Lost in Translation - Using Technology to Bridge Communication Issues in Construction: How Concrete Formwork for Unique Situations Can Learn from Prefabrication and Manufacturing in Other Industries

Morocco McClay Branting

A thesis
Submitted in partial fulfillment of the
requirements for the degree of

Master of Architecture

University of Washington
2024

Committee:
Tyler Sprague
Rob Corser

Program Authorized to Offer Degree:
Architecture

University of Washington

Abstract

Lost in Translation: Using Technology to Bridge Communication Issues in Construction - How Concrete Formwork for Unique Situations Can Learn from Prefabrication and Manufacturing in Other Industries

Morocco McClay Branting

Chair of the Supervisory Committee:
Dr. Tyler Sprague
Department of Architecture

The evolution of design software in recent decades has enabled the realization of increasingly complex, high performance architectural works. It has also highlighted a growing divide between the design and construction sides of the industry as traditional 2D drawings are struggling to keep pace with these changes. As the industry moves to integrate prefabrication and digital fabrication practices at scale, opportunities emerge to combine the two into digital prefabrication. Positioning this as the new standard approach, this thesis looks to alternative visual communication strategies, such as augmented reality or assembly, as ways to communicate assembly in construction. A series of assembly trials were performed to determine the strengths and weaknesses of these means of communication. Results showed high enthusiasm and interest from the carpenters, regarding trying new methods and having the opportunity to critique and collaborate on their development. The alternate assembly instructions also showed over 33% reductions in elapsed assembly times, on average. The results highlight the importance of utilizing all methods in tandem to communicate effectively with the broadest audience.

Acknowledgements

This thesis would not have been a success without the many contributors who provided ideas, critique, experience, and overall assistance in carrying out this ambitious project. I would like to thank the following individuals for helping with this project:

Firstly, Dr. Tyler Sprague, my thesis chair, and Rob Corser, my committee, for the great discussions over the past nine months as we worked through the many theoretical and technical aspects of this project. I am greatly appreciative of the time these individuals devoted to this project, despite having their own academic responsibilities at the University.

My industry partners from Turner Construction, without whom much of the project could not have been realized. In particular, Josh Lohr, Nathan Brown, and Sean Beatty provided incredible support for the project, from regular reviews and discussions to getting the assembly study organized. The lead carpenter, Tim Veit not only provided great feedback, but also produced much of the formwork kits for the assembly tests. Renzo di Furia from RDF consulting also provided great insight on the project. Lastly, a big thank you to the carpenter and surveyor teams who participated in the assembly trials, without whom there would be no results to evaluate.

Special thanks to my partner, Sarah Green, for supporting me through this journey and editing this paper, and also to my parents Jason Branting and Holly Bloom for their support and upbringing; they raised me to be the determined individual I am, and without that I might not have reached this height in education.

In addition to my committee, there were several other voices from the University of Washington. Teri Thomson Randall, the ARC Program Director, and Renée Cheng, Dean of the College of Built Environments, coordinated the Applied Research Consortium portion of this project and provided quarterly reviews and feedback which were invaluable to honing the narrative and focus of this project. During the mid-review presentations, Professors Jeffrey Ochsner, Louisa Iarocci, and Rob Peña provided excellent critique that refined the project as a presentation and as a thesis paper.

TABLE OF CONTENTS

1.0 Introduction
    1.1 Research Objectives
        1.1.1 Research Questions and Goals
    1.2 Scope
    1.3 Definitions
2.0 Literature Review
    2.1 A Selection of Communication Issues Arising from Current Practices
        2.1.1 Novel Issues Arising from Concrete Work In-Situ
    2.2 Potential Solutions from Other Industries and Emergent Practices
        2.2.1 Automated Digital Prefabrication for Human-Centric Construction
        2.2.2 Drawings to Communicate Assembly in Other Industries
        2.2.3 Extended Reality Overlays to Communicate Assembly and Form
            2.2.3.1 Synchronizing Digital and Physical Space
    2.3 Gaps in Existing Literature for Further Research
3.0 Methodology
    3.1 Participant Selection
    3.2 Assembly Instruction Style Selection and Development
    3.3 Survey Format
    3.4 Assembly Trial Format
    3.5 Why Concrete Formwork
    3.6 Formwork Models
    3.7 Impromptu Alterations to Methodology and Challenges
4.0 Results
    4.1 Analysis
    4.2 Evaluating the Repetition-Bias Mitigation Strategies
    4.3 Smaller Trends Observed
5.0 Discussion
    5.1 Strengths and Weaknesses of the Explored Visual Communication Methods

5.2 Leveraging Traditional Practices and Human Knowledge
5.3 The Future of Digital Prefabrication in Construction
5.4 Additional Thoughts and Comments Observed During Thesis Defense
6.0 Conclusion
7.0 Bibliography

1.0 INTRODUCTION

Physical drawings have long been the primary method of conveying design information from office to field, from designers to builders. Although the rapid evolution of Computer-Aided Design and Drafting (CADD), Building Information Modeling (BIM), and parametric software have revolutionized portions of the industry, these developments have done little to change the industry's standard communication method, which continues to be the 2D drawing set. This may be in part borne from a respect for tradition, but it can also be argued that these software suites vary so greatly in technical function and application that holding the drawing set as the common baseline may still be the best practice to ensure design and construction information is translated into a format that is widely understood, culturally and legally.

Although these programs have not yet resulted in a major shift in this communication standard, they have become deeply integrated into the industry. These programs can shape and refine the overall form and individual architectural elements alike, resulting in a more complete 3D representation of the proposed design than previously possible (Deutsch 2011). While the design and construction industries share many software suites such as BIM to incorporate product data, scheduling, and material quantities among other things, many applications are heavily weighted to the design industry with little exploration or implementation in construction. As a result, the design becomes increasingly responsive to certain aspects of the project while becoming increasingly distant from the reality of its construction. This is not to say the design is purposefully irresponsible to the construction side of the industry, rather that the design side of the industry is capitalizing on the strengths of current digital technologies while the construction side is not, at least to the same extent.

This technological communication gap highlights how the designs we are capable of creating and the means we take to convey that information are diverging, as the former evolves rapidly and the latter is held in stasis. Higher quality design tools can produce building models that achieve higher performance metrics and a higher level of expectation for the builder. However, without adopting and applying these tools actively to *construction*, achieving those targets becomes increasingly labor intensive and costly. This communication gap is linked to

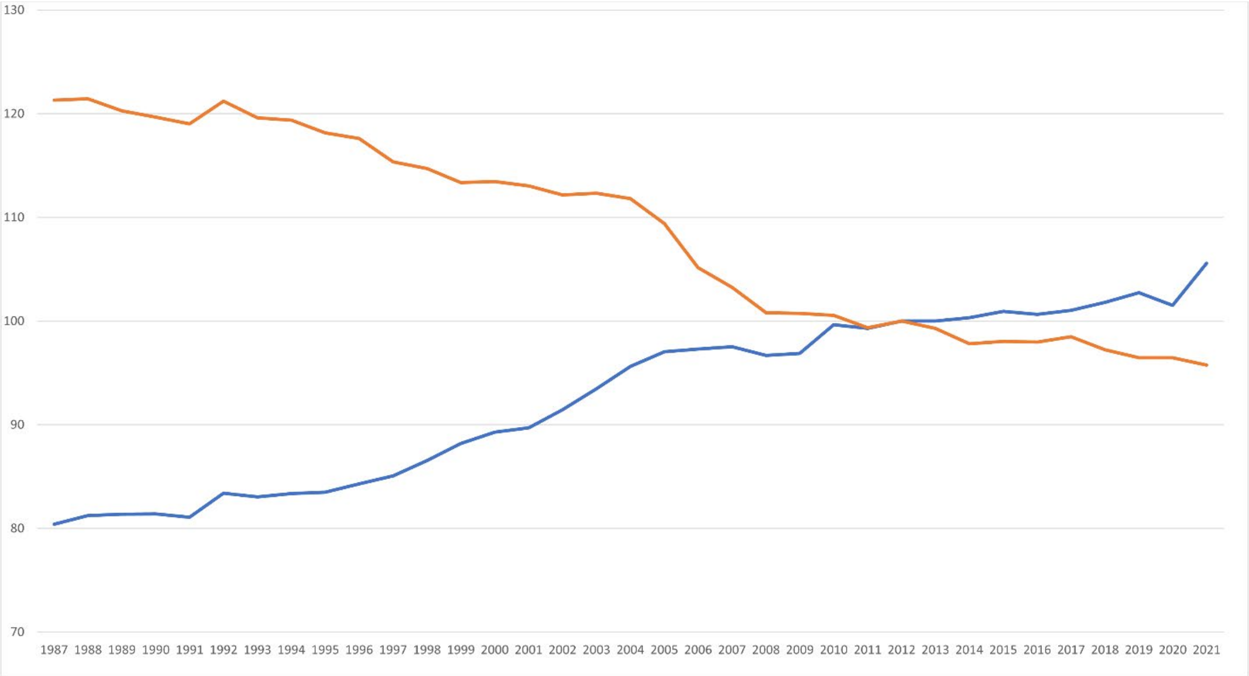


Figure 1: Total Factor Productivity data plotted for non-farm industry (blue) and construction (orange). Index 100 = 2012. Data source: Bureau of Labor Statistics

decreasing efficiency during construction, as illustrated by the total factor productivity data collected by the Bureau of Labor Statistics (BLS, FRED 2021). While it is likely that this negative trend is impacted by many factors, longer project schedules and cost increases resulting from additional time spent reviewing confusing 2D representations of complex designs could have a substantial impact. The issue is then two-fold; not only are we building to continuously higher design expectations in form and performance among other metrics, but we are trying to achieve these forward-thinking designs utilizing communication and construction methods of the past. One factor of these inefficiencies arises from the scale inherent in constructing the built environment, which effectively requires a considerable portion of the work to be performed in-situ. In the case of construction there are then two possible options: to take work into the factory (prefabrication) or to take the factory into the field (robotic automation and 3D printing) (Buchli et al 2018).

The 21st century has seen a number of advancements in prefabrication that have brought the system into the mainstream as a “new” solution to the productivity problem. While recent innovations such as modular mass timber elements do make the approach more viable, it is disingenuous to consider prefabrication an emergent solution; the technique has been used for centuries, dating back to 17th century colonial housing production as prefabricated kit homes (Dougherty 2018). Prefabrication has numerous advantages for companies and for workers, such as minimizing weather impacts or regularizing work location and schedule. The process also has a tendency to create standardized systems and jigs to achieve precision repeatedly and also reduce cost and production times. Despite these advantages, prefabrication has not captured a significant market share and accounted for only 6.03 % of new starts in 2022 (MBI 2023). Part of this can be attributed to coordination and communication difficulties, as prefabrication work must be carried out with the utmost precision from inception to production to ensure everything is correctly manufactured.

While effective in creating repeated elements such as the largely rectilinear structures that are common in our built environment, these standardized approaches often do not accommodate the more organic trends in contemporary design. Prefabricating these specialized and project-specific components offers less benefit, as the labor is intensive whether on site or in the fabrication shop. As a result, the industry is looking more toward computer-controlled means of production to achieve these free-form and unique designs, such as 3D Concrete Printing (3DCP) and robotic automation. These techniques are novel and promising yet have a series of limitations that will be discussed in more detail in section 2.1.1. Fortunately, prefabrication can capitalize on this computer-controlled machinery to achieve the necessary tolerances while also establishing a means for mass customization instead of standardization. Combining prefabrication with parametric modeling and digital fabrication can establish workflows that enable the production of unique projects and components in a way that is efficient for all parties involved.

Positioning digital prefabrication as the new industry standard, this thesis explores best practices in the industry's existing drawing culture as well as alternative visual communication strategies from other industries in an effort to investigate, hypothesize, and evaluate whether any method presents a strong approach to mitigating the inefficiencies currently present in the realization of non-rectilinear designs. It will also demonstrate some ways in which parametric software, typically employed in design development only, can be utilized by builders to produce higher quality work more efficiently by applying the idea of mass customization. This manifests as a series of assembly studies that compare these different cultures of conveying assembly instructions, from which the strengths and weaknesses of various methods can be ascertained.

1.1 Research Objectives

Although rooted in a specific niche of concrete formwork, the primary objective of this research is to explore the relationship of communications between design and construction, from office to field. This thesis hypothesizes that some of the productivity and efficiency issues present in modern construction can be attributed to miscommunications due to discrepancies in our drawing sets, which are the primary method of conveying construction information. Additionally, the project applies Fabrication Information Modeling (FIM) workflows in conjunction with this exploration into alternative methods to convey assembly. A key reason for including both human communication methods and digital production workflows is to establish a path forward for the industry that embraces technological solutions where they are most apt, while also empowering the human element on site rather than replacing it. From this, we derive the guiding research question:

> *How can we leverage technology to make existing human-powered workflows more engaging, accurate, and efficient?*

This will be accomplished by analyzing the strengths and weaknesses of the industry's standard practice (construction and shop drawings), as well as alternative approaches to communicating assembly and construction information visually from other fields (assembly booklets and augmented reality). In these industries, a kit of prefabricated components is packaged with varying instructions, shipped/sold, and assembled in-situ. Depending on the industry and specific manufacturer, these range from two-dimensional drawings to three-dimensional, step-by-step assembly graphics. By conducting assembly tests using different visual communication systems proven in various industries, we do not need to invent new technologies or perform research to determine what the best practices are – we simply need to adapt the existing guidelines and frameworks from those communication styles to a construction context.

1.1.1 Research Questions And Goals

Although helpful in framing the research objectives and targeted outcome, the above guiding research question is too broad to develop actionable research. The three questions below represent more granular investigations that relate to the main argument and that can also be tackled in a tangible manner.

1. Can the existing culture of drawings borrow from the graphics-based languages for assembly in other industries?
2. Can Augmented Reality programs bridge the communication barrier between design and construction by visualizing assemblies on-site, circumventing the need for drawings?
3. Can these communication approaches extend the benefits of prefabrication further?

With these questions in mind, we can begin to outline how to achieve them. While the project goals below are not 1:1 translations of the questions into action statements, they provide a clear path forward.

1. Demonstrate how underutilized design software can be applied to improve and streamline repetitive and/or monotonous construction and fabrication processes.
2. Leverage the knowledge base, expertise, and flexibility of people using technology to enhance communication and productivity on site.

3. Improve communication and understanding between workers in the office and the field, from design to construction, by reevaluating visual communication strategies and best practices.
4. Boost project productivity by reducing errors, rework, and on-site assembly/erection time by achieving the above 3 goals.

To facilitate the large scope of this thesis which includes development, prototyping, and testing, this research is a collaboration between Turner Construction and the University of Washington's College of Built Environments, conducted over the course of the 2023-24 academic term.

1.2 Scope

This research focuses on singly curved, non-structural cast-in-place pony walls as an applied case study to test different communication strategies. This subtype of concrete work was selected because many of these walls exhibit characteristics that are beneficial to study in isolation while also being representative of broader concrete work. Despite the prevalence of organic site walls in contemporary and historic designs, they remain difficult to achieve utilizing the existing approaches to formwork. This difficulty utilizing standard approaches makes this type of wall a strong candidate for the exploration of prefabrication as a tool for mass customization. As half-height walls, pony walls do not carry major loads or forces, so discussions about reinforcement can be postponed and considered as future research. The lower height and overall size of these walls is much easier to perform a 1:1 scale fabrication study with, as the formwork panels can be moved without mechanical assistance and the work can be studied within an enclosed shop area. Lastly, although at a smaller scale, a pony wall retains the core components of a large structural wall and thus is a good representative of other forms of concrete construction.

As each wall is inherently unique, this type is also well positioned to explore the application of parametric design software to enable Computer Numerical Control (CNC) prefabrication of these formwork pieces for greater efficiency and precision. This project will implement existing hardware and software platforms rather than develop new systems. This will allow the research to be focused on effectively communicating the process of assembly, rather than the development of new platforms and frameworks which would require a longer project duration and more outside expertise such as software development. It will also allow for the automation of portions of the formwork modeling process from design to fabrication as a demonstration of utilizing design software in construction. Similarly, the shop drawings, assembly booklets, and augmented reality (AR) models will be developed to industry best practices as identified during literature review, rather than to a proposed new standard. All work will be conducted in an enclosed shop environment to simplify the movement of materials while also providing a controlled testing environment.

Although there are a wide range of different groups that could be impacted by this research, from construction workers to design students and firm employees, we have focused the participant pool to employees of Turner Construction. This decision will be elaborated upon in the methodology section, but in summary simplifies the participant gathering and compensation process and allows the study to focus on the primary impact group. Future research could focus on comparing one or all of these methods across different participant groups.

1.3 Definitions

Automation – In general, automation represents the replacement of specific human labor tasks with mechanical or robotic workers. This thesis will explore automation as it applies to construction. Buchli et al (2018) further divide automation into two methods: In-situ fabrication, and off-site prefabrication. In-situ fabrication capitalizes on recent advancements in mobile, computer-controlled production techniques such as 3D Concrete Printing (3DCP) and robotic fabrication. Off-site prefabrication focuses more on stationary equipment and mass production and has more parallels to typical manufacturing industries. The second method of implementing automation in construction is the definition utilized in this thesis.

Fabrication Information Modeling (FIM) – Fabrication Information Modeling is an emergent workflow or framework that targets the lack of continuity between design development in Building Information Modeling (BIM) programs and contemporary, digital fabrication methods. Slepicka et al (2021) outline FIM as a planning process in tandem with high LOD BIM modeling so that materials, machine parameters, and other fabrication information is encapsulated into the digital model driving the toolpaths and machinery.

Digital Fabrication – Digital fabrication is described by Dunn (2012) as a type of Computer-Aided Design/Computer-Aided Machining (CAD/CAM) process which takes these computer controlled fabrication methods further and utilizes them to "[facilitate] a greater fluidity between design generaration, development, and fabrication than in traditional approaches…"

Design to Fabrication – While there are multiple definitions of "Design to Fabrication," this thesis will utilize one put forth by Raspall (2015): "The automation of the extraction and processing of information from three-dimensional models and the generation of instructions to operate Computer Numerical Control (CNC) machines."

Extended Reality (XR); Augmented Reality (AR); Virtual Reality (VR); Mixed Reality (MR) – This thesis draws from the definitions put forth by the US Government Accountability Office (2022). Extended Reality (XR) is utilized as a blanket term, covering a range of programs that integrate digital and physical realms. Augmented Reality (AR) represents a hybrid digital-physical overlay in which digital content is overlayed with a pass-through video feed of reality from cameras or is projected onto a display in front of the user. This technology can accommodate a range of inputs and levels of interactivity. It is often used interchangeably with Mixed Reality (MR), however AR can be used to differentiate technology that integrates with mobile devices while MR is often used to describe hardware and software tailored to Head-Mounted Devices (HMDs). Virtual Reality (VR) is a fully digital environment that a user is immersed in with no firm relationship to the physical environment and requires HMDs to accomplish this.

Figure 2: A surviving drawing of the Strasbourg Cathedral Façade, circa France, 1260s

2.0 LITERATURE REVIEW

Utilizing drawings as a visual communication tool is an established tradition in the construction industry. Physical record of design drawings exists back to at least the 13th century, such as the surviving façade drawings for the Strasbourg cathedral in France pictured on the proceeding page, but there is evidence for their use in the 12th century and potentially earlier (Bork 2023). These drawings reflect a high degree of skill in their rendering and are works of art in and of themselves. One of the most interesting aspects of these drawings is the visual clarity, which can be attributed to the balance of information contained within them. These older drawings provided only what was necessary for the skilled masons to understand and execute the design through their own knowledge and expertise, and were largely absent of visual clutter that would obstruct the image and what it is conveying. The innate complexity of construction and manufacturing requires a certain level of skill to read and interpret these drawings, which encouraged the development of certain standards and methods to convey three-dimensional information as a two-dimensional representation. As drawings have evolved into contract documents, more and more information has crept into them such as specificity about finishes, products, etc. Although this newer culture of contract drawings continues as today's standard practice, modern drawing sets are under scrutiny because of this growing visual clutter that makes drawings increasingly difficult to interpret (Gao et al 2006).

This literature review will focus on a selection of different communication issues in construction and assembly pertaining to drawings, their production, and the successes and struggles of different fabrication methodologies. The identified challenges will be supplemented with subsequent investigation into potential remedies sourced from prefabrication and manufacturing efforts in adjacent fields like furniture and toys, as well as from emergent technologies such as augmented reality.

2.1 A Selection Of Communication Issues Arising From Standard Practices

As mentioned, CADD, BIM, and various other software suites have become common tools in the design process. Advances in computational software have not only enabled more information to be incorporated into the model of the planned project, but also have allowed, if not encouraged, the creation of increasingly complex designs. While designs and their subsequent representations have always been complex due to the scale and significance of architecture and construction, the rapid industry changes on the design-side during the late 20th through the 21st centuries due to the influx of the computer are highlighting a growing incompatibility between traditional approaches to drawings as construction communication tools and their modern production.

Gao et al (2006) asserts that this division is linked to the rapid and often automatic generation of drawings in CAD and BIM programs, which results in the production of drawings that are divorced from (sub)conscious intent and subsequent detailed review by the project team. Essentially, choices which were once rooted in manual processes and selections based on developed knowledge and skills, choices such as line weights, specific views and the extents of their scale, the level of detail, and others that impact the legibility of the drawing are now left to an automated internal standard. The increasing complexity of the design correlates to an increased amount of information needed to convey its execution effectively, meaning more information on, and in addendum to, the drawings. This visual clutter leads to a lack of clarity in the drawing set and a ballooning sheet count. Gao et al (2016) also questions the pervasive culture of rigid black-and-white drawing sets, despite designers working with color layers in design software and the prevalence of color printing services.

While 3D perspectives and axonometric views provide a better understanding of the project as a whole, the inclusion of this kind of drawing in construction details, shop drawings, and other construction- and fabrication-level drawings is sparce. Crane and Woolsey (1992) advocate for the inclusion of 3D representations when trying to communicate assembly processes, as an individual doing a specific task will need only a general understanding of the whole, yet a higher level of detail and instruction for their section of work. While certain tasks like precision machining might benefit more from "abstracted" drawings such as detailed sections, 3D exploded axonometric drawings seem to be an underutilized approach for communicating assembly. Although other industries such as flat-pack furniture utilize this form of drawing which will be discussed in a later section, it is rare in the construction industry.

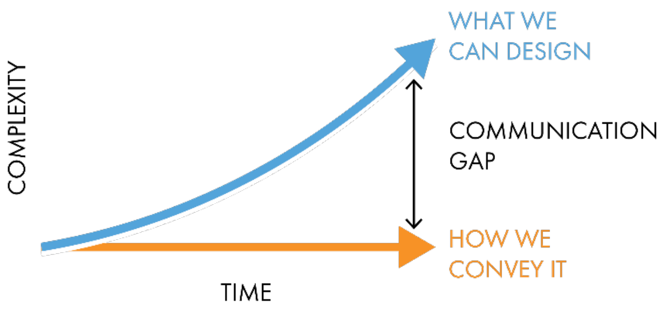


Figure 3: Diagram highlighting the growing gap between what we are capable of designing and the method we use to convey it.

These growing discontinuities highlight what this thesis considers the "communication gap," which exists in between *what we can design* and *how we continue to convey it* (figure 3). Although there are certainly some projects and firms which approach this issue in their own novel ways, the broad industry standard remains deeply rooted in 2D, orthographic shop drawings in black-and-white. The shortcomings of the current approach to construction and shop drawings must serve as a catalyst to push the industry to reevaluate how these drawings are made if construction is to reverse the productivity and efficiency losses in figure 1. As design and construction cultures change, so too must the assembly and installation drawings. This suggests that the construction industry may benefit from the analysis and adoption of communication techniques that are successful in other allied industries that have already surpassed these design and fabrication challenges.

