed community and poorly trained craft workers of developing communities. Testing U.S. construction workers will allow us to compare the two difference between the two groups.

6. VULNERABLE POPULATIONS

No vulnerable populations will be considered for this study.

7. RECRUITMENT METHODS

List recruitment methods/materials and attach a copy of each in eRA
1. Post recruitment flyer around the University of Colorado Boulder campus
2. Ask Engineering Professors to forward recruitment email
3. Read a recruitment script in Engineering classes
4. Ask Industry Professionals to recruit employees.

The study population will be drawn from the University of Colorado Boulder student body. Flyers will be posted on campus billboards with contact information for general recruitment. Additionally, an email will be sent to colleagues of the faculty advisor asking them if they would be willing to forward it to students in their classes that may be interested in participating. Finally with the permission of University of Colorado Faculty, a script will be read before their classes begin to recruit subjects. The classes will not include any courses taught by the Faculty Adviser. The PI will conduct all recruitment. The materials to be seen are the flyer, email, and class recruitment script (all attached in eRA).

Contacts with industry professional will also help recruit subjects. Industry contacts of the Faculty Adviser will been contacted to help recruit students. They will be send the same flyers, email, and verbal scripts. They have the ability to recruit their own employees, but have been instructed to inform individuals that their willingness to participate and subsequent performance within the study have no outcome on their work. These industry contacts also hold engineering fair days to help educate and motivate student to enter engineering professions. They will pass along the same recruitment material to high school teacher to inform students they have the option to participate in the study. Again students' willingness to participate and subsequent performance within the study have no outcome on their school work.

8. COMPENSATION

Participants are not given compensation for this study.

9. CONSENT PROCESS

Consent for University of Colorado students and all construction workers will be obtained at the start of the subject's visit in ECCE 1B47 where the tasks will be performed. Subjects will be given a copy of form "HRP-502 – Consent" as approved by the IRB prior to the beginning of the test or recording. The consent form outlines the research statement, any risks, benefits, alternatives, confidentiality, and compensation for the subjects and contact information for the PI.

Consent for high school students will be obtained prior to the engineering fair day. The PI will send consent forms to the industry professionals hosting the fair. They will intern give the consent form to high school teacher and then the students' parents. All high school students will be required to have their parents sign the updated consent form written for underage participants. Only upon receiving and completing the paper copy of the consent for with the parent's, student's, and PI's signature will the student be allowed to partake in the study. Parents, teachers, and industry professionals will have the opportunity to call and email the PI with any questions about the study. On the day of the fair students, will also have the ability to ask any questions of the PI before and during the study.

The subjects will not be coerced or under undue influence to sign the informed consent form. If a subject decides against signing the informed consent form, they will be immediately removed from the test sample and thanked for their interest in the study. All subjects will be capable of understanding the guidelines put forth by the informed consent form and will be given every opportunity to ask questions and understand the entirety of their participation in the study.

10. PROCESS TO DOCUMENT CONSENT IN WRITING

Subjects will sign and date a copy of the form "HRP-502 – Consent" with the age appropriate signatory page as approved by the IRB to document their consent in writing.

11. PROCEDURES

Name of instrument/tool/procedure	Purpose (i.e. what data is being collected?	Time to Complete
Demographics Questionnaire	Subject background information	3 minutes
Card Rotation Test	Cognitive ability	7 minutes
Structure Assembly	Effect of differing instruction types	30 minutes
Stop Watch	Assembly time	N/A
Video Camera	Accuracy and efficiency of assembly	N/A
Post Assembly Questionnaire	Subject opinions	5 minutes

Visit #	Procedures/Tools	Location	How much time the visit will take
Visit 1	• Demographics Questionnaire • Card Rotation Test • Structure Assembly • Post Assembly Interview		3 minutes 7 minutes 30 minutes 5 minutes

Subjects will be asked to complete a demographics questionnaire which will collect their age, gender, years of education, highest education level, current occupation, years of engineering work experience, and type of engineering work experience. Subjects will be given a card rotation test which examines their two and three dimensional spatial orientation. Next, the subject will be asked to assemble a simple structure using a scale model construction kit. The assembly instructions will be given to the subject in a 2D drawing set, a 3D CAD model, or a physical model. A stop watch will be used to measure the time is takes to complete the assembly task. The assembly will be video recorded so that the footage can be analyzed for indices of direct work, indirect work, rework, and errors. The video recording is mandatory for the study.

