Design, Development and Validation of an Augmented Reality-Enabled Production Strategy Process for the Construction Industry

By

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Abstract

Although execution is generally the phase during which challenges faced by the construction industry become apparent, it only represents the tip of the iceberg. Execution depends on the effectiveness of construction planning and control – an area identified by researchers as in need for improvement. Inspired by innovations in manufacturing, the application of Lean Production and the advancements in Information and Communication Technologies (ICT) have been at the core of addressing the deficiencies in the traditional planning and control system. New innovative production planning and control systems such as the Last Planner® System (LPS) emerged and were empowered with the integration of Building Information Modeling (BIM). While the implementation of LPS results in a more predictable workflow, a greater degree of team-building, respect, and reliable delivery of tasks, the system does not presuppose any specific work structure. Researchers have investigated a location-based work structure, namely Takt-Time Planning. The complimentary nature of Takt-Time Planning and LPS was investigated and studied by various researchers. The concepts of Takt-Time Planning were then added to the LPS in the form of a new stage, named *Production Strategy*.

Production Strategy is an integral part of production planning and control and is essential to developing a reliable and balanced production plan. The Production Strategy Process (PSP) involves a massive information transfer and communication need among the project team. While BIM can improve the flow of the work, the paradox of designing the 3D models in 2D space remains. This paradox indicates that new visualization technologies are needed to leverage the use of information in the PSP. Moreover, the increased competition and customer expectation add more pressure on construction companies to remain competitive and grow in the modern construction – much like the Darwinian theory, industry must adapt or die. As Industry 4.0, the fourth industrial revolution, continues to evolve, it is imperative that construction firms seek, find, and adopt new technologies. Augmented reality (AR), a pillar of Industry 4.0, can be employed as a new user interface technology that introduces a new perspective for developing the PSP.

In order to incorporate AR into the PSP, both the technology and the process must be understood. While AR has been of interest to researchers for some time, no single research effort has yet comprehensively investigated the opportunities, benefits, challenges, and future paths toward implementing AR in modern construction. This study starts with a holistic assessment of AR in construction that explores the potential of the technology from the perspective of the industry. The results of this analysis provide the construction industry with a roadmap to guide the implementation of AR.

Next, the study focuses on designing and developing an AR-Enabled PSP. The current state of practice of the PSP is investigated and current challenges and pain points in the current state are identified. The opportunities to integrate AR are then identified, and an AR-Enabled future state of the PSP is proposed. Next, an AR-Enabled PSP prototype is built for the Microsoft HoloLens headset and validated on an ongoing construction project. The results of the validation show than the AR-Enabled PSP has the following benefits over the Traditional PSP: improved collaboration, reduced miscommunication, increased quality and detection of errors, enhanced decision-making, increased integration of safety considerations, increased input accuracy, better information access, improved information flow, and better documentation. These benefits were tested through a series of hypotheses comparing both processes. However, no significant difference was found between the Traditional and AR-Enabled PSP in terms of spatial cognition and time efficiency of the process.

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Chapter 1: Introduction

1.1. Background

The construction industry is poised for significant growth. It is forecast that by 2030 the global expenditure of construction and related activities will reach $15.5 trillion (PricewaterhouseCoopers n.d.). While the construction industry is a major factor in the prosperity of nations, it is fraught with waste and inefficiencies. The information-intensive nature of construction projects is a significant contributor to inefficiencies and losses in the industry. Per (Forbes and Ahmed 2011), a single instance of rework can cost on average of 10% of the total project cost in the United States. The volume of waste in construction has been estimated at between 25% and 50% of the total project cost. This figure stems from inefficient control of labor, materials, interactions between trades, and the site in general. Between $17 billion and $36 billion are lost annually due to omitted information when design documents are translated into construction documents. Howell and Lichtig (2008) noted that the work executed on construction sites is chronically unreliable and that on average only 55% of work planned and promised to be completed each week was actually completed – no better than a coin toss. Other studies that focus on construction efficiency have documented 25% to 50% waste in coordinating labor and management (Modular Building Institute (MBI) 2010). Oakland and Marosszeky (2017) mentioned that subcontractors are focused on optimizing their piece of work, not the whole.

One common trait with the above mentioned facts is that they all occur during execution, which depends on the effectiveness of production planning and control systems (as shown in Figure 1)[1]. Production planning and control is considered among the top potential areas that need

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[1] Design is also a phase where potential challenges and issues could be identified and addressed prior to execution, but this research specifically focuses on Production Planning and Control.

improvements in the construction industry (Sriprasert and Dawood 2002). Construction researchers agree that major issues in production planning and control are caused by the 1) inadequacy of traditional project management theory and 2) improper applications of information technologies (IT) (Koskela 1992; Ballard 2000; Koskela 2000; Sriprasert and Dawood 2002; Dave et al. 2010).