2.1.1 Novel Issues Arising From Automated Concrete Work In-Situ

Automation represents one potential solution to problems with human communication, understanding, and labor in typical construction practices. Employing CNC machinery to assist with production has a long history in design exploration and research, typically accompanied by strong rhetoric heralding the technology as the tool that can bridge the growing gap between dwindling fabrication knowledge and progressive, parametric design pedagogy (Blough 2012).

This workflow, known as “design to fabrication,” is defined by Raspall (2015) in a prior section. To this end, the CNC has been an effective tool in the realization of a great number of incredibly intricate, geometric forms which would be time and resource consuming to fabricate traditionally. One of the strongest advantages to offloading some of this physical labor to the machine is in the dimensional tolerances and finish quality; achieving high-level construction on unique designs is increasingly demanding in terms of a laborer’s skill and time, so by keeping production linked directly to the designed model this workflow circumvents many of these issues (Fardhosseini 2021). Despite this potential, stationary CNC technology remains somewhat niche, relegated to research and development for prototypes and one-off installations rather than widespread construction industry use. Some of the slowness of implementation could be attributed to the fact that construction is predominantly an on-site industry (Buchli et al 2018); without a revolution in building practices or machine technology, machines that are effective in industrial shop settings are more or less incompatible with the industry as-is. Additionally, while digital fabrication is commanding more attention in the realm of prefabrication, preparing a design for digital fabrication instead of traditional fabrication still requires significant preparation and processing/cleanup work followed by physical assembly and there is a deficit of industry research quantifying these processes.

Over the last decade, interest in robotic production and construction has grown rapidly in response to these limitations. This increase in interest has encouraged further innovation in CNC technology that has finally allowed these machines to leave their stationary factory environments and migrate from job to job. Buswell et al (2018) tracks the delivery of large-scale projects utilizing the additive method of 3D Concrete Printing (3DCP), which has increased year-over-year throughout the 2010’s from six in 2010 to thirty-four in 2018. Other research efforts have explored robotic arms borrowed from manufacturing processes, utilizing them to construct atypical concrete formwork systems that would require a combination highly skilled laborers and a well communicated understanding of the design to realize utilizing traditional construction methods (Hack et al 2020). These examples illustrate how CNC technology can be applied to field assembly and construction to assist in realizing unique forms that might otherwise be cumbersome to achieve due to skill barriers, cost, material usage/waste, or other reasons. However, that does not mean that these automated and highly mechanized approaches to construction are not without faults. Buswell et al (2018) delves into several of the major technical shortcomings of 3DCP technology, many of which can also be attributed to automation in-situ in general. For instance, these machines require highly controlled conditions as a base condition to perform their work successfully, which is counter to the dynamic nature of a job site. Whether it is changing weather conditions or an unexpected obstacle in the operating area, a machine's ability to process and respond safely to the wide range of unknowns and other situations on site is non-negotiable for widespread adoption, and the technology has not advanced to this point yet. Similarly, these machines typically lack awareness when failure occurs, such as 3D prints that continue to "print" after failure, which can result in extensive (and expensive) rework if humans on site do not catch the error. These machines can also have trouble reorienting to their location and task if desynchronized (Buchli et al 2018). Ultimately, these issues are a part of the core challenges at the forefront of robotics research, suggesting that they will be resolved at some point in the future, but until that point widespread adoption is unlikely.

Beyond technical performance, this level and scale of automation in-situ raises a number of questions regarding the social and economic impacts of replacing human labor with machines. While this industry would bring forth new roles as maintenance technicians, operators, and the like, it is unknown how many construction employment opportunities would be eliminated or gained as a result. As this technology continues to progress, the industry is presented with the option to steer its development and implementation. In this way, there is a huge opportunity to draw inspiration from adjacent industries to build a future that is not absent of technology or one that is completely replaced by it; rather a third path can be established that leverages the strengths of both computer-controlled technologies and human skills to offset each's weaknesses and forge a future that is advanced, productive, and human-centric. The aspects of human-centric digital prefabrication will be discussed in section 2.2.1.

2.2 Potential Solutions From Other Industries And Emergent Practices

While construction is lagging behind other industries in certain aspects, this can also be beneficial; many solutions to the same problems have already been hypothesized, tested, and implemented in other industries, so construction is well positioned to identify proven practices that could be adopted and adjusted for construction contexts. One example is the Ikea booklet, which serves to help a range of people assemble a flat-pack kit of parts for a pre-determined design. Several other ideas are derived from construction companies tackling these questions, such as the Fabrication Information Modeling workflows implemented by Turner Construction on select projects. Lastly, there are entirely novel communication technologies entering the industry such as AR, which has untapped potential if the industry were to begin engaging the technology in its infancy, as its development could be steered and tailored for construction uses.

2.2.1 Fabrication Information Modeling - Automating Prefabrication For Human-Centric Construction

If bringing the factory to the field is not a resounding success, then there may be potential solutions to be found by returning to the factory to reevaluate stationary CNC equipment in conjunction with emergent Fabrication Information Modeling (FIM) workflows. Fabrication Information Modeling is a methodology for fabrication-integrated design, construction, and management, meaning that information about the actual tools, processes, and materials that will be used to realize a given design will be encoded within its 3D model (Slepicka et al 2021). FIM is to fabrication what BIM is to construction in general. This mode is particularly effective when a FIM model is paired with the parametric software options commonly used by designers to generate evocative forms, except that by integrating FIM, the designed form now has a degree of realism and constructability with CNC technologies where the 3D model was once was only a conceptual visualization. Using parametric automation, CNC tools can then be employed to produce one-off parts or entire kits for assemblies that would otherwise be inefficient and costly to produce in the field or as one-off CNC projects with manual modeling workflows.

Hamid et al (2018) evaluated one proposed workflow in the development and testing of their proposed FIM framework for custom cabinetry. The goal of their research was to overcome some of the communication issues between designers and millwork carpenters by creating a more intelligent and information-integrated cabinetry model. As identified by the authors, some of the challenges of the prototype workflow were due to interface and communication issues resulting from insufficient orientation and training with this alternative system for both the designers and the carpenters. Although the technology is certainly streamlining much of the production process itself, this research adds to the notion that some of the fundamental issues causing issues on job sites is not the methods of working or the tools used, but the *way we communicate* the work to be done and how to use the tools and materials at hand effectively.

Another example is the work performed by Turner Construction (2023) in the realm of concrete construction, specifically with formwork for the edges of their concrete slabs (“edgeforms”) and sheer core openings (“blockouts”). Turner’s approach capitalizes on parametric modeling software such as Grasshopper to drive a parametric 3D model of the formwork required to achieve a given input geometry defined by the designers. Their script then prepares the generated construction geometry for CNC fabrication. The software and CNC take on the share of work that is repetitive, e.g. modeling an array of formwork and producing the pieces, while carpenters apply their expertise by reviewing the model before fabrication for constructability, producing parts not done by the CNC, and putting it all together. This process can be compared to cooking, where one person prepares the ingredients (the machine) while the other creates the dish (the carpenter). This workflow also overcomes some of the challenges faced by Hamid et al (2018) by including a system of part labeling which is tied to a set of installation drawings. The labels are simple part codes with an indication of which parts join together but have proven to be a profitable success for the company by saving time and energy while producing higher quality work.

This pairing of human and machine represents a strong path to integrate CNC machinery into broader construction practices, retaining skilled labor while also leveraging the strengths of the computer to accomplish the tasks it is best suited for. However, it is important to learn from the existing research in this space that these fabrication methods become ineffective if they are not paired with the proper communication from designer to builder, meaning that digital prefabrication in and of itself is not likely a viable solution to the communication gap in construction.

2.2.2 Drawings To Communicate Assembly In Other Industries

The previous section outlined the promising applications of CNC technology with FIM workflows, such as the shop drawings Turner Construction pairs with the CNC produced pieces for their edgeforms and blockouts. However, these developments are largely removed from utilizing drawings to communicate assembly. Different ways of using drawings to communicate assembly information emerged with the rise of Ikea and Lego in the 20th century, and have become iconic approaches to constructing furniture and toys from a kit of parts not unlike the CNC produced kits from FIM workflows. These companies brought their illustrated assembly booklets to households around the world, and through them have established a deep-rooted culture of utilizing a sequence of images to convey assembly. The success of the packaged assembly kit in these industries has strong implications in the construction industry as a paradigm that could be adapted and combined with the FIM workflows explored in section 2.2.1 to create a more wholistic framework from design to construction. The two greatest strengths of looking to these industries are as follows:

1. The approach employs mass-manufactured kits of parts packaged with all the required items (including instructions) to create a desired end product, which mirrors the desired framework of FIM best practices for concrete formwork.
2. It demonstrates the success of illustrated booklets as a tool proven to effectively communicate the on-site production of a complex assembly to a wide audience with varying skill levels that is separated from the knowledge that develops from producing the design or its parts.

These sequential assembly booklets are often referred to by the developed nomenclature of “Pictorial Assembly Instructions” or “PAIs” (Schumacher 2007). As demonstrated by their prevalence in do-it-yourself products, PAIs are incredibly effective tools to convey the assembly of an object to an untrained audience across many linguistic barriers. Clear illustrations depicting an action are the primary method of conveying the necessary information. However, these simple and diagrammatic images, when viewed in isolation, can create ambiguity in meaning due to cultural differences in interpreting what is presented. Horton (1993) provides an overview of how to approach graphics when communicating internationally. While the scope of this project is centered on domestic labor and work practices, thereby minimizing the potential for the larger cross-cultural misinterpretations raised by Horton, designing PAIs with those concepts in mind can reflect a best practice to accommodate a diverse workforce. One important point raised by Horton that is followed in most assembly manuals is that these illustrations are not typically without words entirely. Whether it is a part code, a verb denoting an assembly action, or a short sentence or paragraph alongside each step, few PAIs are wordless. Wordless instructions can be effective for simpler tasks, such as certain simply assemblies or toys, but can become frustrating and unclear with more conceptual tasks, when multiple pieces are added in one image, or if parts are incredibly similar. For instance, the step-by-step assembly images for many IKEA and Lego products are virtually without words (there are numeral strings representing part codes, however). Simpler builds are typically quite successful with this kind of manual, but more complicated designs can become frustrating, as evidenced by the numerous media articles and social media posts venting about difficulties in interpreting what an illustration is supposed to be conveying. However, the broad success of the PAIs from these companies suggests that the benefits greatly outweigh the inconveniences. Additionally, many of these difficulties can be "designed" out of the PAI through careful consideration and storyboarding of the instructions. When designing a PAI, previous research indicates there are several primary considerations:

1. Planning – The sequence of operations to assemble the object must be represented accurately and logically to establish a flow from diagram to diagram (Agrawala 2003).
2. Presentation – The orientation of each diagram should show the new components for that step clearly and should not completely change the view or scale from previous diagrams, which would disorient the assembler (Agrawala 2003).
3. Consistency – The format and structure of the PAI should ensure that there is consistency across diagrams that show similar operations (Schumacher 2013).

These items are important to address from the first stages of laying out the PAI, before a graphic style or the number of sequences is set. By storyboarding the instructions, these primary considerations can be quickly incorporated into the PAI to ensure a certain minimum level of effectiveness. The flow of the PAI and the drawings themselves should also adhere to a number of best practices derived from literature review:

1. 3D visualization is more effective than 2D elevations and plans for assembly workflows (Schumacher 2007 + Crane/Woolsey 1992).
2. Designing the assembly sequence as a series of sub-assemblies rather than a series of individual items added to a larger whole is more effective. This method is employed by Lego and Ikea (Agrawala et al 2003).
3. Repetitive tasks with no or little variation can be omitted as diagrams, provided there is some indication of repetition (Agrawala et al 2003, Frixone and Lombardi 2015).
4. Action diagrams (exploded views that indicate how pieces join) are superior to static diagrams (views that show a finished step) (Agrawala et al 2003).
5. Rendering style – black-and-white linework illustration following technical illustration conventions is the strongest starting point; gourad shading and outlining spatial edges is also important (Agrawala et al 2003).
6. It is important to consider line weights. A tripartite system can convey much of the information needed for depth, etc., and the level of detail shown should be considered to ensure they are appropriate to bring focus to the proper task and also for the physical size of the instructions (Schumacher 2007).
7. Avoid stylized graphics which border on art, which can complicate the visual's ability to convey the information desired (Horton 1993).

Although developing the language of PAIs is not the focus of this thesis, this area has a number of opportunities for future research. For instance, the work of Agrawala et al (2003) included an interesting proprietary program that automatically generated exploded axonometric sequential assembly drawings for a given design. A similar workflow could be applied to the parametric FIM work demonstrated by Turner Construction and Hamid et al (2018), allowing a large portion of the PAI to be automatically created based on a set of governing rules. This would assist in lowering the overall time and cost requirements of producing these one-off kits, which would otherwise be fairly intensive if the instruction preparation was an entirely manual process. Similarly, this kind of automated PAI generation could help create layout and installation drawings utilizing existing modular formwork systems.

2.2.3 Extended Reality Overlays To Communicate Assembly And Form

In the Architecture, Engineering, and Construction (AEC) industry, visualization and collaboration tools that apply augmented reality overlays are young and not yet well established; companies developing their approach to AR for the industry come and go frequently, with few making a lasting impression. However, this technology gained traction during the COVID-19 pandemic as a digital form of meeting, presentation, and collaboration space, or as a method of overlaying virtual content into physical reality to visualize future work and verify completed items. As an emerging technology, not only are there a myriad of physical explorations underway, but also significant research efforts toward defining, observing, quantifying, and optimizing AR for design and construction. This section will focus on AR technologies alone rather than the other types of extended reality which are summarized in the definitions section. This choice focuses on the application of AR platforms as a communication tool for assembly and construction visualization in the field, whereas the other approaches are more limited to office settings and design implementation only, due to the nature of their hardware and software.

Augmented reality for design and construction can be broken into two groups based on the primary physical hardware platforms: headwear and mobile devices. Head-Mounted Devices (HMDs) typically deliver better performance at a higher price point while mobile applications offer an introduction to AR to a wider audience at a lower cost. HMD software tends to demonstrate a more advanced approach to utilizing AR in construction and fabrication because it can rely on the higher quality, tailored hardware of the HMD in comparison to a cellphone (e.g. the quality and number of sensors and cameras). Being more advanced, it also has a steeper learning curve and is typically used by those who already have a deep interest in using the technology as a means to further its development regardless of its current effectiveness, such as research teams or divisions of companies. These platforms take advantage of AR’s full capacity by shaping completely new approaches to assembly and construction. HMD-based AR enables floating labels and information, wireframe models visualizing where something is supposed to go, and other innovative ideas of rendering 3D ideas in 3D space, all without impeding work by occupying the hands. In contrast, both phone-based applications and traditional approaches with drawing sets require one or both hands to operate, meaning work slows to a halt while interfacing with the construction instructions. The phone-based applications are powerful tools in their own right, however; by utilizing a ubiquitous platform, this approach creates an array of highly accessible options that are still quite effective in demonstrating the strengths of AR in construction and the role AR could have in advancing other forms of assembly instructions such as the PAI.

An application developed by Hartanto et al (2019), demonstrates how a low-cost, easy-to-use and access application can be created for cellphones to walk users through step-by-step assembly instructions with exploded 3D models for each assembly task, instead of 2D illustrations. This approach is a logical translation of 2D PAIs into a 3D environment and shows the potential for AR to provide clearer assembly instructions for complex tasks by capitalizing on 3D models, eliminating the translation of 3D information to 2D. A similar concept developed by Yan (2021) for use with Lego bricks adds realism through occlusion, which is the removal of visualized information on the screen when an object, such as a hand, passes over it and obscures it. Although interesting studies that advanced the development of AR technologies for assembly instructions, these studies did not explore quantifying the improvements (if any) through comparisons with other methods. This leaves space for future research to build on their platforms by comparing the different approaches to AR instructions, rather than developing an alternate approach. Additionally, these developments do not fully explore a “futuristic” view of construction and fabrication that fully embraces the extent of AR technology like the later examples utilizing HMDs, which also provides opportunities for further research.

The work of Funk and Schmidt (2021) illustrates the complexities of implementing AR for the manufacture of smaller assemblies in comparison to traditional paper instructions and provides thorough data collection and analysis with which to draw conclusions between the two methods. Over a series of five trials, participants showed drastic reductions in assembly time across both approaches, attributed to growing familiarity with the procedure in general. The augmented reality conditions proved more effective in reducing assembly times, with statistically significant differences in the completion time between the two options by the fifth assembly test. Although the participants were given time to familiarize themselves with the AR system before the assembly tests, the participants were drawn from a manufacturing company that relies on paper assembly instructions as their standard, meaning they had preexisting skills with that method and little with the AR. Nonetheless, the AR method proved more effective in this metric, which is very promising for this thesis' research. It is also important to note that, although there was a statistically significant difference in elapsed time, many other metrics were very comparable and thus inconclusive. Some of this was attributed to the AR instructions being a translation of existing paper instructions onto an AR platform, thereby not making full use of the platform like other research had done. Given the alignment between this research to determine the most effective method to communicate assembly information and the goals of Funk and Schmidt's research, the methodology employed by Funk and Schmidt is a strong example that outlines many of the important data metrics that should be observed during the assembly trials in this project.

Additional research with LEGO bricks as the construction object by Shi et al (2023) culminated in their Brickpal prototype, a custom AR program for custom Lego designs which overlay generated step-by-step visualizations on an HMD. The greatest strength of this application and approach to PAIs as it relates to this thesis is their implementation of machine learning algorithms to automatically generate the instructions for a given design. This incorporates the automatic generation of instructions, which represents the realization of one of the proposed solutions to a problem identified in 2.2.2 regarding the time and labor involved in manually creating each set of assembly instructions for a given design and kit of parts. This study also encapsulated user testing after development, with the AI generated instructions being compared against paper assembly instructions as well as manually designed AR instructions to establish a "standard" condition to evaluate against. Although their results do not show a statistical advantage to the AR approach in terms of the number of errors or completion time, their survey indicated strong positive responses in favor of both AR options, with interest in the AI approach as a proof of concept for what future AI generated AR assembly instructions could become.

As mentioned previously, HMDs usually deliver better results as they are purpose-built for AR. However, their greatest strength may lie in the fact that the visual overlay no longer requires one hand to be occupied by a handheld device. This enables construction information to be continuously accessed while work is underway, with no need to put down tools or step away from the task at hand to review the instructions or drawing set. In the absence of extensive published literature on the subject, the following case studies serve to demonstrate the effectiveness of AR in actual working conditions.

The Angelus Novus Vault is a collaborative research project spearheaded by SOM, Princeton University, University of Bergamo, University of Salerno, CERCAA, UCHV Research Film Studio, and Eng. Carlo Olivieri (SOM 2023). The project is a built exploration for the 2023 Vence biennale that demonstrates the power of AR to convey construction information, completely circumventing the need for a 2D drawing set. The project utilizes an HMD to overlay linework similar to the stringlines used in traditional masonry coursework, but in this case are wireframe visualizations of a 3D model. This technology assists the master masons in their work, resulting in a unique vault structure utilizing the herringbone techniques of Filippo Brunelleschi's dome in the Florence Cathedral, all without drawings and with minimal falsework. The augmented reality approach to masonry has also been successfully implemented with more routine work, such as the serpentine brick pony walls at the Royal Hobart Hospital in Tasmania by Fologram and All Brick in 2019, utilizing the Fologram platform with Microsoft HoloLens (Fologram 2021).

One strength of these demonstrations is how the technology upholds continuity in the tradition of building with skilled craftspeople on site; workflows are supplemented with additional communicative tools that make work more efficient by communicating the design and construction intent at 1:1 scale, rather than as a stack of construction drawings. This approach also outlines one way to integrate cutting edge technologies without widespread replacement of labor on site, whether it be with machines or workers with less skill. The two examples above are also particularly important case studies of AR in construction because they demonstrate how AR can function as a standalone construction communication tool, rather than being a general visualization tool that is subservient to the drawing set. In order to function as a competent site layout and assembly tool, the model that is running the visualization must not only be crafted at a high level of detail representing actual construction practices, but must also be aligned and synchronized with physical space. Ensuring these models remain properly oriented and scaled throughout the duration of work is critical to the widespread adoption of this technology. Without reliable precision in this synchronization, the development of AR in construction is limited to visualization of future work, verification of completed work, or as a 3D PAI.

2.2.3.1 Synchronizing Digital And Physical Space

While each application and platform may vary in implementation, the core principle is consistent amongst them, which is to utilize cameras or other sensors to gather data about real-world conditions which can then be compared with the digital model. This is accomplished through localization and registration. Localization refers to the process of locating a specific user and their view or device to the digital world, while registration focuses on the synchronization of the digital model to physical space (Mahmood et al 2020). The information gathered varies depending on hardware and software but is often a mix of planar faces, edges, or point clouds from objects in the space. Some processes utilize “targets” or “markers” in the form of QR codes and other scannable objects that are placed at measured intervals or locations in real space. These physical markers are linked to reference points in the digital model. When these markers are scanned by a device’s cameras, the software determines how it should synchronize digital space with real space and orients the AR visualization accordingly. Different systems require different numbers of marker points, but in general more points for the device to scan will result in a more accurate overlay of the model in the headset. The tradeoff is that laying out these points requires both time and skill; if points are not adequately located in real space, or if too few points are utilized, the synchronization algorithms can be thrown off, resulting in areas of inaccuracy and model drift (Fologram 2024). Model drift refers to situations where the visualization is projected with the incorrect scale or location and is minutely shifting around as it tries to reorient itself to the correct place. Additionally, the markers themselves must be legible, which can be difficult on a construction site; lighting may not be uniform, or the marker could be damaged, which would make the program unable to accurately integrate that data point or points (Sadeghi-Niaraki and Choi 2020).

Other approaches to registration are marker-less and focus on developing point clouds to analyze and compare physical space to digital space. These methods typically require a more robust and dedicated scanning device but circumvent some of the layout issues of the marker-based approaches. Rather than using the 3D scanning technology to create a new digital model, the scanner’s point cloud is being compared against the existing digital model to properly orient and synchronize it in real space. This method is very useful for visualization when there is a well-developed 3D environment to scan and analyze. For example, if a number of walls and other fixed elements are already complete, not only can they be verified against the model with high accuracy, but any future work can utilize those elements as a reference to more accurately locate the visualization for that future work. However, this technology is much less effective for visualizing in an "open field" condition, such as a cleared site for construction or other large, unbound space because there is less information to integrate into the point cloud (Sadeghi-Niaraki and Choi 2020).

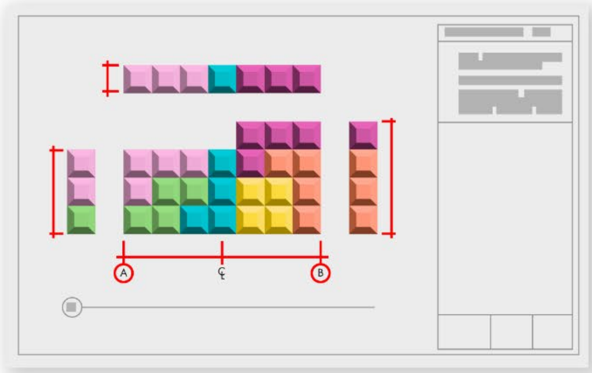
Although promising demonstrations of the strengths of augmented reality for on-site layout and construction, the proceeding discussions of augmented reality overlays with HMDs do not express quantified analysis of the time elapsed to complete the project or other variables, nor do they present a comparison to a baseline of standard practices. There is also a firm barrier to entry with headsets capable of supporting fabrication and assembly work due to their cost. Phone applications marketed as a "lighter" version of the HMD software are beginning to come onto the market and represent an interesting possibility to merge the strengths of both approaches while minimizing the shortcomings.