After the assembly task, the subject will be asked to fill out a post assembly questionnaire which will record their preferred type of engineering instructions. The subjects will only be brought in for one visit averaging 30 minutes based on existing participants. Our initial estimates of 1.5-2 hours was overly conservative to make sure subjects reserved enough time to complete the experiment. The largest time savings has resulted from subjects completing the scale assemblies much faster than expected.

The demographic sheet will be useful in characterizing the performance of different sample sets. For instance, what is the effect of years of engineering experience on an individual's ability to interpret spatial information from a certain format? The card rotation test will allow the PI to examine any correlations between spatial ability and performance on the model assembly. The post-test questionnaires will identify the level of mental workload required to complete the task and individual preferences for the information display formats. This information will tell the researchers which information delivery format requires the most loading to complete and also if one format is preferred over another. The videotape will be necessary to identify what percent of time, during the task completion, was spent actually completing the structure versus waiting or making and correcting errors. The researchers will use that information to identify which information delivery format results in the least amount of errors while interpreting the information. All of the information will be considered together to ultimately draw conclusions from the study.

The location will change for each population, but the environment will be similar. University of Colorado students will take part in the study in ECCE 1B47, a basic class room. The high school students will conduct the experiment in a standard conference room at the location of the engineering fair. The exact location is still being decided upon, but students will already be planning to visit the fair. Thus the experiment will not require any additional planning or transportation on the student's part. For construction workers, the PI will travel to the job site where workers are normally reporting to. They will also be held in conference rooms on site. Dates for all test will be determined by the availability of subjects and industry contacts to avoid inconveniencing research subjects.

12. SPECIMEN MANAGEMENT

No specimens are used in this study.

13. DATA MANAGEMENT

The materials and records that will be kept from the study include the informed consent sheet, a general demographic sheet, a card rotation test, videotape from the assembly task, and the post assembly questionnaire sheet.

The paper based data (informed consent, demographic sheet, card rotation test, and questionnaire) will be stored in a locked drawer, in a locked office of the principle investigator for at least two years. The office is 1111 Engineering Drive, ECCE 153, Boulder, CO 80309. These documents will be transcribed to electronic files by the principal investigator. The electronic files will be stored on a University owned desktop in the locked office of the investigator. The computer account has a password and automatic log off. No unauthorized person will be allowed to access the office, the drawer, or the computer account. Video recordings of the assembly task will be saved onto the same computer immediately after each subject's visit and deleted from the video recorder's memory card. Once the two year timeframe passes, the study materials will be moved to the locked office of the faculty advisor.

All data will have a random number identifier that is consistent across the data for an individual. A Personal Identifying Number (PIN) will be assigned to the study participants and their name will only be on the informed consent form.

When video recording the assembly task, care will be taken to ensure that only necessary portions of the task be videotaped (i.e. the actual task completion, not the subject).

14. WITHDRAWAL OF PARTICIPANTS

Subjects will be withdrawn from the study if they are unable to follow the direction of the study procedures or are unable to complete the structure assembly.

If a subject withdraws from the research before completing the structure assembly task, their collected data will be removed from the study and deleted. If the subject has completed the structure assembly task but withdraws before completing the post assembly questionnaire, the data that has been collected to that point will be included in the study. All subjects that choose to withdraw from the research will be thanked for their interest and to explain their reasons for withdrawing. Replacement subjects, if needed to reach the desired sample size, will be recruited through the same methods.

15. RISKS TO PARTICIPANTS

To the best of our knowledge, the tasks the subjects will be performing have no more risk of harm than they would experience in everyday life. The only foreseen risk is that collected information on paper and portable video recorder will be lost or stolen revealing a subject’s participation in the study.