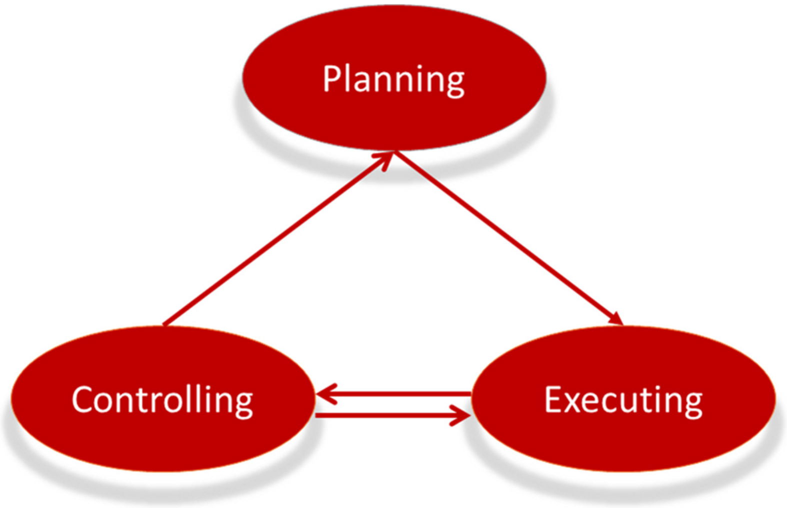

Figure 1 Planning, Executing, and Controlling
(Reproduced from PMBOK Guide)

The first major issue concerns the traditional project management concept in construction which is based on the transformation concept that considers construction as a set of activities aimed at a certain output – i.e. conversions (Koskela 1992). The conversion model is exemplified by the heavy emphasis on the use of the Critical Path Method (CPM) sequencing technique as the beginning and ending of the planning process (Howell and Ballard 1997). The baseline schedule is typically created using CPM and bar charts and is sequenced according to a lengthy list of unpredictable but forecasted construction processes, variable productivity rates, and unknown unknowns (Albdelhamid 2008). The resulting baseline schedule does not address *how* activities will be executed, nor does it model logic constraints, nor does it consider maximizing value or minimizing waste ((Howell and Ballard 1997; Koskela et al. 2002). When construction begins under the traditional approach of construction management, the focus is often transferred to control efforts while disconnecting project planning from execution (Ballard and Howell 1998). Site operations are driven by top-down push system and lookahead and weekly plans are filtered from the detailed baseline schedule, ignoring the actual status of work on site (Tommelein 2015). This model results in an unbalanced system and leads to execution failure (Koskela 1999; Abdelhamid et al. 2010).

Although the construction industry has been governed by the traditional conversion model, this transformation model has been widely criticized as the focus on activities alone results in a significant amount of waste, loss of value, and non-value-adding activities (Koskela 1992). In response to the deficiencies of the traditional production view, and inspired from the manufacturing experience and specifically from the Toyota Production System (TPS), (Koskela 1992) argued that construction should be viewed as flow processes not just conversion processes. Koskela (1999) identified seven resource flows (or pre-conditions) to the execution of any construction work: design, components, materials, workers, space, connecting work and external conditions, as illustrated in Figure 2. Koskela (1999) stressed that the *realization of tasks depends on flows, and the progress of flows depends on the realization of tasks.*

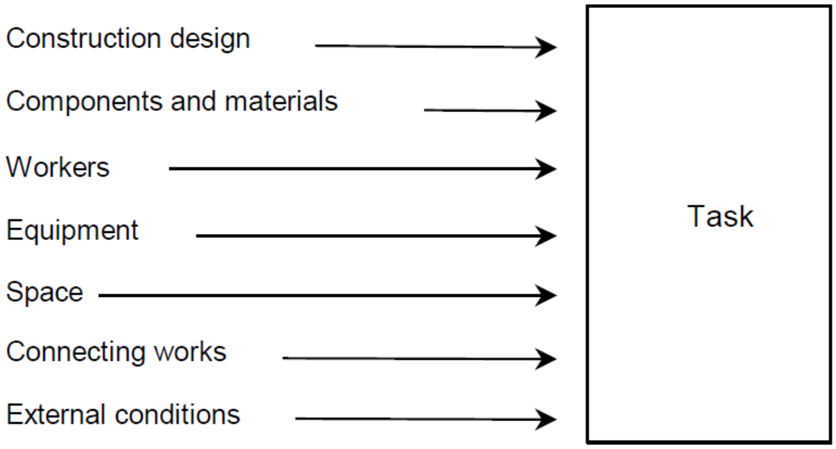

Figure 2 Preconditions for a Construction Task
(Koskela 1999)