2.3 Gaps In Existing Literature For Further Research

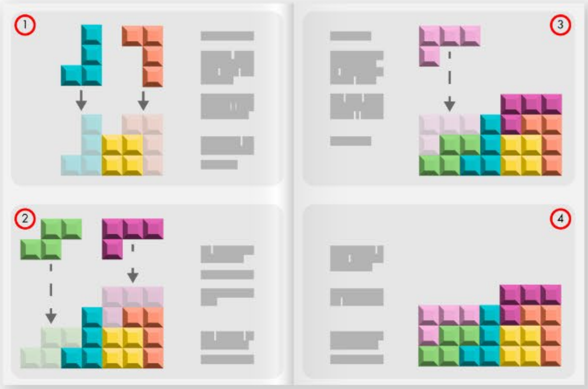
A number of opportunities are present within the existing literature which could be supplemented by this thesis and/or future research. For example, there have been many interesting explorations into the different methods but no comparative studies between "advanced" AR applications such as with the Angelus Novus Vault or the Bogart Hospital projects and step-by-step instructions designed following the principles of Lego, Ikea, and general best practices for that approach. This particular area is where this thesis will focus, however there are a number of other areas with potential.

Isolating AR, the HMD studies such as Angelus Novus Vault show that the more advanced device enables both hands to be free to perform work at full capacity but there has not been extensive comparisons between phone AR and HMD AR. On one hand, the phone application approach requires a user to stop their task and access the application to see what needs to be done, potentially slowing work overall. For instance, the work of Funk and Schmidt (2021) recorded that some participants noted that the smartphone-based AR approach was a nuisance due to having one hand occupied when actively using it, and the frequent need to pick it up to check the instructions. On the other hand, there are concerns about the overall comfort of the HMDs over a typical workday, as well as the adjustment period for integrating a completely new type of technology and a new workflow. Another challenge with AR broadly is that some platforms require an active view of a registration marker, meaning that if the device is set down or a user looks away with an HMD, it would desynchronize and disappear when the marker went out of view of the camera. This could be disorienting or slow down work.

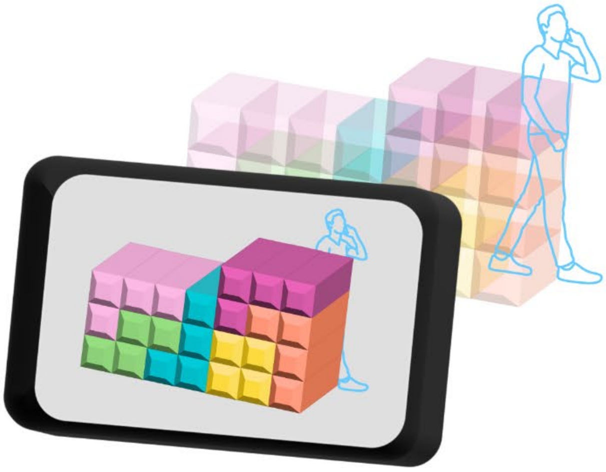
Turning to PAIs and drawings in general, there is a lot of potential for automation similar to the work of Agrawala et al (2003). However, excessive automation can also complicate communication which has been observed with drawing sets after the introduction of CAD/BIM. Further refinement and systematic testing of the best practices could help create stronger guidelines for templates and automatically generated drawings.



Method 1
Shop Drawings (Standard Practice)



Method 2
Sequential Illustrations (Borrowed Practice)



Method 3
Augmented Reality (Future Practice)

Figure 4: A comparison of different mainstream visual instruction approaches for construction and assembly.

3.0 METHODOLOGY

This section outlines how the strategies highlighted during literature review were adapted, applied, and observed in a construction context, specifically concrete formwork. Portions of the procedure and data collection strategies were derived from similar research methods uncovered during literature review, such as the systematic testing performed by Funk and Schmidt (2021). The formal structure of this research was a series of assembly tests comparing three visual approaches to communication:

1. Standard Practice – This approach utilized sets of shop drawings and followed the standard practices of Turner Construction, which represent industry best practices.
2. Borrowed Practice – This approach was represented by PAIs derived from Ikea and other flat-pack manufacturers, following the best practices covered in section 2.2.2.
3. Future Practice – This approach employed AR as the sole means of communication, which has few best practices as of the time of writing (2024).

The primary goal of the assembly trials was to deduce the strengths and weaknesses of these approaches in relative isolation. Beyond statistical data like completion times and usability metrics, the study was structured to gather a wealth of qualitative comments and feedback. The comments and discussions recorded during the trials provide depth and insight into the thoughts and considerations of the participants, which helped to identify ways that these methods could be improved, integrated, and applied in the future that were not originally considered. As this thesis is focused on understanding how best to communicate assembly visually from the office to the field with people rather than machines, the open responses and candid comments directly from the participants were the primary source used to develop correlations and other takeaways. The quantitative data proved incredibly useful in supporting the emerging trends identified with the primary observations. In addition to the notion that the technical metrics are secondary to the observed human experience, the subordinate role of this “formal” data is due to the small data pool recorded (this will be covered in section 3.1), which raised questions about the strength of the drawn conclusions if the quantitative data held a major role. Taken together, the data is particularly valuable in shaping informed correlations and understanding the implications of these alternative practices as this concept begins to extend beyond this specific instance of concrete formwork and into the industry at large.

The study anticipated three groups of participants, which would yield enough data to create averages for each type of instruction to compare. Although a tight data pool, averaging the data collected across these sets of assembly trials provided sufficient information to make initial statements about correlations and other data relationships. Funk and Schmidt (2021)'s data observed a strong connection between repeating an assembly task and internalizing the process, resulting in significant time savings in each successive trial. As the intent of this thesis is to compare these methods as equally as possible, it is important to view this as a challenge to be mitigated. The trial format accounted for this by changing out the wall being assembled for each trial with one of comparable difficulty, and also by changing the starting assembly method for each group. These rotations theoretically ensured participants returned to the given assembly instructions to complete the work, rather than relying on developed knowledge about what the finished form should be. This is covered in depth in sections 3.4 and 3.6.

Drawing from the data collection methods used by Funk and Schmidt (2021), a combination of surveys, video recordings, and direct observations served as the data collection methods. This research utilized the Aptitude for Technology Interaction (ATI) scale to gauge each participant's natural affinity for technology, which is important to observe when presenting workers with alternative work methods that involve the use of technology. After each trial, a survey including the System Usability Scale (SUS) will be given to each participant to collect feedback. Lastly, many open-ended survey questions will ask for written responses and feedback, mostly comprising of qualitative feedback and observations to complement the quantitative survey data. The primary data metrics observed were:

- General comparisons, comments, and opinions through written surveys
- Elapsed time, tracked through video recording timestamps
- Number of errors, tracked through observation
- Effectiveness of instruction system, tracked through the System Usability Scale (SUS) survey

- Participant's technological savviness tracked through the Aptitude for Technology Interaction (ATI) scale survey
- Participant's age
- Participant's years of experience in the industry

3.1 Participant Selection

A wide range of participants were initially considered, with the major options illustrated in figure 5. Based on generalizations and intuitive deduction, the groups were organized by technological savviness, experience in construction, and research impact. This approach helped to classify groups and narrow down our target participants without spending excessive amounts of time at this stage. It is important to stress that these groupings are a diagrammatic abstraction

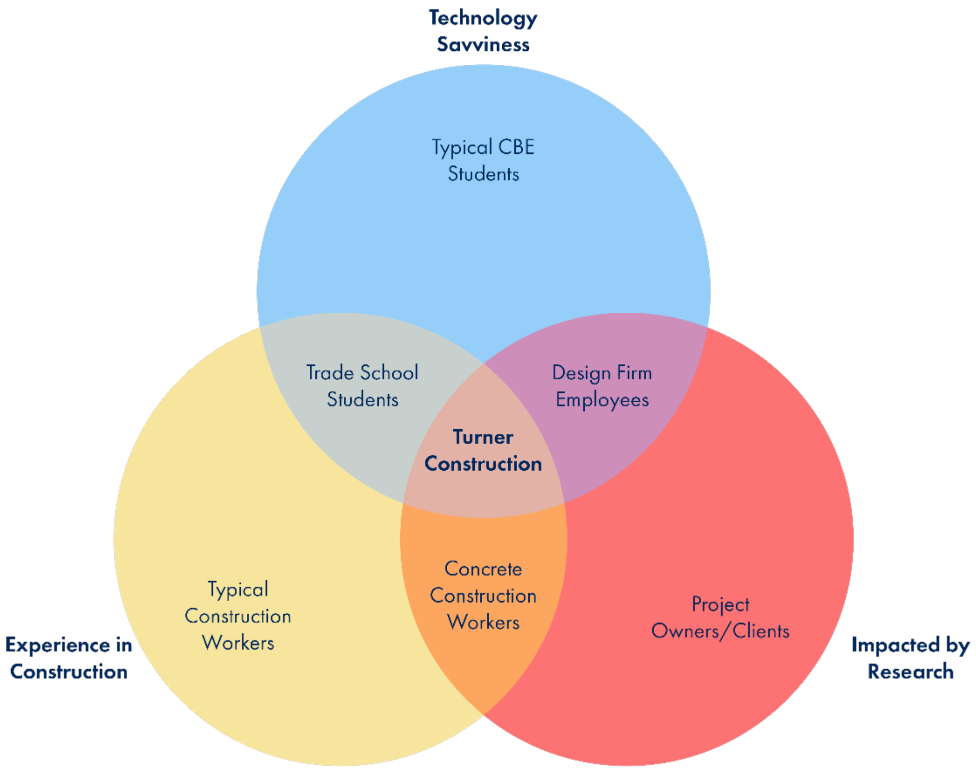


Figure 5: Venn diagram illustrating the potential participant groups and the major, relevant categories they are a part of.

and are not a literal reflection of real-world conditions and relationships. Of these groups, the focus was those that fit within overlapping categories. While the project followed a low-risk methodology comparable to assembling a kit of Ikea furniture, using students or other non-construction-industry participants would mean the assembly trials would be classified as "outside of daily life," even if familiar to the typical college student. As a result, focusing on construction professionals with industry experience began to make the most sense, as the assembly processes involved in the subsequent trials would be of a comparable risk level to a typical "day in the life" in construction, if not significantly reduced. This distinction was crucial to gaining Institutional Review Board (IRB) approval as this study involved utilizing humans as research subjects, albeit for a much laxer study than the typical medical research that the IRB focuses on. Nonetheless, putting the project through IRB was necessary, and this thesis was granted an exemption which allowed the project to proceed as planned (STUDY 00019371).

The selection was further refined to include only Turner Construction employees, which vastly simplified the compensation structure and outreach process by utilizing internal participants and existing company infrastructure. Participants were compensated for their time by logging their hours as if it were a normal day, but instead of being on site they came to the Turner Shop. Given the long duration of sequential assembly trials, it was much simpler to organize in this way, as opposed to bringing in outside construction crews or trade school students. Additionally, sourcing people from within Turner Construction made scheduling much easier, as the kits of formwork parts did not have to be moved around to where the test groups were (e.g. bringing them to a trade school) and it eliminated the coordination efforts required to direct a group of unaffiliated people to an unfamiliar location in the industrial district of Seattle.

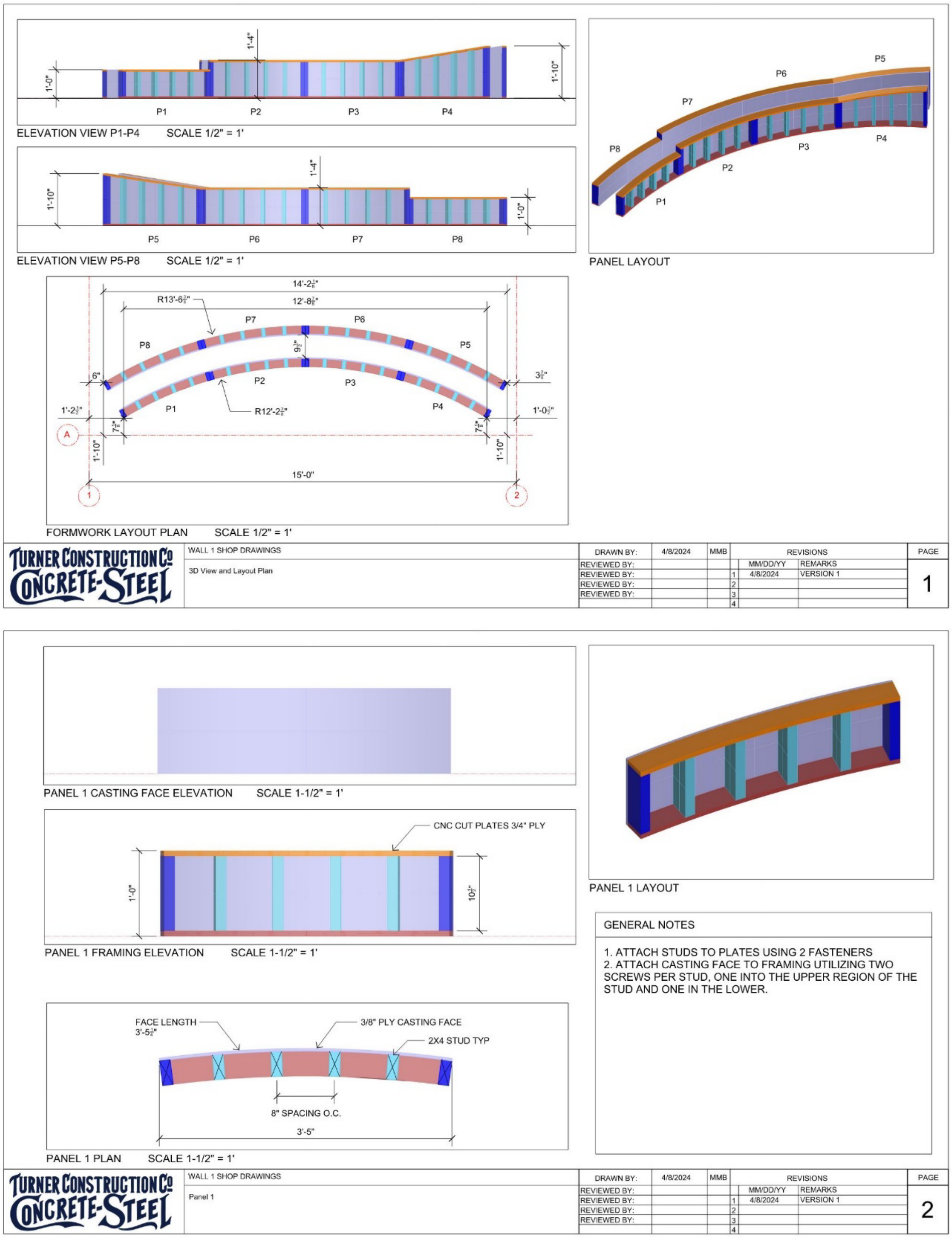
As mentioned previously, the study targeted three groups of 3 participants, making nine the minimum number of participants to hold effective assembly trials. This grouping of three's ensured team lifts could be achieved if the formwork weight grew beyond a single person's capacity. A group of three also implies a team dynamic as would exist on site, potentially with one individual in charge of the assembly instructions that directs tasks, although teams were encouraged to self-organize in any way they wish. While adding more participant triads would be a great approach to strengthen the dataset, this study was limited due to the small pool of employees available at the time of the assembly trials in April 2024. There were also some challenges in final group sizes, as some participants mixed up the schedule and arrived on the incorrect day. These impromptu difficulties and the mitigation strategies are covered in more detail in section 3.7.

The choice to limit the participant pool to experienced Turner Construction employees allowed for a more realistic scope, but also outlined the opportunity for future research in performing the same (or a refined) methodology with a different group. For example, current apprentices could be observed in assembly trials because they represent a group that will go on to become carpenters with different experiences and opinions than those of this study. The chosen participants represent a valuable "point in time" of construction workers today, but opening the research to up-and-coming groups could provide a more robust set of data and feedback from which future projections and other conclusions could be drawn from.

3.2 Assembly Instruction Style Selection And Development

As mentioned in section 3.0, three different visual approaches to assembly were selected: shop drawings, step-by-step assembly booklets (PAIs), and augmented reality programs (AR). The first two methods are straight forward, with implementation based directly on company standards for the former and best practices discovered during literature review for the latter. AR is a somewhat trickier matter, as strong guidelines on how to prepare a model and its visualization are not readily published and accepted as of the time of writing (2024). For the purposes of this thesis, the model for CNC prefabrication was used as the basis for the AR model and the visualization was driven by a preset in the Fologram app rather than something meticulously self-developed.

The standard practice instructions represent best practices within Turner Construction; these drawings follow Turner's approach to shop drawings and represent what their carpenters would typically be given to construct and lay out similar work. These drawings also build upon many of the principles and discussions uncovered during literature review, such as the use of color and simple shading to quickly differentiate parts and establish depth. The drawing sets are on 11"x17" sheets with a typical company title block. The first page provides the overall design and layout information with key dimensions, while subsequent pages focus on the individual panels with more detailed dimensions and callouts. The drawings were reviewed with VDC staff for clarity and correctness, as well as by the lead shop carpenter for Turner Construction. Figure 6 depicts two of the 11x17" shop drawing sheets provided to the teams to construct wall 1.



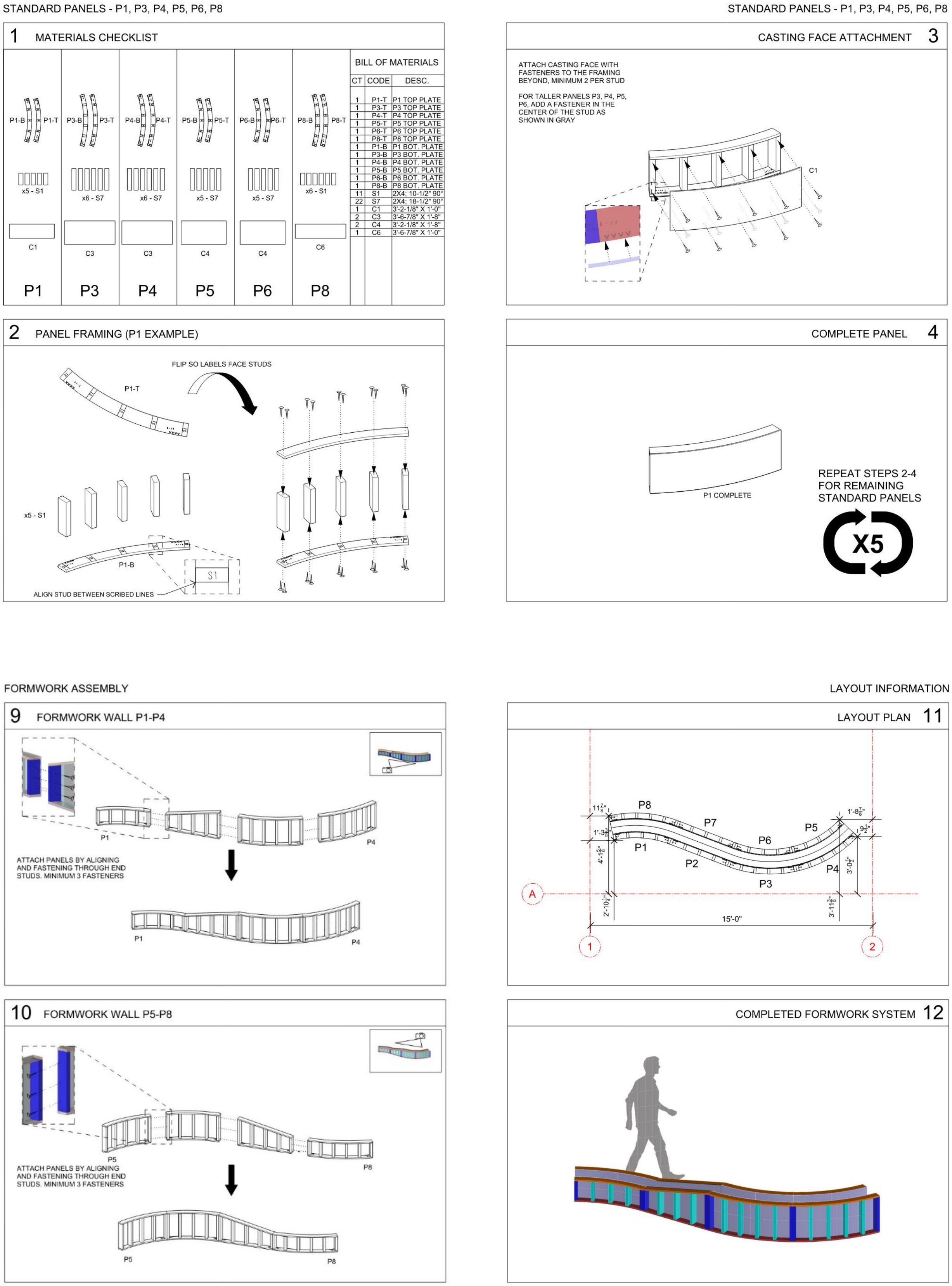
GENERAL NOTES

1. ATTACH STUDS TO PLATES USING 2 FASTENERS
2. ATTACH CASTING FACE TO FRAMING UTILIZING TWO SCREWS PER STUD, ONE INTO THE UPPER REGION OF THE STUD AND ONE IN THE LOWER.

Figure 6: Example shop drawing sheets from wall 1.

Although it would be possible to export these images into a program such as Adobe Illustrator for further graphical refinement, keeping all drawing generation within the Rhinoceros engine reflects a more practical, real-world workflow for drawing generation and also allowed for less processing time. Another purpose of this was to avoid the tendency to push into artistic territories, which is counterproductive as it leads to more open interpretations of the graphics. These drawings in full are located in the supplemental files as item A1.

The borrowed practice set represents a translation of an Ikea or Lego style PAI into the construction sector and reflects the best practices derived from the corresponding literature review section. The PAIs prepared were reviewed internally with VDC staff, as well as with the thesis committee for graphic clarity. One member of the thesis committee, Rob Corser, had extensive experience in preparing PAIs for prefabricated CNC construction. This knowledge proved very insightful while revising the PAIs prepared for this assembly trial. The booklet is on 8.5"x11" sheets and is printed double-sided so that each spread captures a major section of work. The cover page provides a 3D view of the completed formwork design, giving an orientation to the broader picture before diving into the "how to use" section that explains the booklet and how to read the labeling system devised for the project (more on this in section 3.5). The following two-page spreads cover specific subcomponents of the formwork. Rather than have a spread for each individual panel, the representation is streamlined by grouping the panels by type, such as consistent height panels vs. sloping height panels. A materials checklist is provided for each category, and the subsequent steps illustrate the step-by-step assembly process for one panel as an example to follow for the remaining panels of that type. Drawing from the best practices noted in 2.2.2, a repeat symbol is used to show that this process must be repeated a number of times for the remaining panels, rather than creating set after set of repetitive drawings. The last spread covers the assembly of the larger formwork wall as well as layout information. These drawings include limited color details to highlight their importance and draw attention in addition to grayscale values to achieve line hierarchy between spatial edges and other lines. Limited text is provided about some tasks that were difficult to represent graphically in the time allotted for booklet preparation. Similar to the shop drawings, the booklets were produced entirely in Rhinoceros. Figure 7 (following page) depicts two spreads of the 8.5x11" booklet for wall 2. These drawings in full are located in the supplemental files as item A2.