16. MANAGEMENT OF RISKS

As in section XIII Data Management, all collected information will be coded with Personal Identification Numbers (PIN) to remove the subjects’ names from research material. The subjects name will only be on the informed consent form. Additionally, portable information (paper and video camera) will be in the possession of the PI during the subjects’ visits. It will be taken and secured in the PI’s office immediately after each visit.

17. POTENTIAL BENEFITS

There are no direct benefits to the subjects. The potential benefits are to assisting in a contribution to the body of knowledge of the civil engineering and cognitive psychology research fields. The knowledge gained will be critical to understanding how engineering information can be presented for spatial understanding, which will provide unique and insightful findings to the academic and industry communities.

18. PROVISIONS TO MONITOR THE DATA FOR THE SAFETY OF PARTICIPANTS

The data will be reviewed weekly by the PI to ensure that no unauthorized personnel have accessed the secured information.

19. PROVISIONS TO PROTECT THE PRIVACY INTERESTS OF PARTICIPANTS

The data will have a random number identifier that is consistent across the data for an individual. A Personal Identifying Number (PIN) will be assigned to the study participants. Video recording will be focused on the assembly task and care will be taken to exclude the subject from the camera's view as much as possible.

20. MEDICAL CARE AND COMPENSATION FOR INJURY

This study does not involve more than minimal risk.

21. COST TO PARTICIPANTS

There are no costs associated with taking part in the study, other than the subjects' time. The participants will be CU students who will already have to be on campus the day of the test for other classes or meetings.

22. DRUG ADMINISTRATION

No drugs will be administered in this study.

23. INVESTIGATIONAL DEVICES

No investigational devises are used in this study.

24. MULTI-SITE STUDIES

This study will only take place at the University of Colorado Boulder.

25. SHARING OF RESULTS WITH PARTICIPANTS

There are no plans to share the results of the study with the participants.

H. SPSS Outputs

H1. Isometric v. 2-Sided Isometric

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
Direct_Work	Between Groups	.216	2	.108	5.740	.005
	Within Groups	1.015	54	.019		
	Total	1.230	56			
Indirect_Work	Between Groups	.168	2	.084	5.314	.008
	Within Groups	.852	54	.016		
	Total	1.019	56			
Rework	Between Groups	.003	2	.002	1.039	.361
	Within Groups	.088	54	.002		
	Total	.092	56			
Rework_Instance	Between Groups	2.603	2	1.302	.748	.478
	Within Groups	93.958	54	1.740		
	Total	96.561	56			
No_Errors	Between Groups	2.649	2	1.325	2.939	.061
	Within Groups	24.333	54	.451		
	Total	26.982	56			
Perc_Complete	Between Groups	.002	2	.001	.071	.931
	Within Groups	.646	54	.012		
	Total	.648	56			
Tot_Time	Between Groups	30807.550	2	15403.775	.205	.815
	Within Groups	4060959.292	54	75202.950		
	Total	4091766.842	56			

H2. Isometric v. 3D Physical Model

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
Direct_Work	Between Groups	.187	1	.187	7.681	.009
	Within Groups	.755	31	.024		
	Total	.942	32			
Indirect_Work	Between Groups	.140	1	.140	7.574	.010
	Within Groups	.574	31	.019		
	Total	.714	32			
Rework	Between Groups	.003	1	.003	1.967	.171
	Within Groups	.053	31	.002		
	Total	.057	32			
Rework_Instance	Between Groups	.102	1	.102	.045	.833
	Within Groups	69.958	31	2.257		
	Total	70.061	32			
No_Errors	Between Groups	2.227	1	2.227	4.361	.045
	Within Groups	15.833	31	.511		
	Total	18.061	32			
Perc_Complete	Between Groups	.002	1	.002	.144	.707
	Within Groups	.366	31	.012		
	Total	.368	32			
Tot_Time	Between Groups	14587.375	1	14587.375	.241	.627
	Within Groups	1874657.958	31	60472.837		
	Total	1889245.333	32			