Later, a new production theory, namely Transformation/Flow/Value view, was introduced into construction (Koskela 2000). Consequently, new production planning and control systems were put forth to reduce uncertainty, improve flow, improve predictability, increase transparency, and reduce waste (Seppänen et al. 2015)

One of these systems is the Last Planner® System (LPS), a new production planning and control system that complements CPM by addressing its shortcomings at the production level (Ballard and Howell 1994a). LPS fosters collaborative planning was developed to improve construction predictability and reliability by bringing 'Last Planners' forward in the process (Ballard 2000). The 'Last Planner' is the last person in a chain of planners and the output of their planning process is not a directive for a lower planning process, but it results in production (Ballard and Howell 1994b). In other terms, the 'Last Planner' refers to the person that creates tasks for direct workers to perform such as a foreman, superintendent, workgroup supervisor, system owner, tool owner, vendor lead tech (Lean Construction Institute 2016). LPS consists of four phases: master scheduling, phase scheduling, look-ahead planning, and weekly planning (Hamzeh et al. 2012). *production planning* includes master scheduling and phase scheduling and *production* *control* covers look-ahead planning and weekly planning (Seppänen et al. 2015). Instead of directing the project team on what to do, this innovative production planning and control system embraces a new philosophy and creates an environment that facilitates cooperative discussions, debate, and rapid learning (Howell et al. 2011). The implementation of LPS results in a more predictable workflow, a greater degree of team-building, respect, and reliable delivery of tasks (Ballard and Tommelein 2016).

However, as noted by (Ballard and Tommelein 2016), LPS does not presuppose any specific work structure. The authors indicated that work structuring must happen before project control – i.e., before look-ahead planning could occur. Work structuring must ensure continuous process flow, and one core parameter to achieve such flow is Takt-Time.

Takt is a German word which means ‘beat’ or ‘rhythm.’ It is applied to Lean Production to establish flow (Liker 2004). Implementing Takt into processes prevents overproduction, reduces lead times and inventory, stabilizes processes, optimizes workflow, and improves production capacity (Haghsheno et al. 2016). Within Lean Construction, ‘Takt-Time’ is the unit of time in which a product must be produced (i.e. supply rate) to match the rate at which the product is needed (i.e., demand rate) (Frandson et al. 2013). Oakland and Marosszeky (2017) argued that the knowledge and understanding that the pace of construction is predictable enabled all trade crews to plan their resources and logistics in a reliable matter.

The application to Takt-Time into construction is not compatible with the traditional activity-based breakdown structures such as CPM, which are often considered to be “black boxes” that encapsulate all of the production details and reveal only the total duration (Sacks et al. 2017). As a result, researchers indicated that moving from activity-based to location-based planning is essential for applying the concept of Takt-Time on construction projects (Linnik et al. 2013). Consequently, researchers have investigated the implementation of location-based work structuring methods, namely Takt-Time Planning into the LPS (Frandson et al. 2014; Ballard and Tommelein 2016; Ebrahim et al. 2017; Oakland and Marosszeky 2017).

Takt-time planning breaks the work down into individual, manageable, chunks and determines their demand and supply rates (Tommelein 2017). While the use of Takt-Time Planning in construction has been investigated by many researchers through case studies, (Frandson et al. 2014) demonstrated the complimentary nature of Takt-Time and LPS. The authors noted that Takt-Time introduces a standard, continuous flow of work that the LPS then is able to control, and LPS allows the flow of work to remain when obstacles emerge and must be adapted to. Oakland and Marosszeky (2017) also mentioned that Takt-Time Planning enhances the predictability of the pace of the work and allows trades to better manage their resources and to hit the completion date. Oakland and Marosszeky (2017) recognized that implementing Takt-Time planning will not free the production flow from disruptions, but it will allow the Last Planner (foreman for instance) to make an educated guess of how much capacity they need to stay on track. The visible targets for weekly and daily handoffs created in Takt-Time Planning promotes transparency and drives the Last Planner to keep up with their commitments (Oakland and Marosszeky 2017). Ebrahim et al. (2017) then added the concepts Takt-Time Planning as new stage to the LPS and named it *Production Strategy* (Figure 3). According to (Ebrahim et al. 2017), the three objectives of this stage are: 1) implementing sequence and flow analyses, 2) defining production areas, and 3) designing production using Takt-Time principles to achieve stable and predictable construction flows.