STANDARD PANELS - P1, P3, P4, P5, P6, P8

1 MATERIALS CHECKLIST

BILL OF MATERIALS

CT	CODE	DESC.
1	P1-T	P1 TOP PLATE
1	P3-T	P3 TOP PLATE
1	P4-T	P4 TOP PLATE
1	P5-T	P5 TOP PLATE
1	P6-T	P6 TOP PLATE
1	P8-T	P8 TOP PLATE
1	P1-B	P1 BOT. PLATE
1	P3-B	P3 BOT. PLATE
1	P4-B	P4 BOT. PLATE
1	P5-B	P5 BOT. PLATE
1	P6-B	P6 BOT. PLATE
1	P8-B	P8 BOT. PLATE
11	S1	2X4; 10-1/2" 90°
22	S7	2X4; 18-1/2" 90°
1	C1	3'-2-1/8" X 1'-0"
2	C3	3'-6-7/8" X 1'-8"
2	C4	3'-2-1/8" X 1'-8"
1	C6	3'-6-7/8" X 1'-0"

2 PANEL FRAMING (P1 EXAMPLE)

FLIP SO LABELS FACE STUDS

ALIGN STUD BETWEEN SCRIBED LINES

STANDARD PANELS - P1, P3, P4, P5, P6, P8

CASTING FACE ATTACHMENT 3

ATTACH CASTING FACE WITH FASTENERS TO THE FRAMING BEYOND, MINIMUM 2 PER STUD

FOR TALLER PANELS P3, P4, P5, P6, ADD A FASTENER IN THE CENTER OF THE STUD AS SHOWN IN GRAY

COMPLETE PANEL 4

REPEAT STEPS 2-4 FOR REMAINING STANDARD PANELS

FORMWORK ASSEMBLY

9 FORMWORK WALL P1-P4

ATTACH PANELS BY ALIGNING AND FASTENING THROUGH END STUDS. MINIMUM 3 FASTENERS

10 FORMWORK WALL P5-P8

ATTACH PANELS BY ALIGNING AND FASTENING THROUGH END STUDS. MINIMUM 3 FASTENERS

LAYOUT INFORMATION

LAYOUT PLAN 11

COMPLETED FORMWORK SYSTEM 12

Figure 7: Example booklet spreads from wall 2.

Preparing the AR method was much more of an experimental process, as there are few established best practices or rules of thumb when it comes to XR representations in design and construction. The AR instructions utilized the Fologram application and an iPad, although many permutations of software and hardware are available on the market. The primary requirement for selecting the software and hardware was its ability to visualize the 3D model overlayed in real space with some kind of scaling and synchronization, which meant the hardware needed to be capable of LIDAR scanning (or a similar technology) and the software had to be powerful enough to move beyond being a simple visualization tool. The combination of the Fologram app with an iPad was reached after evaluating the prominent HMD, mobile device, and software combinations available on the market at the time of this project's literature review (2023-24). Review of these platforms was conducted based on the following:

- Number mentions in articles on the subject, cross referenced to other articles
- Cost of the platform (hardware and software)
- Technical specifications (processing power, RAM, camera/sensor quality, etc.)
- Tenure of the platform and company (many HMD and software platforms disappear as quickly as they emerged, which makes continued use and support of the often-expensive device difficult)
- Whether a trial was available
- Whether hardware was available internally through Turner's Information Services department (IS)

Ultimately, Fologram was selected as a good entry point that provided a strong basis for the assembly trials without a high upfront investment. One of the selling points not captured in the list above was that the company offers several software options for both mobile and HMDs depending on desired precision, usability, and cost. This would allow the research to extend further into an exploration of implementing and testing a more "commercial" version of the software and hardware used in this experiment if there was continuing interest. The mobile platform approach is generally easily accessible from both a device and cost standpoint, as the devices are ubiquitous and the app cost is fairly inconsequential for any size of company to experiment with. The iPad was chosen over a standard mobile cellphone after extensive testing during the trial period with a phone. The phone provided a lot of great confirmation as a proof of concept but was somewhat difficult to view due to the small screen size. Additionally, the tablet was procured from old stock held by Turner IS, meaning a new device did not need to be purchased. Figures 8 and 9 on the following page illustrate the hardware, software, 3D model, and the model overlay for wall 3. The AR model was based on the model prepared for the CNC labeling process with a few additional tweaks. Callout points were added to the midpoints of the major visible faces for every piece of geometry so that parts would be labelled in a way that could be viewed from further away and different angles. The CNC labels were retained in the AR model but required moving close to the piece to read the label accurately. Drawing from the work of Hartanto (2019), an example panel was taken from the formwork model and deconstructed to create a 3D exploded view which is more or less a 3D PAI but with all steps in one visual model. In this case, the exploded model was created at a 1:1 scale so that users circulated around it to view how components were joined. This example model was on a separate layer that could easily be toggled on and off separate from the rest of the model so participants could hide it once they grasped the assembly logic.

3.3 Survey Format

The survey is perhaps the most critical information gathering component of this project. While a portion of the survey questions were formal, quantifiable, and data-backed, such as the ATI and SUS surveys, there were many open-response questions to collect qualitative feedback from the participants. The open questions captured the human experience of working with these methods, which cannot easily be quantified and observed like the elapsed time or number of errors. As such, these responses provided broader explanations and anecdotes which established a landscape of observations and feedback tied to people and their thoughts. The high value of these surveys meant that they were numerous and issued at multiple stages of the process. One

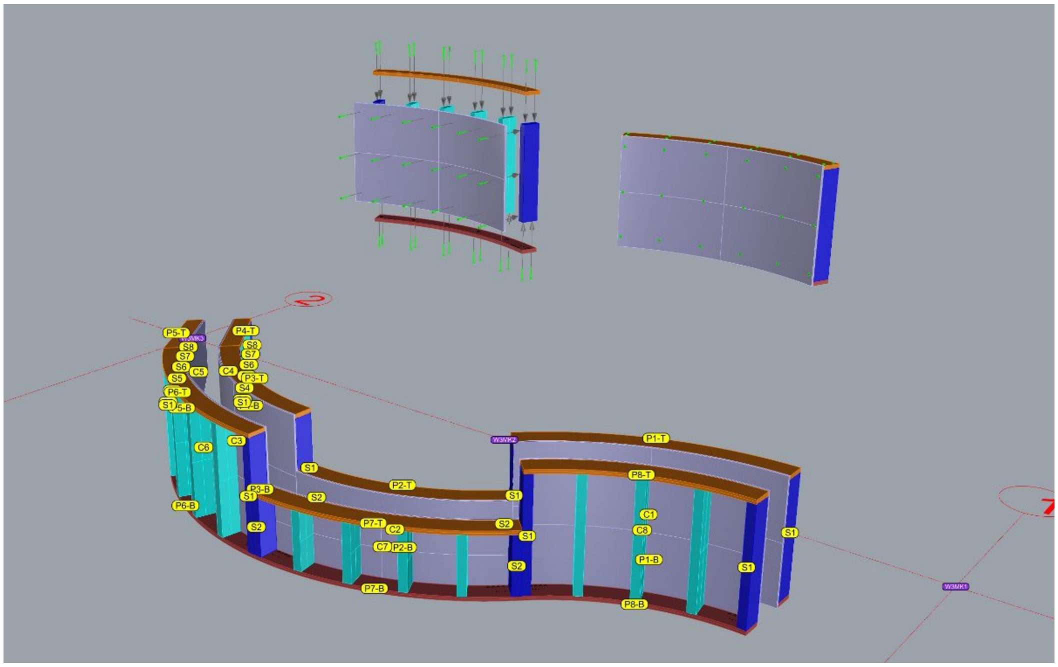


Figure 8: The AR model in rhino contains a number of floating point tags for identification in addition to marker points to be synced with the QR codes in physical space. Also pictured are the exploded panels which act as a 3D PAI.

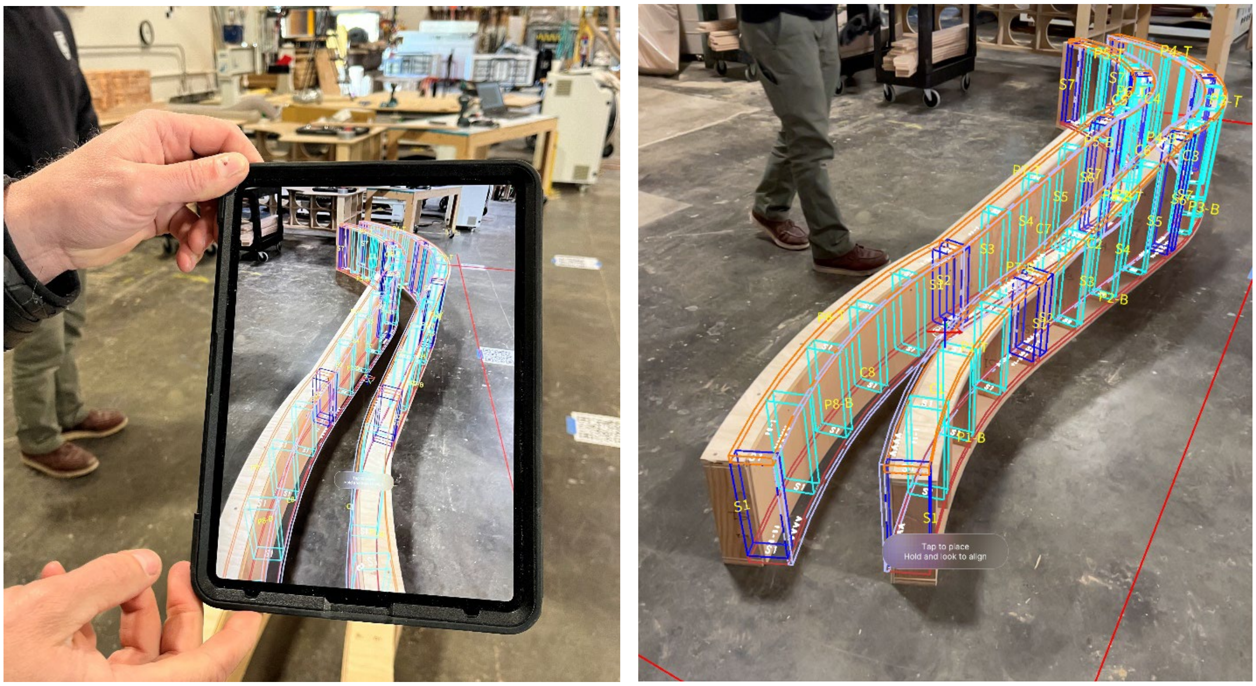


Figure 9: (left) A photograph of the iPad running the Fologram app after synchronizing. (right) A screenshot from the iPad for a cleaner view of how the wireframe view appears in real space.

set went to the participants before starting, another after each trial, and a wrap up comparison at the conclusion of the project. In total, three different surveys were prepared for participants to complete.

The ATI survey was given to participants along with the demographic questions at the start of the orientation session. The ATI scale is a free-to-use survey developed by Franke, Attig, and Wessel and published in 2019 after significant internal testing. It is a 9-question survey that utilizes a 6-point Likert scale from “completely disagree” to “completely agree” which allows the quantification of each response into values that can easily be analyzed and compared. The answers are aggregated as an average score out of 6 which indicates the likelihood of the respondent actively utilizing new technology systems or avoiding them. This scale is meant to be simple and applicable to a broad audience, whereas precedent scales such as the TA-EG used in Funk and Schmidt (2021) are more technical, require more input, and were designed to focus on tech savvy individuals rather than the average population (Franke et al 2019). Although the scale is self-reported, the extensive testing by Franke, Attig, and Wessel (2019) as well as further verification testing by Lezhnina and Kismihok (2020) support the scale’s integrity as a reasonably accurate measurement with minimum required input. This file can be found in the supplemental files as item B1.

The SUS survey was given after each assembly trial to collect data about that isolated test method, so participants filled out a total of three of these surveys. The survey consists of 10 questions and is similar in format to the ATI questionnaire, with a 5-point Likert scale from “Strongly Disagree” to “Strongly Agree.” Developed by John Brooke in 1986 for the Digital Equipment Corporation, it is a tool to determine the ease of use of any system to a new user. The scale was released by Brooke and the Digital Equipment Corporation for free-use in Brooke (1995). Rather than an average across all responses, the SUS survey returns a “score” after summing up responses which can be compared with other respondents and averaged across all datapoints collected for that system. Similar to the ATI survey it is self-reported, but the scale has been used in many subsequent studies and is well supported as a reliable metric (Brooke 1995). In addition to the SUS survey, a brief series of questions were asked after each trial. These questions were intended to capture more qualitative feedback and supplementary information to help explain and understand how the participant rated the particular method. The questions were created following the question styles utilized in the ATI and SUS surveys, namely asking both positive and negative questions to encourage thoughtful responses. The questions included are as follows:

- What are your overall thoughts on this style of assembly instructions?
- Did you find this style more enjoyable to work with than typical practice?
- What worked well with this system?
- What was not effective or difficult to understand with this system?
- Do you have any suggestions?

This file can be found in the supplemental files as item B2.

A conclusion survey was handed out after all assembly trials had been completed by the participant group. This survey focused on having the participants rank the three different approaches tested and also provided space for general, open comments regarding the study. The approach to these questions was the same as with the follow up questions after each trial, but also included a few that asked respondents to rank choices in order of effectiveness, and also select one of the three methods as the most effective method for prefabrication or for site work. The questions are as follows:

- Please rank the 3 options below from 1 (Best) to 3 (Worst) based on how effective the instruction method was, in your opinion.

  Shop Drawings Assembly Booklet Phone-based AR

  Please provide some comments about your ranking above:

- Which system do you think would be most effective for prefabrication work (circle one)?

  Shop Drawings Assembly Booklet Phone-based AR

- Which system do you think would be most effective for field work (circle one)?

  Shop Drawings Assembly Booklet Phone-based AR

- Any general comments about the different systems in this study?

This file can be found in the supplemental files as item B3.

These open comments were an important counterpart to the quantitative data. While direct observation did yield a number of valuable quotes and insights, the written comments allowed participants to stop and think more critically about the process they just utilized. This captured commentary that was forward thinking and/or inward focused, such as how the participant grappled with the changing work methods. The comments were also given an interpretation of being positive, neutral, or negative, to help quantify what way a particular set of instruction's written feedback leaned, which can then be compared against the SUS scores.

3.4 Assembly Trial Format

The assembly trials consisted of a series of three back-to-back assembly projects for each group, utilizing the three different instruction methods prepared (shop drawings, PAIs, AR). The Turner Construction Shop space was the testing location as it provided a large, open warehouse space to conduct controlled trials and most Turner employees were familiar with the location already. Teams were allowed to take breaks as individuals while working, which kept the timer/video feed rolling, but when teams requested a break as a group (e.g. in between trials) the gap time was not counted as a part of their overall elapsed time. Each team started with a different instruction method and rotated through the others, which allowed for the method's effectiveness to be gauged, compared, and averaged in an effort to offset the productivity gains that arise from repetitive tasks observed in Funk and Schmidt (2021). This is visualized in figure 10.

The first thing groups did after arriving at the shop space was attend an orientation provided by myself and the shop's head carpenter covering the following:

- Safety practices and Personal Protective Equipment (PPE) requirements
- An overview of the study and what was being asked of them
- Written and verbal explanation that the process would be observed/recorded
- A photo/video waiver to document consent for use and publication
- The ATI and demographics survey

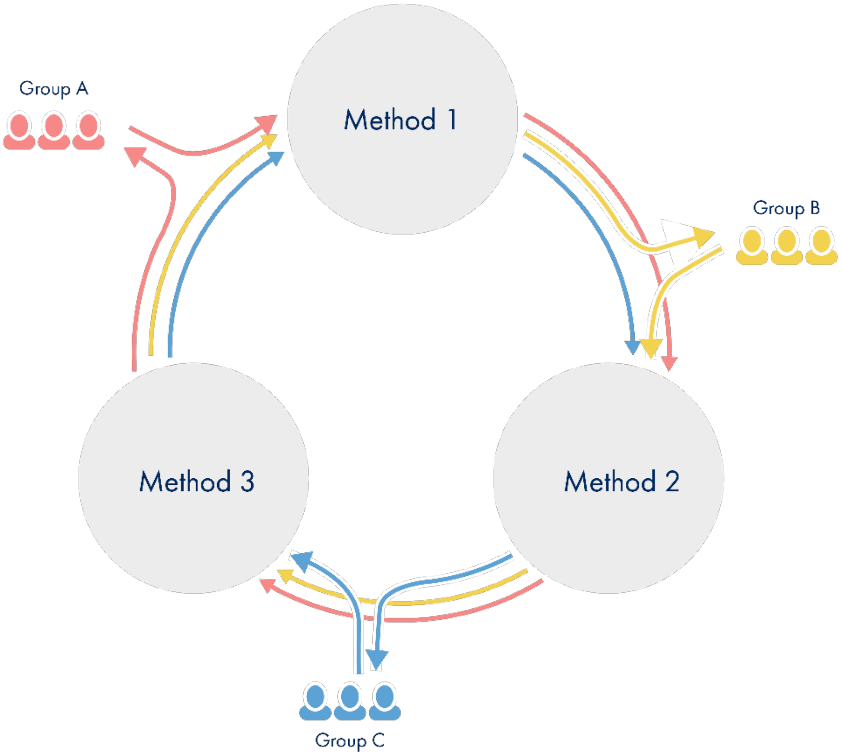


Figure 10: Each participant group began with a different type of assembly instructions and rotated through the remaining sets.

During orientation, it was emphasized that the participants overall thoughts about the tested work methods were the primary observations, with productivity in terms of elapsed time and the number of errors being inconsequential in comparison. Participants were encouraged to work at their own pace and to make comments to each other or the observer to record when they came across something notable, whether it be a positive, negative, or neutral comment. This fostered a collaborative, explorational atmosphere around the trial environment, rather than a "top down" observation by a superior/supervisor. In addition to noting direct comments and quotes, the observer utilized a phone camera to track progress and document the process. The focus of these observations was to catch major quotes from the participants, track errors, and record observations. Although a formal consent waiver or explanation was not required due to the IRB exemption, the orientation included these topics in full written and verbal form, sans the signature for formal consent. As a thesis focusing on construction communication issues, it was important to communicate with the participants clearly and follow best practices, even when not required. The Photo/Video waiver utilized was the UW CBE standard form which is required when taking photos and videos of activity participants. All participants signed the waiver with no concerns.

Figure 11: Parts for each wall kit organized onto rolling carts.

After orientation, groups were guided to the workspace and received specific instructions regarding the first assembly trial and the instruction method involved. All of the required tools and parts were laid out in the workspace beforehand, with the parts organized onto rolling carts for ease of movement. During the assembly trial, I was a silent observer and answered minimal questions. The original intent was to answer no questions, however, some items came up that required breaking this barrier, such as requests for additional fasteners and a question about a piece which was determined to be improperly prefabricated. A phone with a tripod was placed along the wall to record the entirety of the assembly trial and was supplemented by photos taken during the process.

After the first trial was completed, the participants filled out the SUS survey during a short break while the work area was reset with the new pieces. The formwork wall for the following trials changed between different wall kits of similar complexity to combat the repetition efficiencies observed by Funk and Schmidt (2021). The teams repeated this process until all three assembly instruction types and walls had been assembled by the team. Upon finishing, the conclusion survey was handed out and the participants were thanked for their time, marking an end to the tests for that day. After the participants left (and occasionally during the trials), the formwork walls were disassembled to reset the kits for the next day of assembly trials. Subsequent groups rotated through the assembly instructions, starting with a different set than the previous group. The intent was to use their averaged values to offset the efficiency skew that would develop from repeatedly working within the same formwork framing system. Overall, the trials ran very smoothly outside of a scheduling issue and a duration issue. Participants were very enthusiastic about learning and testing new work methods and found the test day a pleasant step away from the typical job site.

3.5 Why Concrete Formwork

From the brutalist monoliths of the 20th century to the contemporary discussions around its carbon footprint, concrete has become omnipresent and inseparable from the built environment. The increasing number of designs employing organic forms are an opportunity for concrete to exhibit its strengths as a formless material that can become anything, provided the formwork can be efficiently fabricated and erected. Historically, efficient organic formwork meant repetition and reuse of the formwork which enabled structures to be justified to stakeholders over other design options. However, as designs move toward free-form expressions, the traditional approach to organic formwork becomes ineffective as there is less repetition and reuse. As a result, the concrete industry is well poised to explore unique solutions to this challenge, such as the digital prefabrication methods outlined during the literature review section. Not only could this enable the efficient production of one-off formwork kits to achieve these designs, but it could raise the quality of typical concrete work by integrating modeling aspects such as form tie locations, rebar, etc., and include that information in the labels on the prefabricated pieces.

While there are many types of formwork that could be digitally fabricated such as foam formwork, wood framing was selected for the trial assemblies. The precedent digital prefabrication workflows at Turner Construction were wood frame systems, which made this a more logical type to analyze rather than looking to something unfamiliar. Similarly, wood framing is more likely to be used to achieve simply curved surfaces than the other options, which are more apt for doubly-curved surfaces. Additionally, this workflow naturally impacts the wood frame construction industry as a whole and could establish an avenue to achieve more organic and experiential designs in wood frame construction without major cost implications but employing the same digital prefabrication techniques to produce organic stud walls instead of formwork walls. This makes wood frame concrete formwork a strong case study to test the different assembly instructions and the digital prefabrication practices, as it is both specific enough to test and observe, but also representative of larger industries so the data analysis can be applied and tested to other areas of construction.

3.6 Formwork Models

Three comparable formwork models were prepared for use in the assembly trials. In addition to reducing the chances of repetition efficiency, these alternate wall designs were prepared to mitigate growing familiarity if the wall was repeated, which could allow participants to skip reviewing the new instruction format entirely and build the wall based on memory. The models were designed and fabricated to be comparable in scale, complexity, number of parts, etc., while also providing enough variance between the three tests so that participants must reference the instructions rather than previous knowledge of the last assembly trial. Each wall has four pairs of panels: one pair of low panels, two pairs of high panels, and one pair of sloping panels. This is theoretically enough parts to necessitate reading through the instructions carefully in order to properly lay out the completed panels and achieve the overall desired formwork wall without being too onerous to produce or assemble. The walls are visualized in figure 12. Without preliminary testing there was not a guarantee that the wall designs were similar enough that they would not impact the data, but by keeping the aspects listed above constant it was inferred that

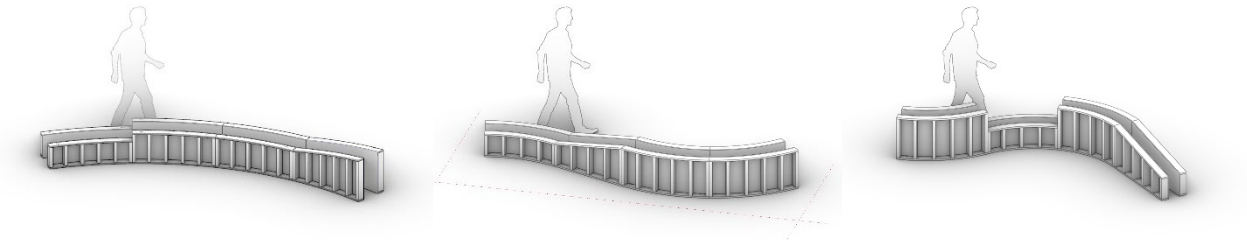


Figure 12: Wall 1 (left) wall 2 (center) and wall 3(right) are visualized in this black and white rendering. All walls are composed from similar elements but in different arrangements.

the wall design would not be a significant factor. The original plan was to produce a prototype to verify whether the CNC produced kit had any major discrepancies but due to the issues discussed in section 3.7, this step had to be omitted. After the trials were completed, certain data points were used to evaluate the similarities and differences between the walls and thereby provide insight on the previous claim.