H3. Card Rotation v. Information Form

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
Direct_Work	Between Groups	.502	20	.025	1.242	.279
	Within Groups	.728	36	.020		
	Total	1.230	56			
Indirect_Work	Between Groups	.451	20	.023	1.431	.171
	Within Groups	.568	36	.016		
	Total	1.019	56			
Rework	Between Groups	.025	20	.001	.675	.824
	Within Groups	.067	36	.002		
	Total	.092	56			
Rework_Instance	Between Groups	48.389	20	2.419	1.808	.060
	Within Groups	48.172	36	1.338		
	Total	96.561	56			
No_Errors	Between Groups	12.894	20	.645	1.647	.094
	Within Groups	14.089	36	.391		
	Total	26.982	56			
Perc_Complete	Between Groups	.163	20	.008	.603	.885
	Within Groups	.485	36	.013		
	Total	.648	56			
Tot_Time	Between Groups	1309113.787	20	65455.689	.847	.647
	Within Groups	2782653.056	36	77295.918		
	Total	4091766.842	56			

H4. Cube Rotation v. Information Format

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
Direct_Work	Between Groups	.420	16	.026	1.295	.248
	Within Groups	.810	40	.020		
	Total	1.230	56			
Indirect_Work	Between Groups	.308	16	.019	1.080	.404
	Within Groups	.712	40	.018		
	Total	1.019	56			
Rework	Between Groups	.024	16	.002	.898	.576
	Within Groups	.067	40	.002		
	Total	.092	56			
Rework_Instance	Between Groups	24.895	16	1.556	.868	.607
	Within Groups	71.667	40	1.792		
	Total	96.561	56			
No_Errors	Between Groups	7.649	16	.478	.989	.486
	Within Groups	19.333	40	.483		
	Total	26.982	56			
Perc_Complete	Between Groups	.144	16	.009	.714	.764
	Within Groups	.504	40	.013		
	Total	.648	56			
Tot_Time	Between Groups	1505394.092	16	94087.131	1.455	.166
	Within Groups	2586372.750	40	64659.319		
	Total	4091766.842	56			

H5. Age v. Information Format

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
Direct_Work	Between Groups	.562	29	.019	.784	.740
	Within Groups	.668	27	.025		
	Total	1.230	56			
Indirect_Work	Between Groups	.494	29	.017	.877	.636
	Within Groups	.525	27	.019		
	Total	1.019	56			
Rework	Between Groups	.043	29	.001	.809	.713
	Within Groups	.049	27	.002		
	Total	.092	56			
Rework_Instance	Between Groups	44.645	29	1.539	.801	.722
	Within Groups	51.917	27	1.923		
	Total	96.561	56			
No_Errors	Between Groups	14.149	29	.488	1.026	.474
	Within Groups	12.833	27	.475		
	Total	26.982	56			
Perc_Complete	Between Groups	.473	29	.016	2.508	.009
	Within Groups	.175	27	.006		
	Total	.648	56			
Tot_Time	Between Groups	1727146.009	29	59556.759	.680	.845
	Within Groups	2364620.833	27	87578.549		
	Total	4091766.842	56			

H6. Years of Experience v. Information Format

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
Direct_Work	Between Groups	.768	25	.031	1.974	.040
	Within Groups	.452	29	.016		
	Total	1.220	54			
Indirect_Work	Between Groups	.564	25	.023	1.549	.128
	Within Groups	.422	29	.015		
	Total	.986	54			
Rework	Between Groups	.047	25	.002	1.523	.138
	Within Groups	.036	29	.001		
	Total	.083	54			
Rework_Instance	Between Groups	42.915	25	1.717	1.120	.382
	Within Groups	44.467	29	1.533		
	Total	87.382	54			
No_Errors	Between Groups	17.061	25	.682	2.047	.032
	Within Groups	9.667	29	.333		
	Total	26.727	54			
Perc_Complete	Between Groups	.174	25	.007	.429	.983
	Within Groups	.471	29	.016		
	Total	.645	54			
Tot_Time	Between Groups	950606.932	25	38024.277	.354	.995
	Within Groups	3116034.050	29	107449.450		
	Total	4066640.982	54			