Production Strategy is an integral part of production planning and control and is essential to developing a reliable and balanced production plan (dos Santos 1999). An analogy can be drawn between Film Production Management and Construction where Production Strategy could be thought of as the read-through where the actors are brought together to read the script. Read-through is an important milestone in the production of a film. It provides an opportunity for everyone involved in the production to get insights into how the actors will approach their roles. Moreover, read-through is a powerful tool for identifying problem areas in the script. Issues that have not been addressed in the script development process often come to the surface and become apparent during the read-through. Using this analogy, the PSP is the read-through process, the project set of drawings and/or BIM model are the script and the last planners are the actors. PSP provides an environment to practice the execution of construction operations and identify potential problem areas before the execution phase begins.

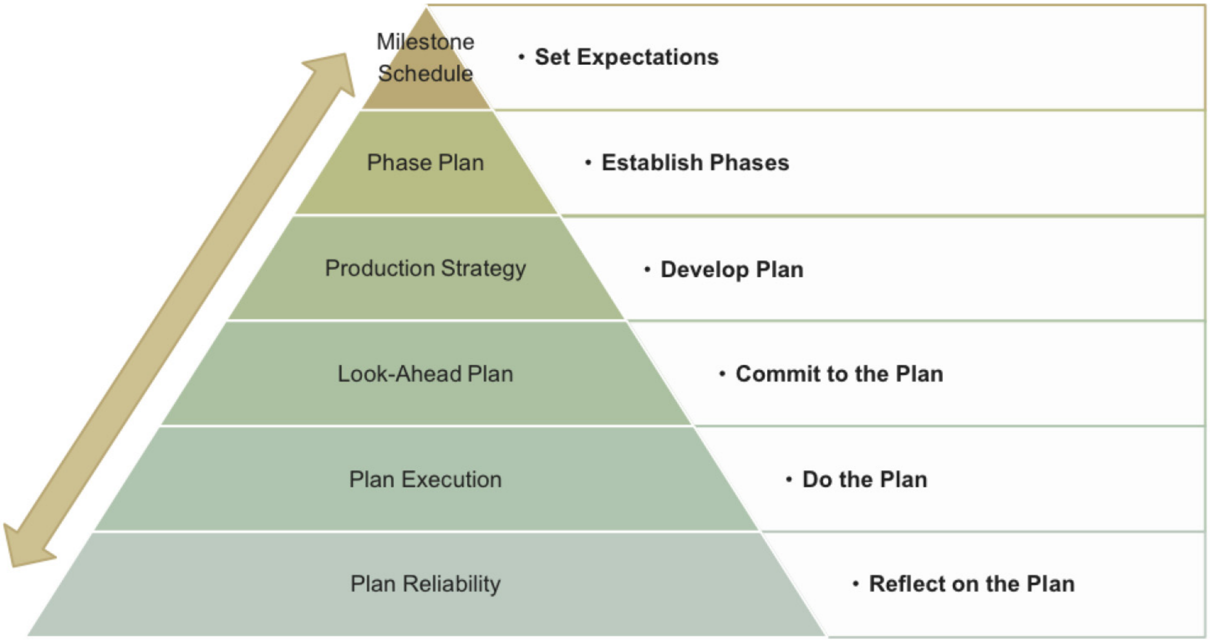

Figure 3 Production Planning and Control
(The Boldt Construction Company)

The second major cause of inefficiencies in production planning and control is the improper application of IT. Production planning and control involves a massive information transfer and communication needs among the project team (Leinonen et al. 2003). Researchers noted that the flow of information in construction affects all other resource flows and is therefore important to manage (Dave et al. 2014). The site team needs resource information about their construction tasks to effectively execute the work and conduct effective look-ahead and weekly planning activities (Dave et al. 2010, 2014). Consequently, the information than transcends from the planning process affects the construction. Thus, the reliability of the planning process affects the efficiency of the overall production system (Dave et al. 2014). Researchers stated that the implementation of Information Technology (IT) can improve information flow and integration within construction (Dave et al. 2010).

Liker (2003) pointed out that Toyota differentiated itself from its competitors and remained flexible by selecting IT opportunity that were needed and which could reinforce the business process and by ensuring through testing that they were an appropriate ‘fit’ to the organizational infrastructure (people, process, and other IT). Ahmad et al., (1995), postulated that the need for teamwork, flexibility, coordination, and communication in construction gave the industry a great potential to integrate IT. Moreover, the use of IT in the construction industry generates new opportunities for collaboration, coordination, and information exchange among project stakeholders (Forcada Matheu 2005).