Another factor in the development of multiple wall kits was to demonstrate the "design to fabrication" workflows explored during literature review by creating a Grasshopper script to translate design geometry into a parametric, fabrication level model. Automating this section of the modeling process led to a script requiring require minimal human interaction to prepare the file for the CNC, which saves the modeler's time for better uses and also allows the model to update quickly if the design changed. Establishing the targeted workflow as a framework was straightforward, in part due to the existing knowledge base within the Turner VDC which has previously developed other Grasshopper scripts to automate aspects of their modeling processes. In particular, the scripting for their edgeform and blockout prefabrication processes mentioned in section 2.2.1 were of use in developing this workflow. This framework is illustrated in figure 13 at a very abstract level, highlighting the major steps, inputs, and outputs. The core challenge of the scripting process was determining the inputs and outputs. The input is a major driver for how the rest of the script processes information; being too specific could make it difficult to apply the script outside of the designed wall type parameters, yet being too general could make it increasingly complex to write which results in longer development times and more opportunities for bugs. The output is also important to consider because it determines how the script's order of operations should be laid out

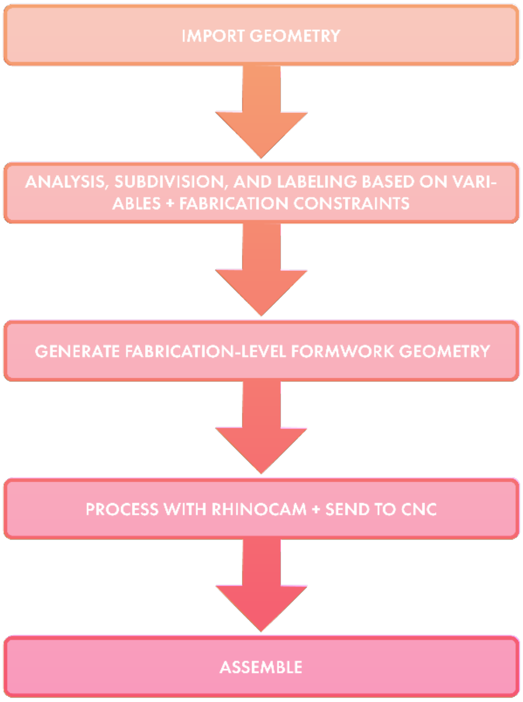


Figure 13: Flowchart of the major steps in the grasshopper powered FIM prefabrication framework.

to achieve the desired outcome. Although this research focused on a single type of concrete wall, the simply curved pony wall, the idea was to have the script be applicable to a broader range of cast in place walls by accurately capturing the wood framing and retaining the potential to add complexity such as reinforcing and form ties as a later project. As such, the inputs needed to have a certain degree of variance to accommodate a broad range of input designs. However, they could be narrowed to a single type of geometry, which in this case was the surface representing the cast face of the designed wall. A project goal was to generate more than formwork geometry alone, so the desired output included an automated labeling system that added to the approaches Turner had developed previously. This labeling system allows for the quick identification of parts without the labor involved in manually marking the pieces (digitally in Rhino or physically, once produced). As the labels are translated into CNC toolpaths along with the part profiles, the labels also assist with the framing stages by showing an outline of the stud locations and other information such as the stud height and the angle of each stud's end cut. The labels will be discussed in more detail in a following paragraph.

The geometry generating section of the script is visualized in figure 14. The script takes the input surface and subdivides it based on an input variable, *sheetmax*, which represents the

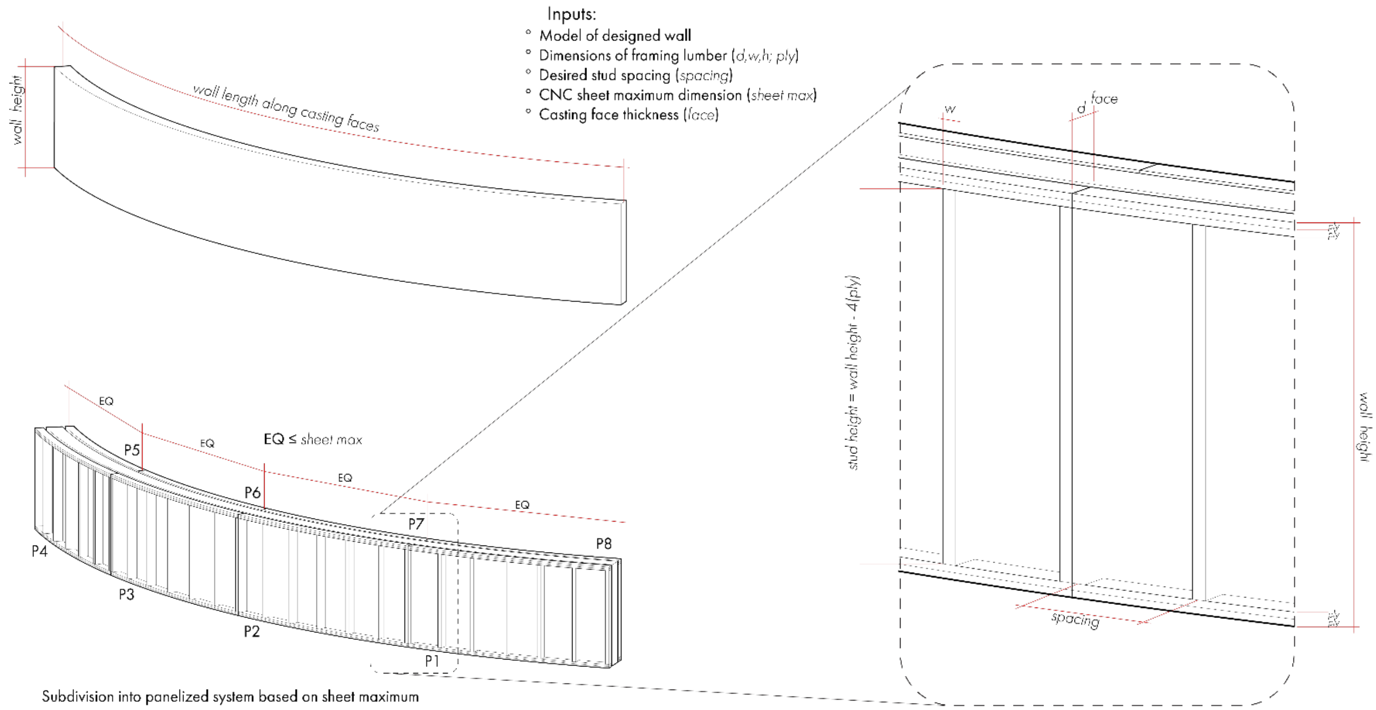


Figure 14: visualization of the formwork generation driven by input variables.

panels. The subdivided casting face is then offset to reflect the thickness of the casting face material, *face*. The top and bottom plate geometries are generated with additional inputs *d,* for dimensional lumber depth, and *ply,* for plywood thickness. Lastly, the studs are created by dividing up the panel length by *spacing,* the desired maximum stud spacing, which returns a number of division points resulting in an equal spacing that is close to, but less than the maximum spacing. The height of the geometry is determined by the wall height of the input surface less the top and bottom plywood plates, which can be single plates or doubled up. The extrusion of the studs occurs slightly differently, so that the middle studs are centered on the division point while the end studs are extruded away from the end of the panel, making the end flush.

Developing this workflow required a large amount of trial and error as different input surfaces were processed to evaluate what worked and what did not. For instance, a surface in Rhino can be made in a variety of ways – directly with a surface command, by lofting or patching curves, by extruding a curve, by revolving a curve, and so on. Every one of these methods has a different order of operations in creating the surface geometry, which complicates parametric modeling because the edge curves will be in a different order and the direction of the surface normal is often random. To ensure the scripting did not become a time sink, the input surface was processed manually in Rhino before bringing it into Grasshopper to ensure the input was modelled in a compatible way with the script rather than create a script that could analyze and "fix" the surface if required. Similarly, inputting a complex surface with a profile that captured the height changes of the overall wall caused complications as the script struggled to deal with immediate height changes and kinks in the boundary curve. In response, the workflow integrated another step of manual processing with some revisions; the initial surface is modeled at a constant height, input into a section of script for subdivision, and then baked into geometry. At this stage, the edges of the surfaces can be easily changed to the desired form, and then each individual subdivided surface is reconnected to the script for the formwork geometry generation stage. Ideally, this would be a completely integrated process, but the workaround developed allowed for a demonstration of the core concept that achieved the desired outputs and avoided unnecessary development times.

The script included a separate segment that created a series of labels on the top and bottom studs which served as the CNC labels but also as the floating part labels in the AR model. This segment of script runs after the formwork geometry has been baked back into Rhino to simplify the information streams. Most of the labeling process is quite simple, and the initial concept is visualized in figure 15. The script takes a few text inputs, such as "T" or "B" for top and bottom plates, and adds the text string to another string generated by the geometry to determine the panel number, resulting in codes such as "P1-T." The casting face is denoted with caret ^ marks. These labels are created by selecting the desired edges of the plates and inputting them into another short Grasshopper script. The last major labeling innovations are the stud locator marks paired with fabrication information labeling. Utilizing the 3D model, the stud geometry is broken down, the end faces are duplicated, and their long edge curves are analyzed to determine the length of the stud. The edge curves are evaluated for the longest length which is then put into a text string parameter in Grasshopper. The duplicated end faces are analyzed for rotation of their planar geometry against the model's XY plane which returns an angle in degrees. These are adjusted by subtracting them from 90 degrees which represents the standard perpendicular cutting angle of a chop saw, meaning that any degree variation in the end face of the stud is recorded as an angle less than 90°, or 90° if the face is parallel to the world XY plane. This information is stored in another text string which is combined with the length text string to get something similar to that shown in figure 15. The end face's perimeter curve is also duplicated and, together with the combined text string, is paired with the plates and labels, rather than with the studs. It is important to note that, although the initial workflow included the approach above, the actual CNC labels were a simple S1, S2, S3, so

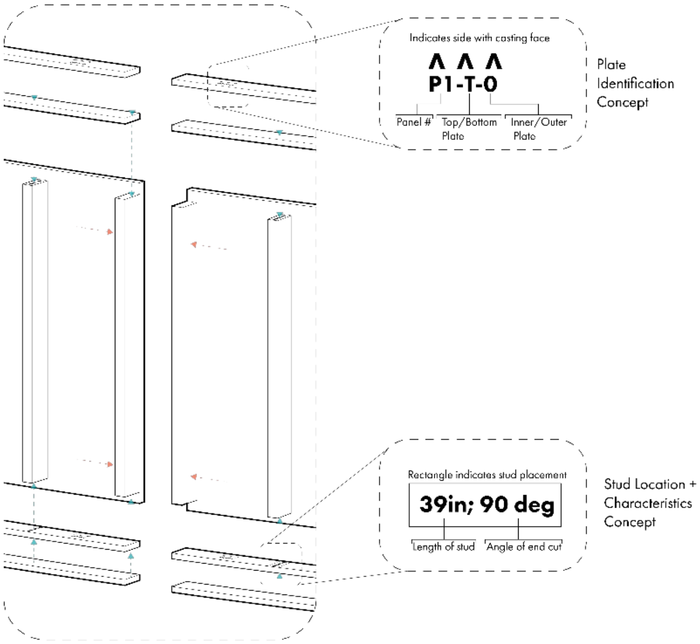


Figure 15: labeling conventions and locations.

on. This change made it much easier to run the assembly tests as observations of an Ikea style assembly, in which specific fabrication dimensions are not relevant. It also greatly reduced the cutting time operation which was critical to the success of the assembly trials (more on this in section 3.6). The first labeling system was created because it is incredibly useful when producing the studs given only the labeled top and bottom plate. However, this thesis is focusing only on the assembly of the flat-pack kit of parts and not the production of said kit, so the most apt symbols to engrave were simple codes rather than more in depth FIM information.

At this stage, the wall geometry can be saved as separate copies to begin developing the individual assembly instructions. Regarding CNC production, the model is partially deconstructed, leaving only the important CNC information. The major steps are deleting the unnecessary geometry, rearranging and flipping the plates so that the labels face upward for proper machining, and then duplicating the edge curves of the plates so the 3D geometry can be deleted, leaving only curves. Additionally, text must be converted into curves in order to be cut with the CNC. The RhinoCAM process itself is not important to detail, but in summary involves importing tooling data, linking operations to the right curves, and simulating the cut before sending it over to the machine. For each wall, two sets of plates were produced; one set had the full set of labels, and the others were simple, blank profile cuts. The blank set is to allow the shop drawing tests to accurately reflect the process, as carpenters would need to measure and label all of the information that is CNC carved for the other kits. Although Turner Construction has developed their own scripted method of processing 3D geometry for RhinoCAM, for this research a manual operation was employed so that I could get better acquainted with the RhinoCAM process.

Given that this research involved creating three different sets of formwork walls and additional duplicate plate blanks for the shop drawing tests, materials were a major concern for the project. From a cost standpoint, utilizing new materials would have required an approved budget in excess of $1,300. While the cost would not have been unbearable, the use of new material for a series of assembly tests that may eventually end up as waste seemed like an unsustainable approach to performing research. To minimize the dependence on virgin material, Turner’s inventory was reviewed and alternative options were identified. The plywood sheets utilized to produce the plates came from another CNC project’s waste stream that was diverted to this project. The plywood was in great condition, with enough 32” x 48” mini-sheets waiting to be disposed of that we did not need to acquire more plate plywood. The studs were produced from old, trimmed down 2x6 lumber which was used on earlier job sites until it became unusable. Since the assembly test panels are no more than 1’-10” tall, it was easy to cut the bad sections of board out and reuse a majority of this lumber, allowing us to avoid purchasing new material. Although the facing plywood came from new material, it was excess stock purchased for a different job that was completed, leaving extra bending plywood. Overall, all materials were able to be sourced from waste or extra inventory which was a worthwhile exercise in sustainable material streams. Additionally, the three walls are intended to be reused after the research concludes as a brief training and teambuilding exercise for new apprentices.

3.7 Impromptu Alterations To Methodology And Challenges

Despite careful planning, there were a series of hiccups during the assembly trials that threatened to complicate the data validity and required quick thinking and alterations of the methodology as things were already underway. One concern was the amount of time the participants were scheduled to be at the shop. The initial ballpark was a full half-day to a whole day. However, the actual amount of time reserved during scheduling (which was conducted by a separate party within Turner Construction) was limited to 3 hours. After the first group’s time-in-shop was roughly 4 hours, the scheduled time was confirmed insufficient. Later groups also averaged a total time-in-shop duration of about 4 hours. While this did not escalate into an experiment-stopping issue, in some cases participants had to join late or leave early in order to accommodate jobsite work they needed to do, or important phone calls and meetings they had to step out for.

Another challenge was the number of participants each day, which influenced the three trials taking place that day. The first day, four carpenters showed up, one more than planned. At first it seemed as though the scheduling manager had found one more person to participate and had not relayed that information, but it was actually a different scheduling miscommunication. Due to an email mix up, the extra person did not know they were supposed to come on the second day, which meant that on day two we only had two carpenters. As their other site work had been scheduled, they could not be sent away and expected to return the following day, so the assembly trials proceeded with these changing numbers of participants.

Mitigating these fluctuations required some impromptu discussions, and eventually the following revisions to the methodology were formulated. These alterations were meant to be working solutions that would allow for reasonably accurate data despite the differences in the number of participants on different trials and on different days. The first group with four people was required to put in all screws per the instructions, as if it was going to be a real piece of formwork. This ensured there was ample work to perform, despite having an extra set of hands. The later groups were instructed to put in roughly half of the screws indicated in the documents, essentially enough to hold the formwork together as a mock-up but not as a "real" piece of formwork, ready to be poured. Additionally, in order to reduce time elapsed overall, the layout portion of the assembly task was cut for all walls except AR, as the layout is inherent in the technology. Although the time elapsed was potentially impacted, these deviations were deemed acceptable solutions as the quality of the written feedback would remain true, as the participants would still be going through all of the motions of assembling the wall with the given instructions. The data that is impacted by these fluctuations is noted with an asterisk * in the datasets to follow.

In the weeks preceding the assembly trials, two other challenges emerged that threatened the project schedule and the assembly trials overall. The first challenge was that the Turner CNC broke down shortly after cutting out the first set of labeled plates, which were intended to be a prototype kit to test the production quality and ensure there were no constructability problems with the design. As time went on, the diagnosis became more complicated and there were no guarantees the machine would be operational in time to cut out the assembly kits. After a few more days of inconclusive testing on the Turner machine, the project pivoted and the UW CBE Fab Lab was contacted to see whether the project could be completed on the CNC machine in Gould Hall. It took a few days of discussion to clarify the project scope, review the CAM files, and gain clearance, but eventually the project was approved for production on the UW machine. Although this solution enabled production, the UW machine was vastly underpowered in comparison to the Turner machine, which extended the production timeline by over 3 times the original planned time on the Turner machine. As a result, there was not time to cut out a fourth set, which would be identical to the prototype set produced on the Turner machine but with the updated “S1, S2, S3…” labels. A sharpie made quick work of the revised labeling structure on the original prototype plates but opened the door for some confusion during the tests with that wall kit due to having a type of engraved labels with different information and no key. This machine failure raised a series of interesting questions: if production moves toward mass-prefabrication, what happens when the machine breaks down? How are the schedule shifts and other delays handled? Will these future carpenters, trained primarily in these alternative building methods, be able to effectively switch back to traditional fabrication methods in the meantime? Although this thesis does not pose any answers to these questions, the considerations are important to keep in mind as the technology and ideas are further developed and implemented in the future.

The second pre-trial challenge was sourcing participants. Anticipating scheduling difficulties, this process began early in 2024; if it had begun any later, the project may have not reached the assembly trial phase. The participant selection was left to a different party within Turner which streamlined the outreach process, but it was not until the last few weeks before the assembly trial that the nine participants were confirmed. Although the minimum number was reached, the participant pool ended up consisting of two different labor groups within Turner: 6 carpenters and 3 surveyors. The unexpected diversity of the participant pool allowed for broader feedback than what was originally expected, but it also means that the quantitative component to the data, particularly the averages, were a bit weaker.

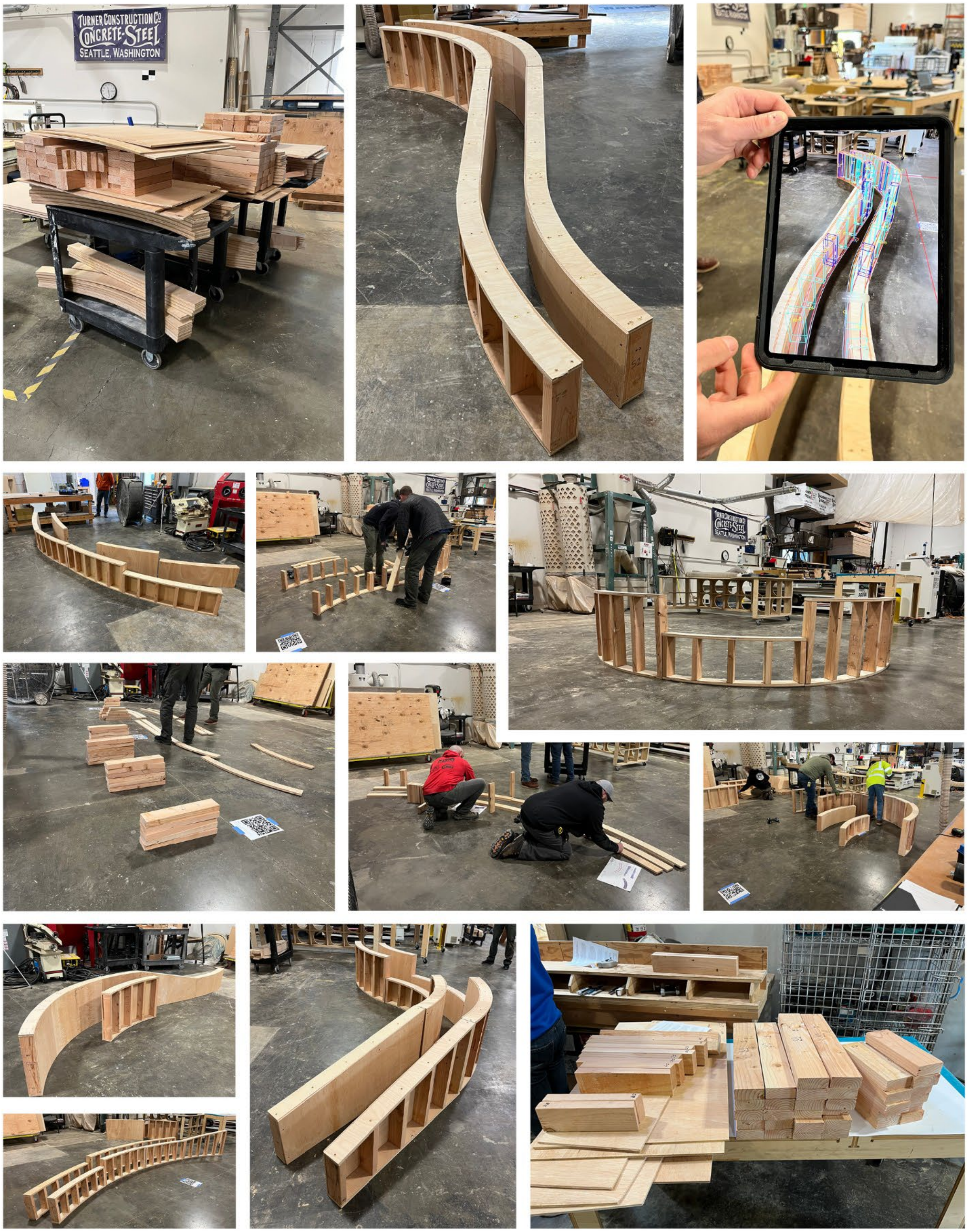


Figure 16: Photocollage of images captured during the three days of assembly trials.

4.0 RESULTS

Despite the difficulties encountered while setting up and carrying out the assembly trials, the trials themselves were a resounding success. The participants brought a strong sense of positivity and collaboration to the assembly tests, providing even greater feedback and critique of the instruction systems than expected. This enthusiasm seemed tied to the fact that they were being asked directly for their thoughts and opinions about how aspects could be done differently, rather than told how to do something. As mentioned in the previous section, the thoughts and ideas of the construction workers were intended to function as the primary data source to shape the analysis and results, so this excitement about the research in practice was incredibly welcome and lent itself to a much more rich and nuanced series of analyses and takeaways. This approach centers the discussion around the direct human experience of communication rather than indirect results such as the time to complete the assembly task, etc., and gives a better understanding of the strengths and weaknesses of each method with a limited pool of data. The various quantitative data collected was still useful as supplementary evidence to back up the initial takeaways, and in almost all cases the qualitative and quantitative data were in alignment. This is one of the most interesting trends across the two data sets, as this similarity suggests that the participants consistently answered with their authentic opinions across all of the different survey formats. The charts included as figures as well as extras not included are located in the supplemental files items C1-C7.

4.1 Analysis

The comments, aggregated from observed statements during the tests and those recorded from the surveys, showed overwhelming support for the CNC engraved labeling system that was incorporated into the AR and PAI approaches. One participant said that they “could have done it without drawings,” a sentiment shared by others who had similar high praise for the combination of an effective labeling system with the PAI. Although the labeling system was a core part of the digital prefabrication workflow, the labels were seen as a means to enable the AR and PAI methods to be the most successful rather than a stand-alone instruction method to be observed in this thesis. Without collecting and reviewing these comments first, it likely would not have been possible to ascertain this result, which is integral to explaining some of the overall success and positive reception of both the AR and PAI approaches. Additionally, the overwhelming popularity of the labels was valuable feedback not only for this thesis but also for Turner, as it will inspire revision and future research into the existing approaches to CNC part labeling within the company. Figure 17 depicts the first iteration of the labeling system that was illustrated in the previous section. Although these labels were revised for the assembly trials, they demonstrate the core idea of integrating fabrication and assembly information directly into the CNC produced parts. Turner has experimented with other systems such as joint markings in the past, and there are a great number of different methods and symbols for part marking used by carpenters. A deeper dive into labeling could involve these approaches for another exploration of instruction methods to determine if there is a particular style of labeling that is noteworthy or situations where one is better than another.