Advanced computing technologies have the potential to empower construction stakeholders, for instance project managers, to make quick decisions based on accurate information that can be visualized, studied, optimized, and quantified with greater accuracy (Salem and Mohanty 2008). Ying and Lee (2016) clustered Information and Communication

Technologies (ICT) in construction, an extension of IT, into eight groups. This research focuses on the two groups of ICT where the construction industry has made significant strides: 1) product modeling and 2) visualization.

The construction industry has undergone a significant and radical transformation in its design and documentation process as it evolved from the days of the drafting board to today's Building Information Modeling (BIM) process. At each stop along that journey, gains were made in information density and exchange. BIM has transformed the traditional paradigm of construction industry from 2D-based drawing information systems to 3D-object based information systems (Arayici et al. 2011; BIM Alliance n.d.). BIM serves as a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its lifecycle from inception to commissioning and beyond (Rossini et al. 2017).

Although the new concepts of Lean and the advances in ICT (namely BIM) are different initiatives and can be applied individually, researchers have indicated that integrating them together results in greater benefits (Sacks et al. 2010a). Cheng et al. (2010) claimed that the use of IT is beneficial to Lean processes, especially when IT is applied to improve the information flow. Researchers such as (Sacks et al. 2009; Gurevich and Sacks 2014) showed that communicating process information clearly and fully using visual aids such as BIM can enhance the flow of the work itself.

However, for all the progress made thus far, the paradox of designing the 3D in 2D space remains. This paradox indicate that new visualization technologies are needed to leverage the use of information in construction, and in the Production Strategy Process (PSP) particularly. As Industry 4.0 continues to evolve, it is imperative that construction firms seek, find, and adopt new technologies – both to remain competitive and to grow the industry. One of the nine pillars of Industry 4.0, augmented reality (AR) is an emerging technology which has great potential to transform the construction industry (Rüßmann et al. 2015). A study conducted by (Oskouie et al. 2012) revealed the interactions between BIM, AR, and Lean Principles and reported that the integration of AR with BIM can achieve a continuous work flow and reduce variability. Specifically, AR can be employed as a new user interface technology that introduces a new perspective for developing production strategy based on Takt-Time Planning.

1.2. Research Motivation

Most literature which was reviewed focuses on the avenues to integrate AR into site operations (visualizing blueprints, safety, etc). However, as stated by (Globerson and Zwikael 2002; Beary and Abdelhamid 2005) planning has a great impact on execution and control, and is ultimately a major contributor to project success which is determined by how well it is executed in comparison with the plan.

Although the construction industry has made improvements by adopting Lean principles and integrating ICT into its processes, increased competition and customer expectation add more pressure on construction companies to remain competitive and grow in the modern construction – much like the Darwinian theory, industry must adapt or die. As Industry 4.0 continues to evolve, it is imperative that construction firms seek, find, and adopt new technologies – both to remain competitive and to grow the industry. One of the nine pillars of Industry 4.0, Augmented Reality (AR) holds perhaps the key to this advancement.

Fenn and Raskino (2008) explained that there are five major stages in the growth, dissemination, and development of a technology. Collectively, they are referred to as the 'innovation hype cycle,' as depicted in Figure 4 . The hype cycle begins with the trigger (step 1) where a breakthrough event or prototype generates interest in an innovation. Once this trigger occurs, there is a rapid increase in hype as the cycle reaches the peak of inflated expectations (step 2). In this stage, advanced companies and consumers seek out the innovation and adopt it early. However, as time passes but before measurable results are returned, impatience produces the trough of disillusionment (step 3). However, the innovation does not simply waste away into nothingness at this point. Some early adopters and researchers overcome the challenges and begin to reap benefits, then commit to moving forward. This is the slope of enlightenment (step 4). Finally, after the aforementioned enlightenment, the applications of the technology to the real world are defined and the innovation reaches the plateau of productivity (step 5).

The growth and lifecycle of AR can be plotted on the hype cycle, as shown in Figure 4. Per Gartner, who developed the hype cycle, AR is a promising technology that is still in its developmental phases. As of 2018, Gartner placed it in the trough of disillusionment (Panetta 2018). As of yet, there has been no significant use of AR in construction. Therefore, now is the optimal time to develop such an application and investigate the impact that AR can have on existing processes. AR can serve to leverage the use of BIM in the Production Strategy Process (PSP) and enable a new generation of PSP. Just as Lean was a differentiating innovation for companies ten years ago, AR has the potential to follow suit in the near future. Such AR application allows early adopters to gain a competitive advantage in the smart construction market.

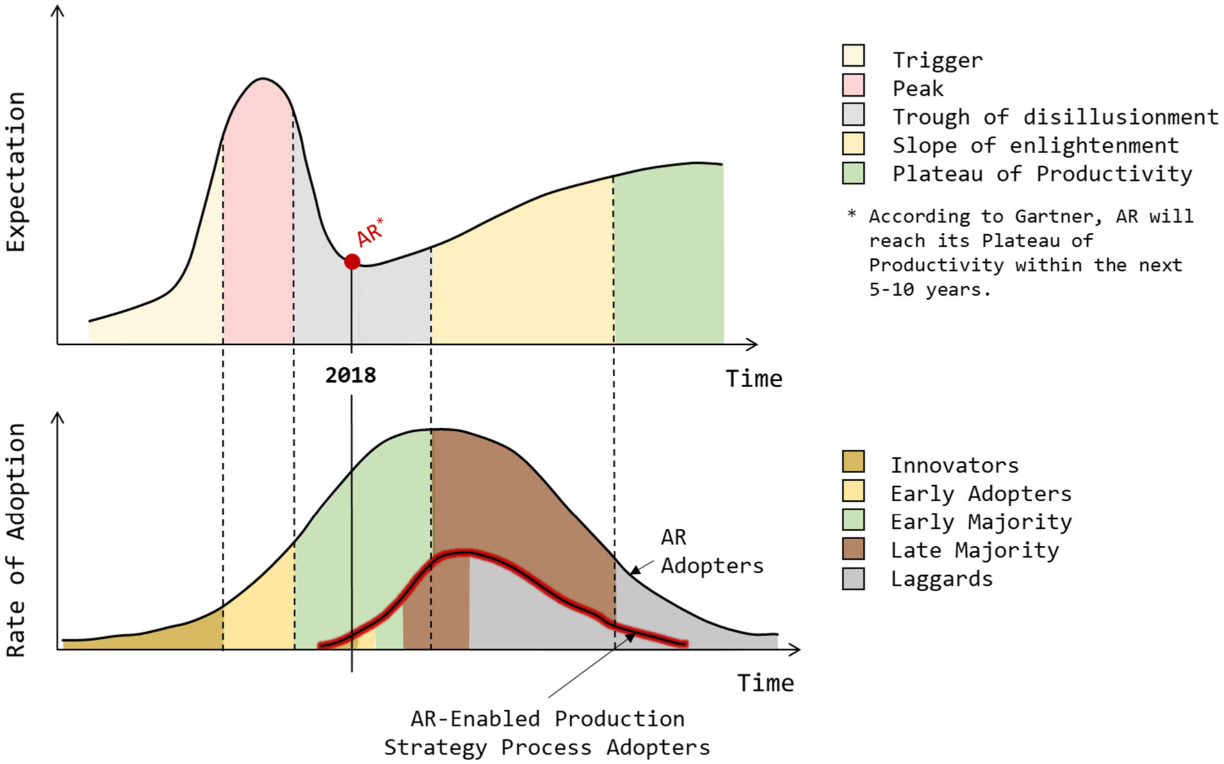

Figure 4 The Innovation Hype Cycle of AR, its Rate of Adoption, and the Estimated Rate of Adoption of the 'Smart Project Production System' Application
(Expectation graph reproduced from Gartner 2018 and Adoption graph reproduced from Rogers 2003)

1.3. Research Objectives

In order to incorporate ICT (AR here) into a process, the technology itself and the process must both be understood. Therefore, this research covers two main objectives:

A. To explore AR in construction from the perspective of the construction industry (**Objective A**)

B. To design and develop a new AR-enabled Production Strategy Process (AR-PSP) (**Objective B**)

This research will achieve Objective A through a series of intermediate objectives:

1. Archive the current state of the practice of AR in the construction industry
2. Investigate use-cases of AR across the project lifecycle, highlight potential benefits, identify obstacles to entry which have slowed the implementation of AR thus far, explore who benefits the most from AR and where the technology is most useful in construction
3. Provide insights into the potential future of AR in construction

The approach undertaken to achieve Objective B entails the completion of the following sub-objectives:

1. Investigate via literature review and expert interviews the current state of PSP
2. Identify current challenges and bottlenecks in the current state PSP
3. Identify leverage areas for the integration of AR
4. Define an AR-Enabled PSP future state
5. Develop a prototype of the AR-Enabled PSP as proof-of-concept
6. Validate the prototype on an actual construction project

The outcomes of the Objective A provide the construction industry with a roadmap to guide the implementation of AR. The results of Objective B provide the early adopters of AR with a new frontier to leverage existing innovation (BIM and Lean) and innovate their PSP and consequently, gain a competitive advantage in the smart construction market.