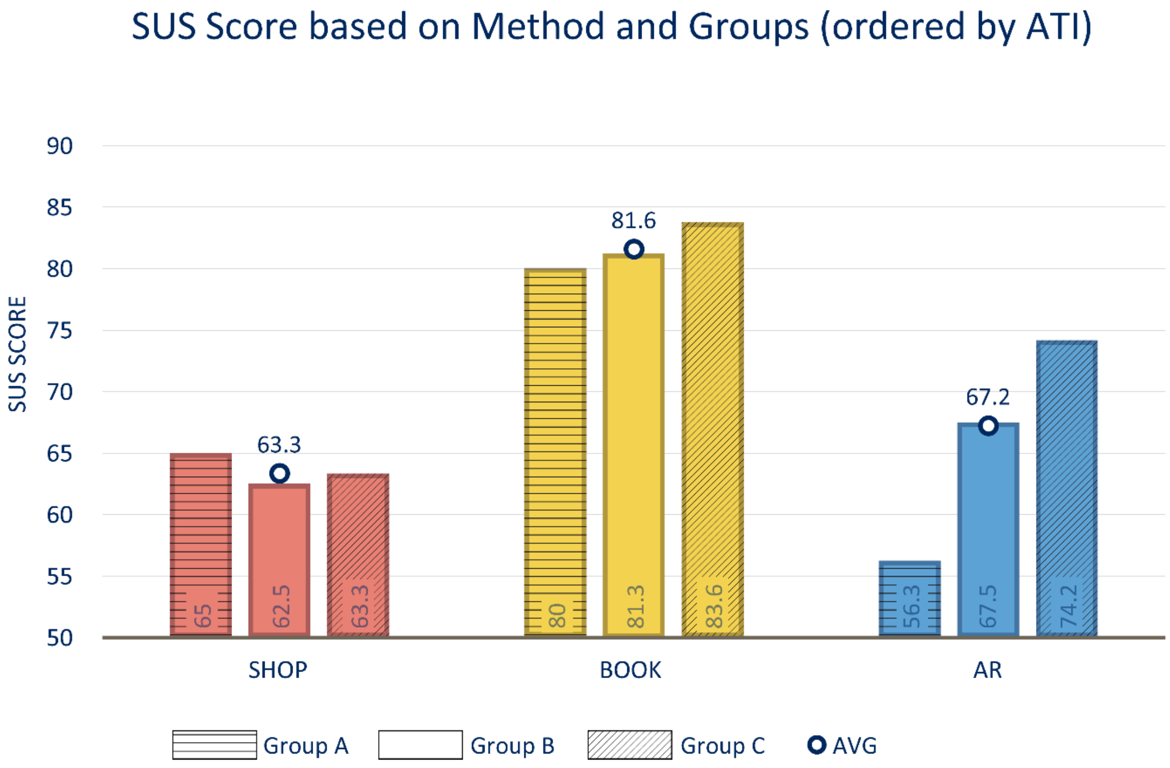
Figure 17: This labeling system represents an approach that will be further investigated by Turner Construction as a way to encode fabrication information into the CNC'd parts, as opposed to the assembly information encoded into the parts used in the assembly trials.

In alignment with the high ratings of the labeling system, it is no surprise that in the comparison survey 87.5% of the participants ranked the methods in the same hierarchy. From most to least effective, the booklet came in first, followed by the AR approach, and lastly the shop drawings. The booklet coming out on top can be thought about from a few different angles, but its primary strength is its familiarity to the workers despite not having built formwork with a PAI before. With the prevalence of prefabricated furnishings and other objects, it is reasonable to assume that few people have not been exposed to an assembly booklet at one time or another, and one comment which simply read “Very easy, IKEA Kit!” sums up this notion. The PAI can also be thought of as shop drawings formatted in a different way – both systems rely on a longstanding culture of reading and interpreting drawings, pull from the same best practices for legible drawings, and lastly both are tangible methods to convey assembly and construction information. Looking to further refinement and implementation, the general populous’ broad familiarity with reading and interpreting instruction booklets could prove a useful tool in communicating with crews that may be less practiced with reading traditional drawing sets.

Conversely, the AR approach applied the well-liked labeling system but in a manner that was entirely novel. Although many people are aware of what AR is as a concept, cost and access barriers to the technology mean that few have had the opportunity to actively utilize AR for any purpose, even coming out of the COVID-19 pandemic which brought the concept of XR to the foreground. As a result, many comments regarding the AR approach specifically mentioned that AR seemed effective once set up, but that it “requires more knowledge than the assembly booklet,” could be “daunting to [workers] in the field,” and that “some people might have a little tech setback.” This is a case where a more diverse range of participants would be beneficial, as younger generations may find the AR visualization approach to be more intuitive than the experienced professionals involved in this thesis. Other participants voiced concerns about the accuracy of the technology in achieving the required tolerances for high performance construction. While a valid concern, the precision of the program is governed by forces external to the scope of this thesis that is focusing on the broader concept of utilizing AR as a drawing-less form visual communication. As such, the specific implementation constraints of the chosen application are not being considered as major stumbling blocks for the technology as it pertains to this work. As a type of visual instructions, AR was quite successful in creating accurately positioned and scaled visual mockups and participants voiced their support for the technology as a means to convey the general size and shape of work to be performed rather than as a layout and assembly tool. Although AR was not a sweeping success, AR was successful in establishing a use case with today’s workforce, and as younger, more technologically savvy people integrate into the trades in the years to come it may grow into a more central role in the industry. Speaking to this point, several participants with leanings toward the traditional methods commented that the strengths of well implemented alternative practices like AR would be most effective with the younger, apprentice level folk who have grown up with more advanced digital technology. If these groups could be involved in testing and developing the more technology-centered methods in future research, the implementation of said technology would be much more effective, as those who would be working with it throughout their careers could steer it to their best envisioned uses.

The shop drawings were noted by some individuals as being incomplete and missing information, although they did not specify what was missing. As the drawings were reviewed with a carpenter and the VDC during development, this may be indicative that different carpenters prefer different information included in the shop drawings they are given or the drawings and labels they produce themselves. This speaks to the value of implementing a more wholistic prefabrication approach that brings in trade knowledge early on, which is in part why the labeling system was so effective for the PAIs and AR. The kit of parts provided for the shop drawings were intentionally left unlabeled to create a control dataset to compare against, so some groups may have grown accustomed to the CNC engraved labels which could explain why some were confused about the lack of labels on these parts in the shop drawing tests. Overall, the greatest strength of the shop drawings are their deep roots in construction, which enabled "the carpenters [to make it] it work well," meaning they could fully leverage their expertise and skillset with this approach as it required more manual processes than the other methods. Although there are certainly positive aspects of utilizing shop drawings, the general consensus was that "after doing the assembly book and AR first, the traditional way seemed more complicated."

The SUS survey scores for each method follow the comparison survey, with the booklet leading significantly, the AR instructions in the middle, and the shop drawings tailing. Without previously identifying the labeling as a key reason for a particular systems success, this data might otherwise only be interpreted as a success story for the PAIs on merit alone. In aligning with the participant's ranked choices, the scores reinforce that the participants answered consistently across all of the surveys, and that the surveys accurately reflect their expressed thoughts regarding each type of instructions. Figure 18 on the following page depicts the average SUS scores for each group's test with a particular method, as well as the average for that method



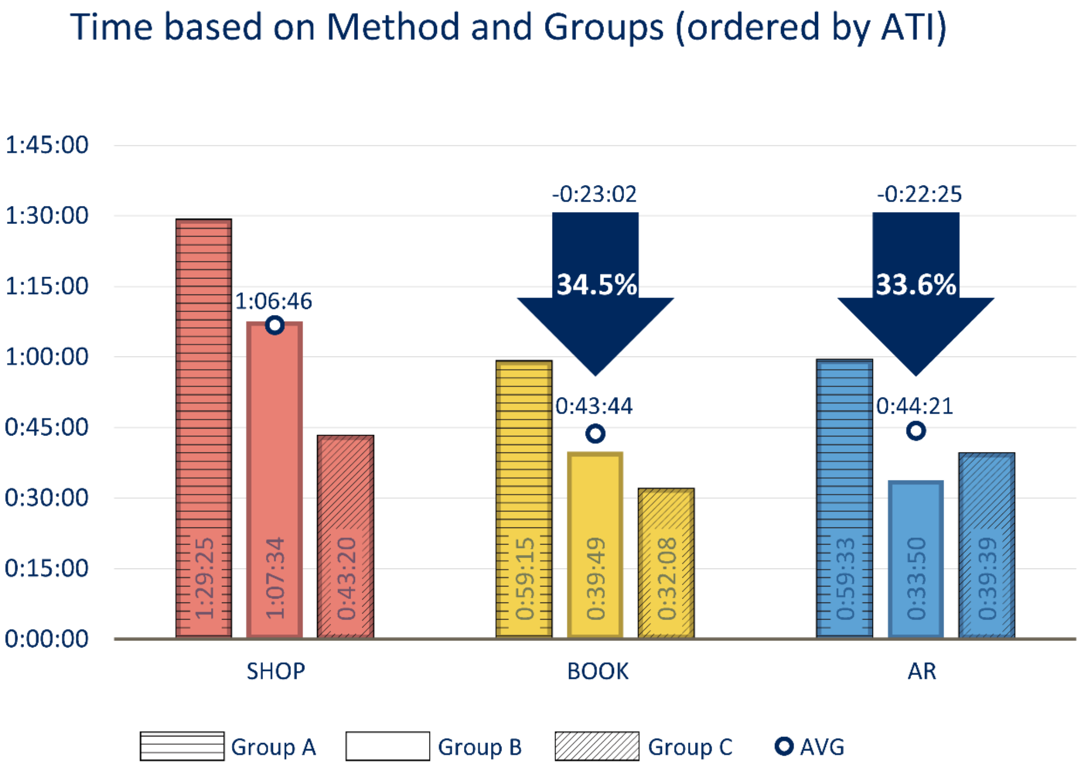
	GROUP A	GROUP B	GROUP C	AVERAGE
SHOP DRAWINGS	65*	62.5*	63.3	63.3
ASSEMBLY BOOKLET	80*	81.3*	83.6*	81.6
AUGMENTED REALITY	56.3*	67.5*	74.2	67.2

Data with an asterisk * was impacted by a fluctuation in the number of participants.
Note: Trial averages per instruction method are group averages, while the total average is taken using individual particpants rather than an average of the group aggregates
Note: Groups are ordered based on ATI score from low to high.

Figure 18: The graph above tracks each group's average System Usability Score (SUS), collected from the survey given after each assembly test. This is in the supplemental files as item C1.

across all groups. Groups A, B, and C are ordered from lowest to highest average ATI score for the group, which were 3.67, 4.22, and 4.56 respectively. These scores are all above average, but utilizing the ATI scores to organize the data highlights some notable trends. Looking at the relationship between the ATI score of each group and their respective rankings of the alternative practices, the data reinforces the ATI scale as a reliable predictor of a given person's interest in technology and in implementing new systems. A particularly interesting observation is the tight groupings for the shop drawings and booklet versus the spread of SUS scores with AR, the most novel approach of the three evaluated. As methods that draw from the culture of drawings in construction, there is a certain level of familiarity even with the booklet, which likely allowed the workers to leverage past experience to understand the new methods rather than storing that knowledge away. This reinforces the value of familiarity in performing work and introducing new systems, as it provides a point of connection and understanding that enables quicker learning and adoption of the new practices.

The strongest quantitative reinforcement of the alternative practice's success comes in the form of the average elapsed times for each method, which is visualized in figure 19. The



	GROUP A	GROUP B	GROUP C	AVERAGE
SHOP DRAWINGS	1:29:25*	1:07:34*	0:43:20	1:06:46
ASSEMBLY BOOKLET	0:59:15*	0:39:49*	0:32:08*	0:43:44
AUGMENTED REALITY	0:59:33*	0:33:50*	0:39:39	0:44:21

Data with an asterisk * was impacted by a fluctuation in the number of participants.
Note: Groups are ordered based on ATI score from low to high.

Figure 19: Graph of the assembly times for each method, collected by reviewing video timestamps. This is in the supplemental files as item C2.

alternative practices reduced construction time by over 22 minutes in comparison to the shop drawings, equating to a roughly 33% reduction in overall assembly time. Not only does this reinforce the comments about the alternative practices' ease of use and the effectiveness of the labeling system, but the similarity between the assembly time of the two methods indicates that the time required to convey the design and assembly information was effectively minimized with those communication techniques, leaving only the actual time required to build the formwork. This similarity also supports that the labeling system is a decisive factor in the overall success of the alternative practices, as it is the only commonality between AR and the PAI which otherwise have very different comments and SUS scores. Paired with the high SUS scores and overall ranking of the booklet, PAIs emerged as the instruction type with the highest overall potential for application in shop or on site.

Another major takeaway, one that was not necessarily intended to be a point for feedback, was the high value participants placed in the prefabrication approach in general, even when they were unlabeled for the shop drawing tests. Although some participants noted that they "missed the cutting of materials," the general consensus was that the prefabricated plates were useful as they skipped the lengthy processes required to cut the desired radii for the plywood curves in-situ. Even the blank plates, which required the carpenters to label the pieces and layout the stud locations manually, "seemed faster than fabricating by hand." At a minimum, the success of the prefabricated pieces in this instance indicates that there are areas of work that could be optimized without massive changes to the typical workflow of carpenters on site by leveraging computer-controlled production methods. By shifting the responsibility of select, tedious tasks to the computer, certain aspects of precision and fabrication speed can be greatly improved without large disruptions to standard practices. However, the labeling approach shown in figure 17 functions as a better compromise between complete prefabrication and total in-situ fabrication, as it encapsulates higher precision with the engraved labels while retaining some material processing work for the carpenters, such as cutting out the studs.

In addition to looking at the comments individually and by method, viewing them more abstractly as a quantified set was valuable in reinforcing the high rankings of the assembly booklet and AR methods. Figure 20 highlights the support behind the two alternative approaches by quantifying each comment as positive, neutral, or negative, and then turning those into percentages of the total comments received for that method. Given that the open questions in the surveys included some asking for the participant to outline any shortcomings, the 68.97% positive comments for the booklet and 59.46% for AR are strong indications that reinforce the idea that the alternative practices were a success. While the shop drawings had a relatively low percentage of positive comments and the most neutral and negative comments, many statements in favor of the method mentioned that the main strength was familiarity with the process. Changing an industry workflow represents a huge amount of inertia to overcome, and it might not be possible to get a significant percentage of the current, experienced workers on-board with broader implementation of these alternative practices. However, what is "familiar" can change from group to group throughout time, which circles back to the idea of introducing these alternative technologies at the trade school/apprentice level to get people engaging with these other systems sooner rather than later.

Although there is a lot of enthusiasm for these new methods, there is also a stigma that this approach is "taking the thinking out of it" which seems to pervade almost every group's

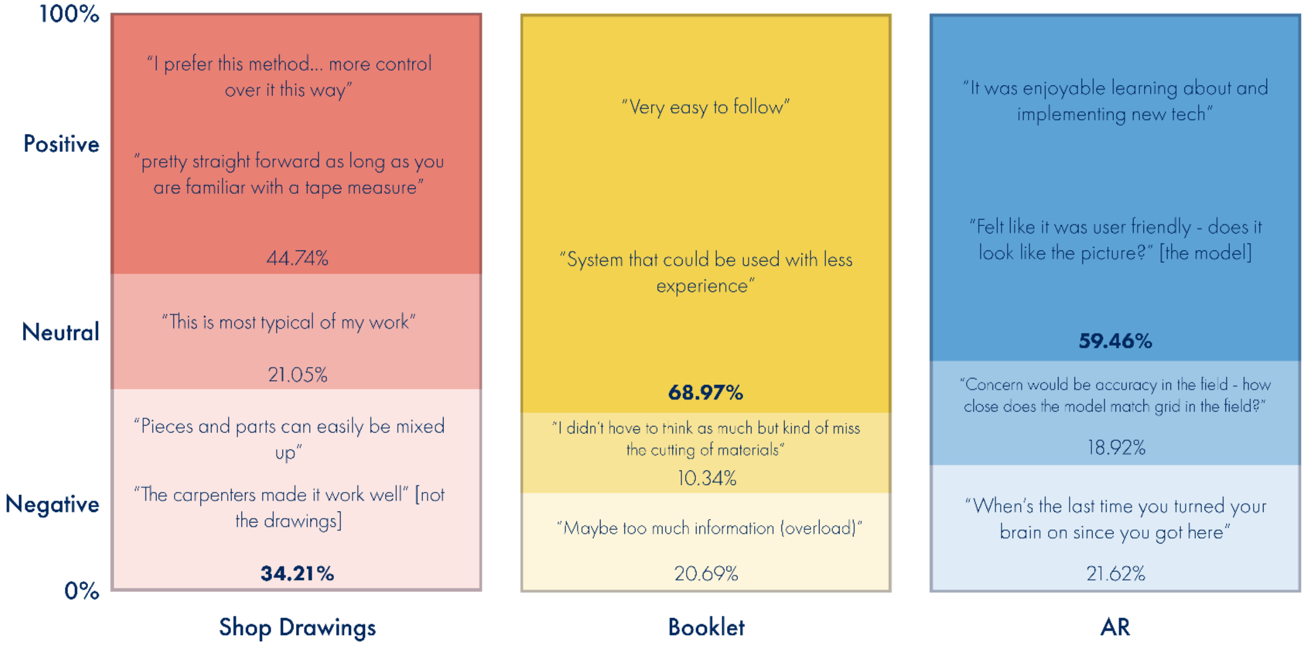


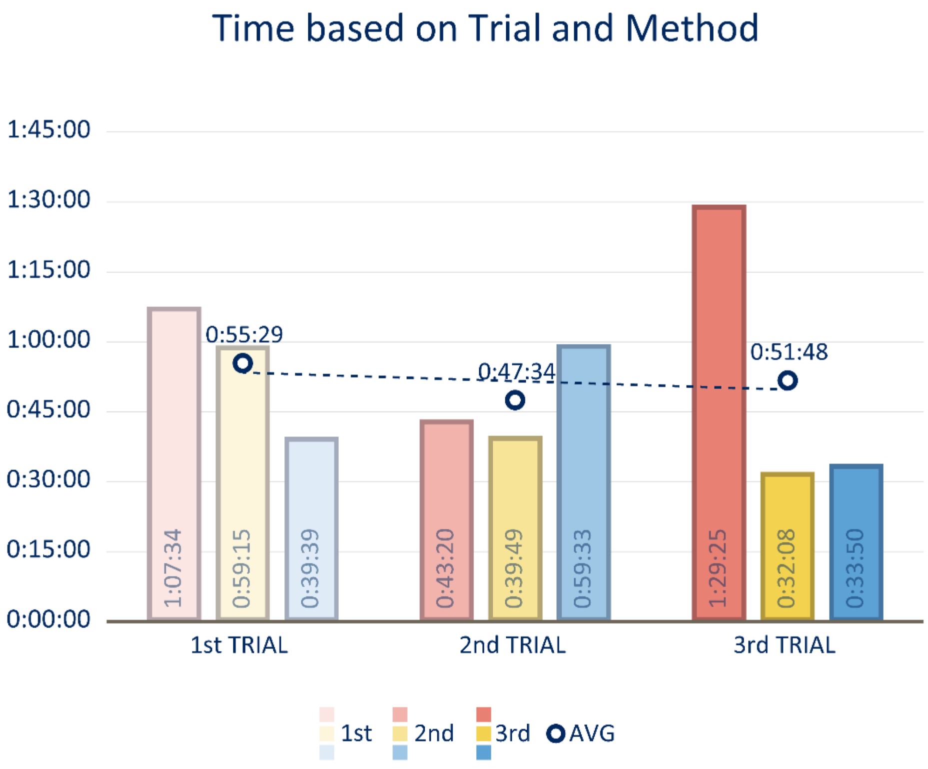
Figure 20: This chart calls out key comments that summarize the positive, neutral, and negative viewpoints for each instruction method. This is in the supplemental files as item C3.

comments. This idea will be considered in more detail in the discussion following, but to summarize: the removal of thinking is only present when zooming into a short segment of the prefabrication workflow, which this thesis does by focusing on the assembly of prefabricated formwork kits. As such, it is natural for these comments to emerge as the work on site becomes streamlined and simplified, because the thinking really is being taken out of that particular stage in the process. However, a strong prefabrication workflow integrates trade knowledge early in the modeling/design process for FIM (similar to having the shop's head carpenter review the instruction methods for clarity, accuracy, etc. in this thesis), thereby addressing potential field problems or constructability issues early, with the full team involved. In this way, prefabrication does not take the thinking out, rather it shifts it forward, off of the site and into the office. As review of the instructions was outside of the scope asked of the participants (and might impact the data collected), they did not get to be a part of the early critical thinking and problem-solving process. This is not meant to invalidate their comments, rather highlight that this issue has been considered in the past and ways to mitigate it have been devised and implemented previously.

Another consideration that counterbalances the overarching enthusiasm is the number of responses that indicated the workers were indifferent to the alternative practices in terms of whether or not they found it enjoyable. Several noted how the AR and booklets were fun to use during the assembly tests, but mostly for the novelty of doing something different. While these may seem like inconsequential statements about the different instruction methods, one of the core goals of this thesis was to make work more enjoyable through these alternative practices, not just more efficient or easy to understand. This may be another case where sampling a different group may yield entirely different results, e.g. trade school students today might find these methods to be much more engaging and enjoyable than the traditional practices that the participants in this thesis are accustomed to. In any case, this observation raises the question of what the true exchange would be if implementing these work practices, as the productivity gains would need to be compared with the changes in worker satisfaction which is difficult to quantify.

4.2 Evaluating The Repetition-Bias Mitigation Strategies

As discussed in the methodology section, the relationships between the recorded quantitative metrics and the considered variables and challenges could not be ascertained without the ability to isolate and analyze the data from different angles. To verify that the approaches to mitigating the challenges of familiarity and repetition from Funk and Schmidt (2021), the collected data was analyzed based on both trial order and wall version. Figure 21 illustrates the relationship between trial number and average completion time. While there is a decreasing trend



	TRIAL 1	TRIAL 2	TRIAL 3	AVERAGE
SHOP DRAWINGS	1:07:34*	0:43:20	1:29:25*	0:55:29
ASSEMBLY BOOKLET	0:59:15*	0:39:49*	0:32:08*	0:47:34
AUGMENTED REALITY	0:39:39	0:59:33*	0:33:50*	0:51:48

Data with an asterisk * was impacted by a fluctuation in the number of participants.
Note: Trial averages per instruction method are group averages, while the total average is taken using individual particpants rather than an average of the group aggregates

Figure 21: This graph compares the average time elapsed for each trial. While the trend line has a negative slope, it is quite shallow and does not show any strong relationship to the 33% time savings observed with the alternative practices. This is in the supplemental files as item C4.

in the averages, it is not a sharp trend line as seen in other research and thus cannot explain the significant time savings observed for the AR and PAI approaches. The red bar in the third trial may appear to be an outlier, however this is simply representative of the longer amount of time it took this particular group to complete the shop drawings as their third trial, after having the two alternative practices first. As such, it was expected to be significantly slower than the other methods on the third trial. The SUS scores were also examined on a trial order basis and showed no significant relationships, which implies that fatigue through the ongoing trials did not impact the scoring in one way or another. The three wall versions were also measured in this way to see if wall design had any observable relationship/impact on the data. Although there was some variance in the times elapsed similar to the above, the differences are not exaggerated enough to have a strong relationship to the time savings recorded between the different approaches on average. The SUS scores across the different walls were also within a slim variation, implying that the wall design did not have an impact on the SUS ratings. While it remains challenging to completely isolate the variables for completely objective testing and observation, the quality of the dataset implies that the mitigation strategies developed were effective enough to draw conclusions of reasonable accuracy, at least for this group of participants.