1.4. Research Methodology

This research consists of two methodologies – one for each objective. In a nutshell, the methodology of Objective A consists of an extensive literature review of AR in the construction industry, a survey development and data collection, data analysis, and conclusions. Chapter 3 provides a detailed description of the methodology employed to achieve the overarching Objective A and its intermediate objectives.

The approach undertaken to fulfill Objective B consists of three main phases: ‘Understanding’ phase, ‘Conceptualizing’ phase, and ‘Implementing and Validating’ phase. Each of these phases consists of a number of stages and each stage is broken down into tasks. Chapter 5 describes this methodology in greater detail.

1.5. Dissertation Organization and Structure

The dissertation is composed of four sections, each including a number of chapters. The dissertation is organized as follows:

- Section I includes Chapters 1 and 2
    - Chapter 1 consists of an introduction, providing the background and motivation for this research effort
    - Chapter 2 presents a review of the literature, divided into **4** main parts:
        - Lean
        - Information and Communication Technologies (ICT)
        - Augmented Reality in the construction industry
        - Synergies between Lean and ICT
- Section II includes chapters 3 and 4

  - Chapter 3 outlines the research methodology used to investigate the potential of AR throughout the lifecycle of a construction project (objective A). The methodology includes:
    - Survey development and testing
    - Data collection
    - Characteristics of the collected data
  - Chapter 4 discusses the statistical analysis performed on the various survey data and presents the results regarding the current and future states of AR in construction
- Section II includes chapters 5 – 8
  - Chapter 5 presents the research methodology employed to investigate the integration of AR with BIM to build upon the existing production strategy process (PSP) (Objective B). This methodology includes three phases:
    - ‘Understanding’ Phase
    - ‘Conceptualizing’ Phase
    - ‘Implementing and Validating’ Phase
  - Chapter 6 discusses the ‘Understanding’ phase and provides an in-depth analysis of the current state of PSP
  - Chapter 7 discusses the ‘Conceptualizing’ phase and outlines the challenges encountered in the current state of PSP, identifies potential opportunities for

    integrating AR into the existing PSP, and maps out the future envisioned state of the AR-Enabled PSP

  - Chapter 8 discusses the ‘Implementing and Validating’ phase and illustrates the steps undertaken to develop the AR-enabled PSP prototype and validate the developed prototype. This chapter also reports the results of the validation of the prototype

- Section IV includes Chapter 9 and the Appendices
  - Chapter 9 presents the summary of the work as well as the conclusions and presents an outlook into future work
  - Appendices A – D

Chapter 2: Literature Review

The first step of this research effort was a comprehensive review of existing literature concerning 4 holistic areas of this research: (1) Lean, (2) Information and Communication Technology (ICT), (3) Augmented Reality in Construction, and (4) synergies between Lean and ICT.

2.1. Lean

2.1.1. Lean Production

The notion of innovative production philosophy originated in Japan in the 1950s with the Toyota Production System (TPS) (Koskela 1992). The New Production System (NPS) (n.d.) defines this philosophy as a management philosophy for manufacturing, as well as a method of enhancing corporate vitality which aims to totally eliminate waste and achieve the maximum possible quality with the shortest possible lead time. The TPS integrates a set of methods and tools with management concepts to completely eliminate seven forms of waste (Muda), including overproduction, excessive inventory, poor quality, unnecessary conveyance, over processing, unnecessary motion, waiting for work, and to produce profit through cost reduction (Wagner et al. 2017).

The term “Lean” was first coined by John Krafcik in 1988 in his report on Toyota’s manufacturing systems where he described the advances in productivity of the Japanese automotive industry in comparison with western manufacturers (Krafcik 1988). In the early 1990s, the term ‘Lean production’ was first introduced as *The Machine that Changed the World* to contrast Toyota with the Western ‘mass production’ system (Womack et al. 1991). The operational prerogative of Lean is the reduction of waste and maximization of value, and as such it has quickly become popular in healthcare, service, administration, production development, and construction

(Koskela 1992; Tezel and Aziz 2017). Frigo et al. (2016) described Lean as a powerful antidote to waste and a concept that goes beyond the company and applies to the entire set of activities from conception to delivery to end user. Shah and Ward (2003) stated that the most often revealed practices commonly associated with Lean production are: bottleneck removal (production smoothing), cellular manufacturing, competitive benchmarking, continuous improvement programs, cross-functional work force, cycle time reductions, focused factory production, just-in-time/continuous flow production, lot size reductions, maintenance optimization, new process equipment/technologies, planning and scheduling strategies, preventive maintenance, process capability measurements, pull system/Kanban, quality management programs, quick changeover techniques, reengineered production process, safety improvement programs, self-directed work teams, and total quality management.