4.3 Smaller Trends Observed

The correlations noted in this subsection are present in the data but have little relationship to the core questions of this thesis. These concepts are presented mainly as interesting areas for future research rather than an important observation for this thesis. One such correlation is between ATI score from low to high and the average elapsed time for each group. The group with the lowest ATI score took the longest on average, and the group with the highest the shortest. While interesting, it is not particularly relevant to this thesis on two counts. First, this observation could be caused by fluctuations in the number of participants; the lowest ATI group had 2 participants, the middle group had 4, and the highest had 2-3 depending on which trial (persons joined and left to participate in meetings). Rather than a result of each participant's ATI, this could be indicative of 4 persons being too many for the scale of the assembly tests, 2 being too few, and 3 being the perfect number for an effective team assembly. Second, evaluating different groups based on ATI alone is not a focus of this research, which is more so about understanding the relationship between ATI and reported effectiveness of a type of system, especially AR. While this line of analysis could provide insights into what demographic groups are best suited for tech-integrated construction approaches, scrutinizing different participant groups and comparing them is counterproductive to creating more engaging, effective, and enjoyable work environments in construction as it begins to rank certain types of workers as more or less suitable. Although there is value in looking at different groups and how they might rank and interact with the different means and methods, the focus has never been creating competition between different groups.

Another minor trend observed was the number of errors over time, which increased with each successive trial. While this is counter to what might be expected as workers grow more familiar with the assembly systems, the increases could be attributed to unexpected fatigue due to the scheduling issues mentioned previously in the methodology section. The errors are tracked in figure 22. As teams approached the 3-hour mark that they were originally scheduled for, errors increased because they felt the need to hurry up and finish so they could pivot to critical work on site. Without more data, it is hard to determine if there is a strong causal relationship between these workstyles, wall design, time constraints, and the number of errors, but fatigue and schedule concerns are the most logical assumptions to attribute the increase to at this time.

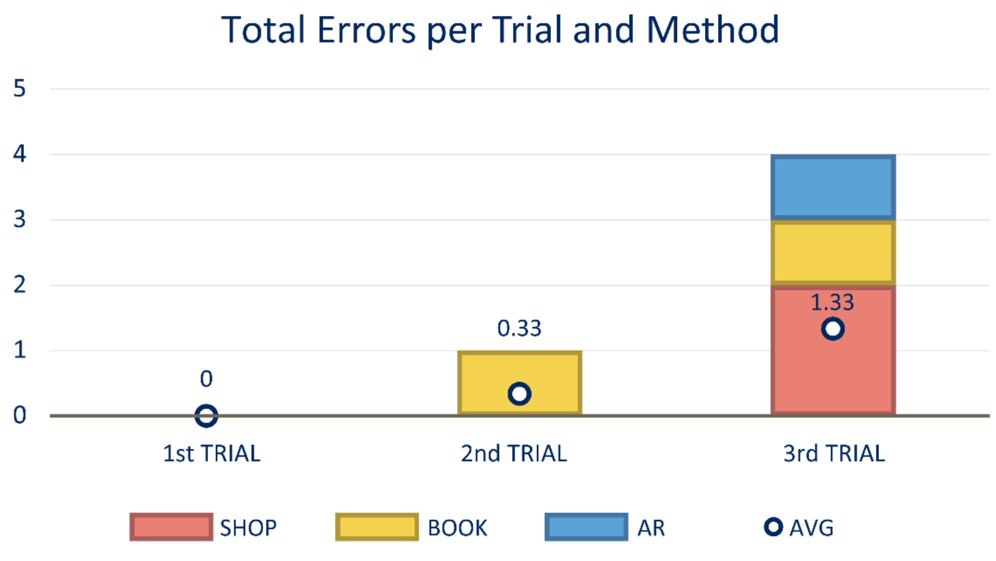


Figure 22: The number of total errors increased greatly by trial 3, likely to fatigue and stress over scheduling concerns. This is in the supplemental files as item C5.

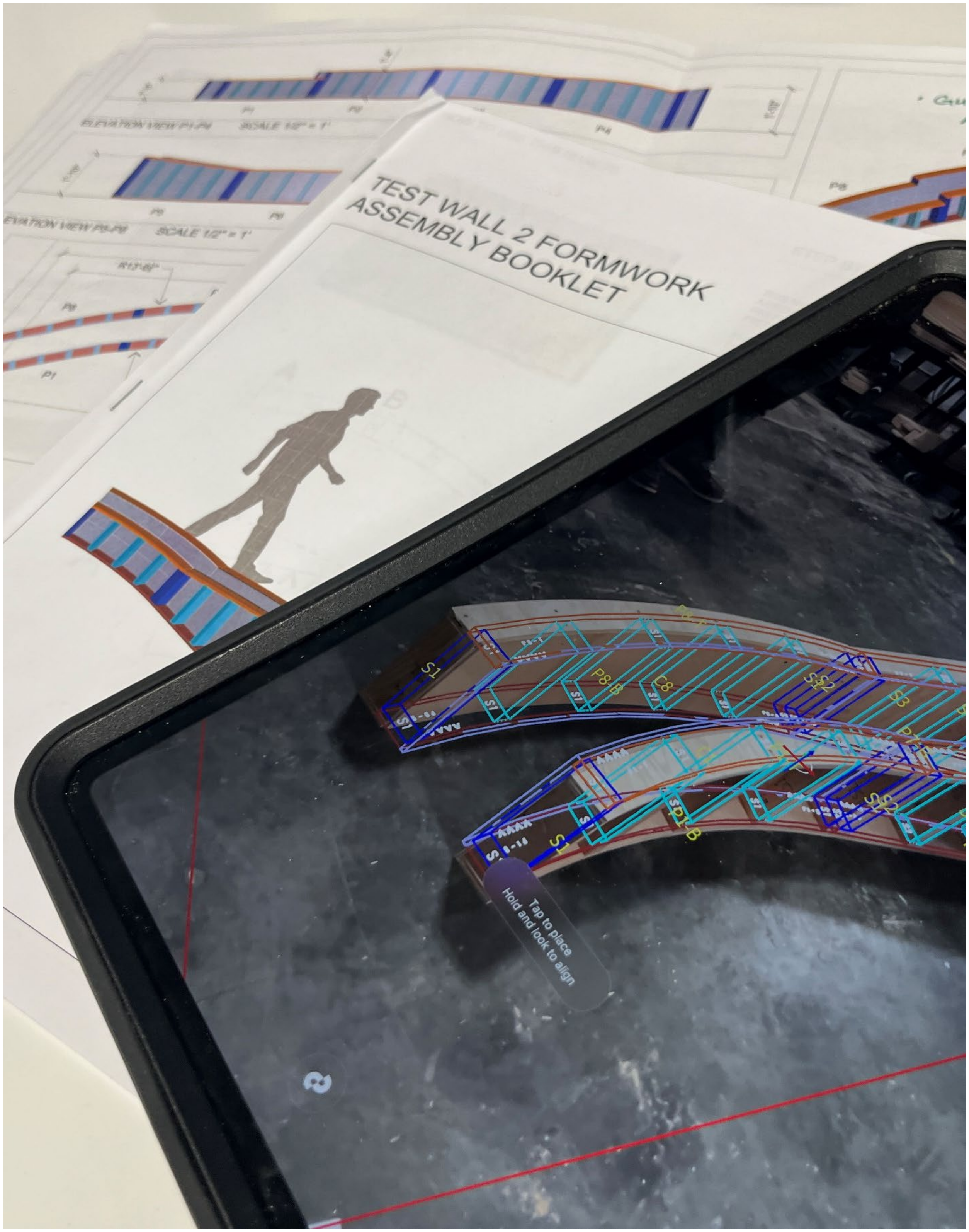


Figure 23: This photograph captures the continuum from traditional practices to futuristic practices.

5.0 Discussion

If this thesis has revealed one thing, it's that the construction industry is more open and enthusiastic to innovation than common stereotypes may lead us to believe. The positive reception of the assembly instructions echoes a point made by Buchli et al (2018), in that the construction industry is constantly integrating new technology, materials, etc., into the fold, but in a way that is not an overt display of innovation that could easily be observed by industry outsiders. Although construction is a capital-intensive affair, there are still many companies, researchers, and workers who are willing to experiment and embrace changes that could improve their lives, their work, and jobsite productivity. While this raises questions about access to this information, it is proof of movement away from "business as usual," which has proven to be falling increasingly behind the times.

The abundance of commentary from the teams backs up this idea of personal interest in advancing the field, with several trends standing out in particular. For instance, individuals that were less prone to fully integrate new technologies and work strategies based on their ATI score still acknowledged the value of the alternative practices in this thesis, even if they continued working exclusively within the traditional practices. Several others highlighted how the AR approach could resonate with a new generation of builders who have grown up alongside the rapid digital evolutions of the past few decades. This is particularly important, because this thesis only shows a snapshot in time for a particular, dominant group in the industry, and does not capture how different methods of communication fare over a longer continuum with different demographic groups and generations flowing into, and out of, construction.

Overall, the participants provided a great wealth of insight and feedback into how the systems could be changed in ways that would serve them even better. While they might be expressing individual preferences rather than recognized industry practices, many of the ideas presented would be very useful in developing and testing a set of best practices for an instruction system for actual field implementation. The number of insightful comments highlights the intuition and knowledge of experienced construction professionals, which inherently demonstrates why that knowledge must be retained and fostered rather than replaced. It is reasonable to claim that they were particularly focused during the assembly trials and the surveys because the value of their thoughts, opinions, and feedback was explicitly stated to them as the purpose of the research. The importance of this cannot be stressed enough: *the implementation of new technology and workflows should be a discussion and a collaboration*, not a directive from higher up. This is a case of textbook participatory design, and it is imperative to give construction professionals agency and personal investment in the discussion about changing industry-wide communication culture so that everyone involved is designing the new framework together. Allowing people to give their honest feedback by thinking critically about the task at hand and then following through by analyzing that feedback and revising the system(s) being implemented is pivotal to the success of any transition. Without this, the workplace environment becomes one of tension and discomfort instead of one of learning and improvement because the external force is rigid and authoritarian by nature. This could even lead to a completely unsuccessful attempt at implementation for the new technique(s) in question as a result to resistance toward the forced changes.

Although there are a great many things that could be discussed, this section will focus primarily on the following questions:

- How much “better” does something need to be to make it worth replacing the dominant approach? Is there value in using multiple methods at once?
- What differentiates a simplified process from a mindless one?
- What happens to the labor force and their wages as work is reshuffled in the proposed digital prefabrication process?
- What is the role of a carpenter in digital prefabrication?
- How much automation is the right amount?
- What happens when a machine breaks in this workflow?

5.1 Strengths And Weaknesses Of The Explored Visual Communication Methods

As a formal investigation into communication techniques, the results of this thesis demonstrate that reevaluating communication is an area of high potential for further research and implementation that extends beyond doing what we have been doing, just more efficiently. A

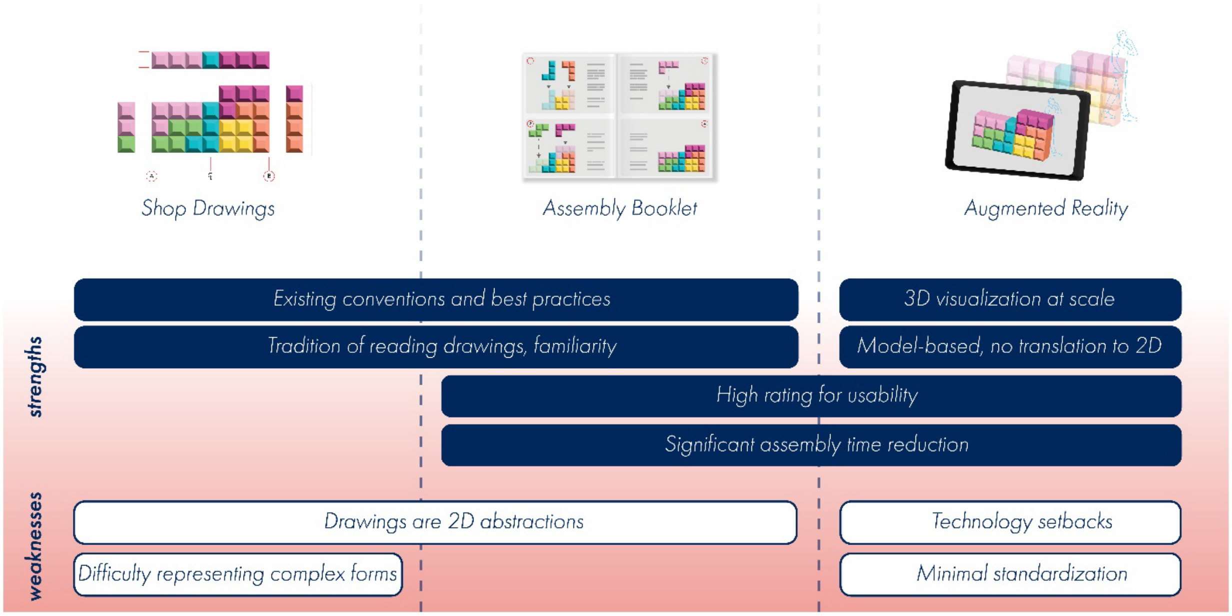


Figure 24: Diagram of the strengths and weaknesses of each method. Each method has distinct advantages and disadvantages.

number of comments mentioned how these approaches could positively impact the buildability of more complex forms, which is significant because the participants were aware of one of the core aims of this research without being informed of it. Investigating how different approaches to communication, modeling, prefabrication, and assembly can enable the realization of more complex forms is critical as our buildings aspire to meet higher performance requirements and more ambitiously designed forms. However, this does not mean that these methods are perfected, even though they are rooted in a myriad of best practices. Despite the enthusiasm to engage with these new communication tools and the quantitative data showing a 33% time savings in addition to the other metrics, each of the tested methods had its own set of strengths and weaknesses. Figure 24 provides a visual comparison of these strengths and weaknesses and how certain aspects are shared across multiple instruction types. The greatest strength of the assembly booklet and shop drawings are their shared relationship to the longstanding tradition of utilizing drawings in construction which means that there is not only a sense of familiarity but also a certain established set of standards and best practices. Although the booklet is a “new” method of building concrete formwork, leaning into the existing culture of drawings results in its dominant rating and high usability overall. Meanwhile, AR had many standout aspects relating to the 1:1 visualization of the form before it is built, allowing workers to observe and circulate around the mockup in real space rather than a scaled down image on a piece of paper. Being model based, there is no translation from 3D to 2D that could be misinterpreted, and it also does not require the production of additional drawings or information beyond the synchronization points which reduces the overall workload for the office side of the job. Many of the drawbacks of each method align with the issues identified during literature review, such as the interpretability of drawings which are 2D abstractions of reality or the technological setbacks for certain user groups when given AR as their assembly method. The major takeaway from this comparison is that no particular method, even the highly successful booklet, is without its own shortcomings.

While it is interesting to consider the world that one participant imagined, one in which the industry shifts to "abandon drawings and build based on marks on plywood" by completely embracing the alternative communication methods, such a sweeping overhaul as a "this or that" dichotomy is unlikely. Even with extensive future research to mitigate the weaknesses of a given method, it is unlikely to become so flawless that it becomes effective enough to completely replace the dominant tradition of utilizing drawings. Thinking about the methods more as a series of sometimes overlapping and sometimes unique strengths and weaknesses than as a stark A or B comparison, the discussion of implementation becomes a "this *and* that" approach, with each method bringing its unique strengths while having its weaknesses compensated for by the other methods. Figure 25 illustrates this concept of overlap, which is a logical step toward clearer communication across age, skill, technology, and language barriers, to name a few.

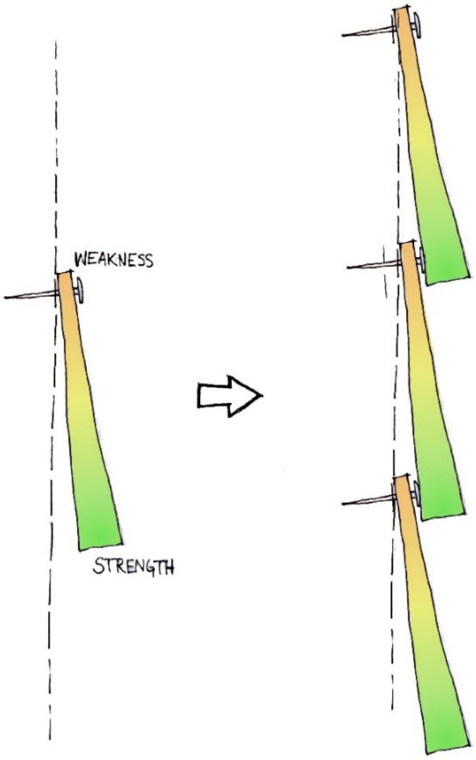


Figure 25: The overlap of strengths and weaknesses can be likened to shingle siding. A lone shingle is a weak weather protection barrier, but by overlapping them to function as parts of a larger system they become effective.

Recent developments in education have focused on the division between the fact that people have different learning styles, yet much of education remains rigidly tailored to a few styles at the detriment of the rest. As such, it stands to reason that we should diversify the channels we use to communicate in construction to better accommodate our diverse populations. Continuing the practice of only utilizing one method to convey design and construction information, be it construction drawings or an alternative practice, is inherently unable to effectively reach the broad audiences present on construction sites today. Supplementing the existing methods by creating new communication tools that account for the former's shortcomings ensures that we can communicate an understanding of construction information in multiple ways that is both clearer and more detailed. Building on this idea, debrief discussions with the Turner VDC about the potential applications of the research results in their workflows focused on supplementing known and familiar practices with new approaches. For instance, AR could be used to visualize work tasks during the daily pre-task planning and orientation meetings. 3D visualization could be provided as either a small model to rotate linked to a QR code on a drawing sheet, or as a full-scale model to provide a rough mockup of what it should be, similar to how it was utilized in this thesis. The traditional drawings would be used to actually perform the work and ensure it is in the right location per the design, but the AR visualization would assist in quickly orienting workers to the task at hand. Overall, the study was successful in raising awareness that standard methods alone may not be the best path forward as the industry moves to incorporate CNC machinery at larger scales. Looking to other industries can offer adaptable solutions to supplement, rather than replace, the traditional approaches – why reinvent the wheel if it isn't absolutely necessary?

5.2 Leveraging Traditional Practices And Human Knowledge

As mentioned previously, a major discussion point of the alternative practices is the degree to which they simplify the work. This is best captured by a rhetorical question posed by a participant: "when's the last time you turned your brain on since you got here?" While streamlining the work so that it doesn't require as much skill presents many productivity and cost advantages, taking the thinking out of the work is certainly detrimental to the overall enjoyment and fulfillment of performing said work. Viewed in isolation, this could be seen as taking the art, craft, and critical thinking out of construction and replacing it with mindless, repetitive assembly tasks. This is a very real and valid concern and is counter to the project's goal of investigating methods to leverage human knowledge in these new processes. However, it is also important to zoom out and observe the function of the broader prefabrication workflow which does not delete critical thinking from the role of the carpenter, rather it reshuffles those highly engaging steps to different stages in the process.

As mentioned in the previous sections, the assembly instructions and FIM workflow developed were reviewed not only by VDC engineers by also by the Shop's head carpenter. This review by actual tradespeople is not unique to this project, rather it is representative of Turner's approach to prefabrication which incorporates many best practices. In this method, the builder's critical thinking, constructability analysis, and experience are brought into the process early, far before any component reaches the site. By including discussion and review by construction professionals during the modeling stages, the process inherently catches errors and identifies revisions before they reach the site by continuing to value the input of trade knowledge. In some regards, inviting these experienced professionals to the design table celebrates their knowledge more than traditional practices; in this way, they become important contributors to the design and its constructability, rather than the bearers of bad news when major issues are identified after work is already underway on site. The trial participants were not included in the broader prefabrication process, only the portion that reflects the on-site assembly work, so it makes sense that there would be concerns about the level of simplification and omission of critical thinking.

This returns to the earlier idea of bringing in more participatory processes and collaborative discussions when changing workflows so that every voice is heard. A lack thereof could be contributing to the industry's sluggishness in productivity relative to other industries which are constantly on the rise, as illustrated back in figure 1. It is not difficult to imagine an example where integrating prefabrication sans carpenter review creates a workflow with a high probability of inaccuracy leading to rework and sowing dissatisfaction, all due to the exclusion of certain parties at the discussion table. Overlooking trade knowledge relates to the stereotype of traditional relationships between design offices and construction crews being one of rigidity, hierarchy, and legal boundaries around responsibility. The builder is expected to listen and execute the design, not provide feedback; at least, that is until something goes wrong. While this may have been an efficient method in certain cultures and eras, achieving high performance projects in the diverse and multi-faceted industry of today demands more collaborative and flexible environments that focus on the team as a whole and the value they bring to the table. This needs to go beyond the company leaders, owners, and the typical faces on an integrated design project team and include the trades who will actually build the project. A better understanding of their ideas about how to build something can help catch design problems early on and develop a sense of camaraderie amongst the office and the field. Creating a team dynamic instead of a loose gathering of individual actors could also begin to address some of the finger pointing that happens when something goes wrong on a project.

Another concern raised by the carpenters was that the work on-site might be "so easy someone's gonna [mess] it up." Whether or not the parts are digitally fabricated with labels or if the parts come with alternative instructions that are not shop drawings, this simplification is inherent to an effective prefabrication process. The biggest conversation point is understanding the line between "brainless" and "efficient" before implementing changes to ensure the best result. Creating a disengaged workforce is against the aims of this project and is also a dangerous proposition; mindless existence and construction sites do not mix. Although simplification results in a task requiring less critical thought and focus, the worker retains agency and responsibility over what they bring to the role. Ideally, they would work with the same mental sharpness as usual, but it would be disingenuous to the prefabrication process and these alternative communication styles to attribute the 'self-mechanization' of the workforce to them rather than individual choice. With this in mind, the streamlining of site work by simplifying the labor requirements is advantageous rather than disadvantageous as it streamlines production and reduces the probability of major schedule slips resulting from unforeseen problems as they arise through RFIs.

The idea of reshuffling labor, skill, and review, to maximize the effectiveness of prefabrication workflows in conjunction with alternative instruction methods could lead to some shifts in wages, which was raised by several carpenters who voiced concern that it would devalue their work. It stands to reason that simplified sitework would depress wages for those doing the assembly work since the skill requirements are lower. However, it is important to create a distinction between *whose* work it is; what is the role of the carpenter in this workflow besides a reviewer? Rather than lower wages for carpenters, it is likely that a new type of less-skilled assembly laborer would fill out the ranks of the on-site crews while the carpenters would continue to operate as normal, fabricating constructions that are difficult to prefabricate. While a powerful tool, the CNC-powered digital fabrication workflow will not produce everything that goes into a given kit of parts. As a fairly automated process, it excels at certain types of tasks such as cutting out the curving plates with labels like those visualized back in figure 17, but the kit of parts would not have been complete without complimentary manual carpentry work. In the future, machines will accomplish a share of the work, but there will still be a huge demand for skilled carpenters that may operate from a prefabrication shop environment rather than on site. This represents an improvement in terms of weather exposure, regularity in job-location, access to better stationary tools, etc. An example of this in practice is the work of Turner's Shop carpenters, who work in these digital prefabrication workflows. VDC engineers model the parts and prepare the CNC toolpaths while the carpenters run the machinery and produce the other parts with stationary saws and hand tools. This is all in addition to the aforementioned constructability review that the carpenters perform during the modeling process.

Alternatively, another in-between prefabrication workflow would involve the CNC production of certain parts with full labels that are then sent to site with drawings. Rather than the full kit of parts, this partial kit would retain carpenters on site to produce the remaining parts and would lighten the workload of the prefabrication shop. The value of keeping a number of carpenters on site is that if there is some issue and something needs refabricated, the carpenters can do it immediately rather than sending it back to the prefabrication shop and waiting for a new part to arrive. It also keeps a connection to making and craft embedded in sitework, which could lead to impromptu innovations as a carpenter could come up with an idea and fabricate it right then and there, rather than someone having to relay the idea back to the office for development and production. Overall, integrating these prefabrication workflows could also create a kind of pathway from field to office, a career progression that moves folks away from physical labor and into review/oversight in the prefabrication process. This would ensure everyone in management has firsthand building experience while also retaining the knowledge developed from a number of years of hard labor, rather than having that knowledge base disappear as the individual transitioned away from construction and into a different field.

Another great question raised was what happens when the prefabricated components do not match the site once they arrive for installation? This is a problem that has plagued many projects, from kitchen renovations to sprawling complexes. Due to production and shipping lead times, mistakes in the prefabrication process can lead to schedule slippages that wipe out the productivity gains from moving to prefabrication in the first place. While this problem is a strong argument in favor of traditional workflows, it is not unsolvable. The solution to this problem lies in due diligence and a well-thought-out prefabrication workflow. Ensuring the site is accurately captured through surveying is crucial, as this information is the basis for the prefabrication model and subsequent parts. Achieving this is not rocket science, and simply requires care to be taken in the beginning of the project. This may result in higher costs for the surveying process, but it also acts as insurance that protects the potential gains from prefabrication. In the event that there are discrepancies, the trade review portion of the prefabrication workflow can act as a secondary quality check to flag any issues. While the idea of prefabrication inaccuracy is a valid concern based on earlier, poor implementations, there are well developed best practices and subsequent strategies to mitigate potential issues if they arise.

5.3 The Future Of Digital Prefabrication In Construction

While this thesis asserts the value of the human element in prefabrication workflows, the question which is likely to be at the forefront of many companies and decision makers is whether or not prefabrication in this manner is efficient enough to justify the costs. Although the results of the assembly studies showed a roughly 33% time savings for the alternative practices, this thesis was focused on observing only one stage of the prefabrication workflow. A myriad of work occurred outside of that observational scope boundaries and thus was not logged or quantified in any way, such as setting up the Grasshopper script to generate the FIM models, processing them with RhinoCAM, cutting them on the CNC, or creating the assembly instructions. Without studying the production times for these segments of the prefabrication process, it is difficult to determine whether the benefits outweigh the inertia of continuing business as usual following the embedded, traditional practices. These alternative instruction types would not eclipse the drawing set entirely and thus would be supplemental items to create in addition to the typical drawings. This addition of work hours in the office could offset the productivity gains on a time and cost basis, at least if the drawings are manually produced for every project. Seeking ways to automate the drawing process or the steps to turn the FIM model into an AR ready model, which would follow the same workflows every time regardless of the geometry, could be the path that makes widespread implementation of these alternative methods possible from a cost standpoint.

This leads to the topic of automation in construction, which has been explored at different scales in this project. This thesis implemented automation to streamline certain repetitive tasks which provided diminishing educational returns to the worker, whether it be the automation of modeling in Grasshopper or the automation of production with the CNC router. Looking at both avenues of automation employed, the goal of automation in this sense is thinking of the machine *as a tool, used by people, to accomplish repetitive tasks faster,* thereby freeing up capacity for higher and better uses. This approach to automation and digital fabrication is what this thesis considers human-centric prefabrication. It is not intended as a replacement for labor outright. Rather, it is meant to push back against the mainstream idea of automation that is rooted in the replacement of human labor with a robotic workforce. Although the rhetoric is comforting, the degree of automation in selected tasks and in the workflow overall must be considered carefully to avoid 'human-washing,' or making the technology appear more empowering and valuable to human-centric lifestyles than it actually is. For instance, a more advanced Grasshopper script than the one developed in this thesis could be implemented to completely automate the FIM workflow from processing the source geometry into a fabrication model to producing those pieces and the accompanying assembly drawings. This would take significant effort to develop and likely some ongoing support to fix bugs, but afterward a significant amount of work which was once the responsibility of a VDC engineer will have been automated. Will the workforce be reduced, or will these individuals be assigned different higher and better uses of their work hours? Similar to the argument of prefabrication, it is most likely that labor will be shuffled around to fill better uses but nothing is guaranteed in a prediction. Additionally, if the only parts of the process that require people are the brief quality control and oversight reviews and the assembly on site, it is hard to consider it human-centric; it is human dependent for select tasks that might one day be automated – what will our role be in that workflow? Will our cities build themselves?

Mentioned in section 3.6, greater integration of high-tech systems into standard workflows can provide value as demonstrated by this thesis, but it can also make those processes more vulnerable. When technology proves incredibly effective, the ability to perform that work manually begins to wane as individuals and companies move to the more efficient practice and turn away from tradition. While this is not inherently detrimental, integrating technology creates dependence on these new machines if knowledge and application of the traditional approaches is not viewed as valuable to continue teaching, which can result in complications when faced with situations where the technological systems are absent. This can be likened to the use of arithmetic, which has been revolutionized by the common calculator to the degree that doing it without a calculator seems like a task only for pre-modern eras. The concern then lies in when an incredibly effective tool becomes dependency. Research indicates that students perform significantly better when using a calculator (Boyle and Farreras 2015) and are more engaged in the learning process (Hussin et al 2017). For all intents and purposes, this seems like an incredible success, as the tool makes working more efficient and accurate, and the users of said tool find learning about mathematics more enjoyable. However, in the absence of a calculator, students' low performance demonstrates a level of dependence on the technology to effectively complete problems (Hussin et al 2017). While it is hard to conceive of a time in the 21st century that a calculator would not be close at hand given that they're integrated into cellular devices, this issue highlights the importance of continuing traditional practices as a method to fall back on during unforeseen complications.

Recentering this idea of technological dependence on the automation methods in this thesis, the problems encountered and highlighted in the methodology section demonstrate some of the potential challenges when a workflow integrates technology to the point of dependence. These machines, though marketed as more durable and capable than human laborers, are actually quite fragile. Due to the machine's complexity, the diagnosis and repair of any breakdown can take weeks or months as the appropriate technician and chain of custody must be involved in the process to preserve warranties. The repair work itself can extend the timeline further due to part availability, as many components are not kept in stock and need to be shipped to the production facility with the broken machine from across the country or abroad. In some instances, the machinery itself even needs to be shipped out, which was the case with the Turner CNC. At the time of writing, the machine was out of operation for nearly two months with no resolution in sight as different companies shipped the broken parts back and forth around the globe. While this is more indicative of organizational failures on the part of the manufacturing group, the end result remains a broken piece of machinery that was integral to the new work processes. So, what happens in these situations? Who is responsible for the delays, cost overruns, and other subsequent challenges? In some cases, the necessary workers and knowledge base are still available to shift back to manual production, but in other cases an entire job schedule is dependent on automated production with no provisions for machine failure. This impacts current jobs that were slated to use the technology, upcoming jobs, job bidding, and other areas which can result in millions of dollars in lost contract value. Ultimately, this line of questioning provides sound reasoning that alternative assembly instructions and prefabrication workflows should supplement traditional human processes rather than entirely replace them.

Given the need for accurate, buildable 3D models in proper digital fabrication workflows, a future of mass prefabrication will likely necessitate a change in our contracting structures between designer and builder. As ideas of the designer-fabricator and digital fabrication gain traction in the industry, it makes sense to consider modifying contract requirements and other legal aspects in tandem with the changing job tasks and responsibilities in these emergent workflows. Rather than a set of drawings, the contract document becomes a detailed 3D model, or provisions for its creation before starting construction. In some highly complex designs, such as with the Seattle Aquarium Ocean Pavilion, including the 3D model as a part of the contract given to the builder was incredibly important to the success of the project. This requires a higher fidelity model from the designer (or provisions for the contractor to utilize a VDC department to make the model), which has costs associated with it in addition to a myriad of scope questions. Will this increase architectural fees and the value architects bring to projects? Will there be resistance from any parties? What if a designer-provided FIM model is inaccurate? Will 3rd party modeling services for hire emerge? If contracts remain rigid with 2D construction drawing sets being the gold standard, will more contractors have VDC departments to do the modeling instead of architects? The list of questions is endless, but the important consideration is that the impacts of moving toward mass prefabrication go beyond the job site and fabrication shop. In some ways, this represents more inertia that digital prefabrication will have to overcome by demonstrating its value. It also suggests that digital fabrication workflows may never become widespread industry practices if the value observed from the practice is not worth the effort to change all of the related fields that are intertwined with the construction industry such as the legal side of projects.

5.4 Additional Thoughts And Comments Observed During Thesis Defense

The discussion during the thesis presentation was very active and engaged, with participants from different firms, trades, and occupations. Many points raised were similar to those already in this thesis which was interesting that the audience and reviewers had similar thoughts without prior exposure to this research. Two questions in particular stood out, challenging the thought processes behind this research:

- Specifically, what are the positive human elements involved? How is the work more "human-centric" beyond just naming it that?
- What if full automation is the necessary step to save enough time and cost on projects to enable the more complex and high performance builds of the future? Is holding on to the human element in construction holding the industry back in comparison to other sectors?

Both of these are great questions, particularly because they could be justified in many ways. For example, if the benefits to human workers in hybrid digital prefabrication workflows are only "human centric" in name, what is the value in them at all? Why not push to full automation? However, if the work could be made and evidenced as more enjoyable, for instance through the gamification of AR construction work or some such addition, that could provide sound reasoning as to why the work shouldn't be entirely automated – *its enjoyable*. It is difficult to formulate any strong responses without more research, consideration, and assembly trials, but it remains important to consider these questions as the industry integrates this technology.

6.0 Conclusion

By utilizing wood frame concrete formwork as a case study in implementation, this thesis has demonstrated strengths and weaknesses of incorporating different communication strategies in an industry moving toward the integration of more digital technologies. While the case study was focused on one specific area of concrete work, the value of using different communication methods for prefabrication can be extended to other areas of concrete formwork and to broader areas of carpentry. Although the more empirical takeaways make switching to PAIs or AR seem compelling, this is not likely what is best for advancing project quality or and the lives of the construction workers wholistically. It is important to utilize the alternate methods to *supplement* traditional practices rather than replace them. In this way, the strengths of different communication methods can be leveraged to quickly convey design and construction information while the shortcomings are mitigated by continuing to use 2D drawings where they are most apt. It is also worth considering that this thesis focused on implementation – reviewing what options were available and then testing them in new settings. The research did not focus on developing new methodologies or platforms, which could be a strong next step to advance this research by finding ways to combine the communication methods more effectively, amplifying their unique strengths while minimizing their shortcomings in the process. Similar to creating new best practices, future research could focus on development of new programs and approaches to modeling for construction, rather than this thesis which implemented existing practices and platforms.

Although the scope was focused on one applied research study for subsection of the digital prefabrication workflow, the demonstrated value adds from the qualitative and quantitative analyses are noteworthy and can act as a catalyst to spur further investigation into optimizing the prefabrication process as a whole so that the benefits can extend further into the field. As discussed, it is important to go beyond optimizing performance metrics and include the human experience of the process, which is perhaps best gauged through user testing and feedback. This takes extra resources to perform meaningfully but is well worth the effort. Automating segments of the modeling or drawing production process could also free up time to spend on those more qualitative and contemplative tasks like interpreting feedback. The enthusiasm and overall positivity toward these more efficient prefabrication workflows should be held in high regard – the carpenters saw value in many aspects of the implemented digital prefabrication workflow and how it could benefit them and their work.

As expected with complex research, situations arose that required flexibility and quick thinking. Although the methodology was meticulously planned and drew from the best practices to identify and mitigate issues before they occurred, it was the areas that were not considered that became troublesome. Having a highly intelligent team backing the project was a great help in overcoming the obstacles that arose, whether it be machine failure or participant schedule mix ups. While this does make it more difficult to draw strong conclusions from the quantitative data, the small sample size already makes strong quantitative conclusions a difficulty. However, the independent consensus of the nine participants on almost all matters remains strong qualitative evidence of the value of diversifying the means of communication in construction as digital prefabrication workflows take root.

The key summary of everything in this thesis is that the effectiveness of something being implemented comes down to collaborative development and implementation with a focus on growth, not the termination of any one way and its replacement with something ‘better.’ The construction industry is innovative and is open to change, even radical integration of technology like in this thesis – but it is imperative that the changes be discussed and workshopped with all impacted, from the entry-level laborers to the c-suite. Participatory design is a ‘must’ for new workflows to implement new technology and communication structures, not a ‘maybe.’ Furthermore, to ensure longstanding success, new techniques must be in tandem with traditional techniques, supporting each other and diversifying the available methods to reach a desired goal. Although efficient in a vacuum, automation is a tool, just like any other. It has advantages, disadvantages, and it can break down right when you need it. As such, it cannot be, and should not be, construed as a substitute for labor. Interpreted in another way, this is about looking to the past as a learning experience to build a better future, not building a future divorced from precedent. There is no reason to throw away tradition simply because it seems like an outdated hinderance – there is value inherent in the method, and there is a reason they’ve stood the test of time.

As the future races toward AI and more advanced robotics, it is important to rise to meet the occasion instead of trying to hold the tide at bay. The world is constantly evolving, and stepping into that vision provides an opportunity to steer the future toward the vision we think is best. This thesis argues for just that, by championing a human-centric vision for digital fabrication technology. We have the agency to shape what comes to pass, and while this project is but one small building block, it will hopefully be joined by many more, eventually shaping a foundation for the future that does not remove the human element. Innovation and the implementation of new ideas into our workflows should focus on making the world – including our lives – a better place, for people by people, rather than serving the mechanical demands of the shareholders to extract more profit. This is precisely why qualitative data comes first. It is incredibly hard to analyze and interpret human responses and experiences, but what other way is there to understand the human experience of something? Designing systems that only focus moving towards 'perfect optimization' regarding quantitative metrics is hardly living, rather it is being a part of the machine – a robot in a human's skin. The romanticized idea of modernization, of cutting ties with tradition and following only logic and efficiency can be seductive, but unchecked it becomes a new problem, as we've seen emerge in our built environments and other areas of human society. Without the record of the past (and continued practice of the techniques), we may be unable to overcome the unforeseen obstacles of the future. While digital prefabrication and alternative assembly instructions are very different ways of accomplishing the construction of something, they are meant to enhance the process, not rewrite it. ▪

"It's all in your hands, It's your move," Diana Ross

7.0 BIBLIOGRAPHY

Agrawala, Maneesh, Doantam Phan, Julie Heiser, John Haymaker, Jeff Klingner, Pat Hanrahan, and Barbara Tversky. 2003. “Designing Effective Step-by-Step Assembly Instructions.” *ACM Transactions on Graphics* 22 (3): 828–37. https://doi.org/10.1145/882262.882352.

Blough, Lawrence. 2011. “Digital Tracery - Fabricating Traits.” In *Matter: Material Processes in Architectural Production*. Taylor & Francis Group.

Bork, Robert. 2023. “Paper Thin? The Evidence for 12th-Century Gothic Design Drawings.” *Arts* 12 (6): 220. https://doi.org/10.3390/arts12060220.

Brooke, John. 1995. “SUS: A Quick and Dirty Usability Scale.” *Usability Eval. Ind.* 189 (November).

Buchli, Jonas, Markus Giftthaler, Nitish Kumar, Manuel Lussi, Timothy Sandy, Kathrin Dörfler, and Norman Hack. 2018. “Digital in Situ Fabrication - Challenges and Opportunities for Robotic in Situ Fabrication in Architecture, Construction, and Beyond.” *Cement and Concrete Research*, SI : Digital concrete 2018, 112 (October):66–75. https://doi.org/10.1016/j.cemconres.2018.05.013.

Buswell, R. A., W. R. Leal de Silva, S. Z. Jones, and J. Dirrenberger. 2018. “3D Printing Using Concrete Extrusion: A Roadmap for Research.” *Cement and Concrete Research*, SI : Digital concrete 2018, 112 (October):37–49. https://doi.org/10.1016/j.cemconres.2018.05.006.

Crane, Robert, and Jeremiah Woolsey. 1992. “Isometric Drawings Enhance Assembly.” *Assembly* 35 (May). https://go-gale-com.offcampus.lib.washington.edu/ps/i.do?p=GBIB&u=wash_main&id=GALE|A12274454&v=2.1&it=r.

Deutsch, Randy. 2011. *BIM and Integrated Design: Strategies for Architectural Practice*. Newark, UNITED STATES: John Wiley & Sons, Incorporated. http://ebookcentral.proquest.com/lib/washington/detail.action?docID=697537.

Dougherty, Connor. 2018. “Piece by Piece, a Factory-Made Answer for a Housing Squeeze - The New York Times.” *New York TImes*, June 7, 2018. https://www.nytimes.com/2018/06/07/business/economy/modular-housing.html.

Dunn, Nick. 2012. *Digital Fabrication in Architecture*. London, UNITED KINGDOM: Laurence King Publishing. http://ebookcentral.proquest.com/lib/washington/detail.action?docID=1876132.

Fardhosseini, Mohammad Sadra. 2021. “A Quantitative Analysis of the Impact of Integrating Digital Technology for Formwork Fabrication on Human Factors Perspectives.” Seattle: University of Washington Libraries. https://digital.lib.washington.edu/researchworks/bitstream/handle/1773/47369/Fardhosseini_washington_0250E_22891.pdf?sequence=1&isAllowed=y.

Federal Reserve Bank St. Louis. 2021. “Private Non-Farm Business Sector: Multifavtor Productivity (Total Factor).”

Fologram, dir. 2021. *Using the HoloLens to Build the Royal Hobart Hospital*. https://www.youtube.com/watch?v=swA0pQcS-Is.

———. 2024. “Model Placement.” Fologram Instruction Documents. 2024. https://docs.fologram.com/ee913f72885c43d6b727ec7d025e4d13#Model_placement.

Franke, Thomas, Christiane Attig, and Daniel Wessel. 2019. “A Personal Resource for Technology Interaction: Development and Validation of the Affinity for Technology Interaction (ATI) Scale.” *International Journal of Human–Computer Interaction* 35 (6): 456–67. https://doi.org/10.1080/10447318.2018.1456150.

Frixione, Marcello, and Antonio Lombardi. 2015. “Street Signs and Ikea Instruction Sheets: Pragmatics and Pictorial Communication.” *Review of Philosophy and Psychology* to appear (March). https://doi.org/10.1007/s13164-014-0216-1.

Funk, Johannes, and Ludger Schmidt. 2021. “Evaluation of an Augmented Reality Instruction for a Complex Assembly Task: Comparison of a Smartphone-Based Augmented Reality Instruction with a Conventional Paper Instruction for the Teach-in Phase in Manual Assembly.” *I-Com* 20 (1): 63–72. https://doi.org/10.1515/icom-2021-0005.

Gao, Zhili, Russel C. Walters, Edward Jaselskis, and Terry J Wipf. 2006. “Approaches to Improving the Quality of Construction Drawings from Owner’s Perspective,” November. https://ascelibrary.org/doi/epdf/10.1061/%28ASCE%290733-9364%282006%29132%3A11%281187%29.

Hamid, Montasser, Osama Tolba, and Ahmed El Antably. 2018. “BIM Semantics for Digital Fabrication: A Knowledge-Based Approach.” *Automation in Construction* 91 (March):62–82. https://doi.org/10.1016/j.autcon.2018.02.031.

Hartanto, Hugo Adrian, Irena Krishanti Makrie, Violitta Yesmaya, and Permana Gustav Halfian. 2019. “The Development of Furniture Assembly Instruction Based on Augmented-Reality.” *ComTech: Computer, Mathematics and Engineering Applications* 10 (2): 75–81. https://doi.org/10.21512/comtech.v10i2.5853.

Horton, William. 1993. “The Almost Universal Language: Graphics for International Documents.” *Technical Communication* 40 (4): 682–93.

Lezhnina, Olga, and Gábor Kismihók. 2020. “A Multi-Method Psychometric Assessment of the Affinity for Technology Interaction (ATI) Scale.” *Computers in Human Behavior Reports* 1 (January):100004. https://doi.org/10.1016/j.chbr.2020.100004.

Mahmood, Bilawal, SangUk Han, and Dong-Eun Lee. 2020. “BIM-Based Registration and Localization of 3D Point Clouds of Indoor Scenes Using Geometric Features for Augmented Reality.” *Remote Sensing* 12 (14): 2302. https://doi.org/10.3390/rs12142302.

Modular Building Institute. 2023. “2023 Permanent Modular Construction Report.” https://mbimodularbuildinginstitute.growthzoneapp.com/ap/CloudFile/Download/LwYRWRzp.

Raspall, Felix. 2015. “A Procedural Framework for Design to Fabrication.” *Automation in Construction* 51 (March):132–39. https://doi.org/10.1016/j.autcon.2014.12.003.

Sadeghi-Niaraki, Abolghasem, and Soo-Mi Choi. 2020. “A Survey of Marker-Less Tracking and Registration Techniques for Health & Environmental Applications to Augmented Reality and Ubiquitous Geospatial Information Systems.” *Sensors (Basel, Switzerland)* 20 (10): 2997. https://doi.org/10.3390/s20102997.

Schumacher, Peter. 2007. “Creating Effective Illustrations for Pictorial Assembly Instructions.” *Information Design Journal (IDJ)* 15 (2): 97–109. https://doi.org/10.1075/idj.15.2.01sch.

———. 2013. “A Pattern Language for Pictorial Assembly Instructions (PAIs).” *Information Design Journal* 20 (December). https://doi.org/10.1075/idj.20.2.03sch.

Shi, Yao, Xiaofeng Zhang, Ran zhang, Zhou Yang, Xiao Tang, Hongni Ye, and Yi Wu. 2023. “BrickPal: Augmented Reality-Based Assembly Instructions for Brick Models.” arXiv. http://arxiv.org/abs/2307.03162.

Slepicka, Martin, Simon Vilgertshofer, and André Borrmann. 2021. “Fabrication Information Modeling: Closing the Gap between Building Information Modeling and Digital Fabrication.” In *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction*, 38:9–16. Waterloo, Canada: IAARC Publications. https://www.proquest.com/docview/2642454729/abstract/667894E9CE7C4334PQ/1.

SOM. 2023. “Angelus Novus Vault – Palazzo Mora, Venice.” SOM. May 18, 2023. https://www.som.com/story/angelus-novus-vault-palazzo-mora-venice/.

Turner Construction. 2023. “Case Study: Innovation in Digital Fabrication Prefabricated Formwork.” https://www.turnerconstruction.com/uploads/Case-Study-Innovation-in-Digital-Fabrication.pdf.

US Bureau of Labor Statistics. 2021. “Total Factor Productivity for Construction (NAICS23).”

US GAO, U. S. Government Accountability Office. 2022. “Science & Tech Spotlight: Extended Reality Technologies | U.S. GAO.” GAO-22-105541. US GAO. https://www.gao.gov/products/gao-22-105541.

Yan, Wei. 2022. “Augmented Reality Instructions for Construction Toys Enabled by Accurate Model Registration and Realistic Object/Hand Occlusions.” *Virtual Reality* 26 (2): 465–78. https://doi.org/10.1007/s10055-021-00582-7.