While Lean Production continues to evolve, the concepts underpinning production systems are well established:

- Identify and deliver value to the customer by eliminating what doesn't add value
- Organize production as continuous flow
- Perfect the product and create reliable flow
- Pursue perfection

2.1.2. Lean Construction

Influenced by the gains that resulted from the TPS, researchers in the construction industry investigated the potential of applying the theory, principles and techniques associated with TPS to the construction industry (da CL Alves and Tsao 2007). Lean as applied to construction was first discussed by (Koskela 1992). In 2000, Koskela explained that Lean construction projects should be viewed as production systems, with the output being the built product (Koskela 2000). This departs from the traditional view, or the transformative view, in which construction production is performed through individual activities that transform inputs (raw materials) into output (built product). Koskela put forth the Transformation/Flow/Value (TFV) theory, which prescribes that construction be viewed as the transformation of resources (raw materials), flow of materials and people, and the creation of value. In this system, construction projects are considered temporary production systems, with three pillars: eliminate waste, collaborate, and optimize the value-added chain (Koskela 2000). The focus on the traditional-view of construction results in many challenges, including: neglection of flow, lack of coordination among stakeholders, and segmented control. (Koskela 1992) indicated that there are two main flow processes in construction: design process and construction process. The latter is composed of two different types of flows:

- Material processes which consist of the flows of material to the site, including processing and assembling on site
- Work processes of construction teams which represent the temporal and spatial flows of construction teams on site. These work processes are closely associated with the material processes.

Koskela served as a catalyst whose work sparked a wealth research into the adoption of Lean in the construction industry and the Lean Construction Institute (LCI) was founded in 1997 by two well-known lean advocates, namely Glenn Ballard and Greg Howell. Howell (1999) noted that waste in construction and manufacturing arises from activity-centered thinking which places immense pressure on reducing the cost and duration of each step as the key for improvement. In the *Parade of Trades* (Tommelein et al. 1999) highlighted two shortcomings of the activity-centered thinking in construction: 1) the dependence of ongoing activities between trades or within operations are not modeled and 2) variability is not explicitly represented. Howell (1999) stated that construction is directives driven and that measuring and improving the performance of the planning system is key to improving the reliability of flow. The crucial challenge to construction is the spatial and scheduling coordination of the vested parties and disciplines, and Lean advocates recognized the need to develop new forms of planning and control to better manage work flow and production (Howell 1999; Tommelein et al. 1999). As such, innovative Production Planning and Control (PPC) methods have come to the fore. Production Planning and Control are complementary in construction (i.e. two sides of the same coin) and are dynamic processes that keep revolving and are maintained throughout the course of the construction project (Howell 1999). Planning defines the success criteria and production strategies for achieving project objectives and Control ensures that executed events conform to the planned events which triggers learning and re-planning when the previously established sequence is no longer application (Howell 1999).

2.1.3. Production Planning and Control Systems

2.1.3.1. Last Planner® System

In response to the challenges and deficiencies in traditional production planning and control, one of the main research efforts in Lean construction led to the development of the Last Planner® System (LPS). LPS was initially developed by Glenn Ballard and Greg Howell in 1992 as a PPC system to smooth variability in work flow, reduce uncertainty, and improve construction predictability and planning reliability by bringing ‘Last Planners’ forward in the process (Ballard 2000; Mossman 2013). The last planner is the project party who is responsible for the control of operative tasks – typically trade foreman. As such, the LPS involves these foremen with general contractors, architects, and owner’s representatives to bring site knowledge and practical experience to the table, making plans more realistic (Eilers et al. 2016). LPS decentralizes management tasks and improves cooperative work (von Heyl and Teizer 2017). LPS addresses the deficiencies in the traditional production planning and control through the implementation of the following practices (Hamzeh 2009):

1. Planning in greater detail as we get closer to performing the work;
2. Developing the work plan with those who are going to perform and execute the work;
3. Identifying and removing constraints as a team ahead of time in order to make work ready and increase the reliability of the work plan;
4. Making reliable promises and driving work execution based on coordination and active negotiation with trade partners (i.e. subcontractors) and project parties;
5. Learning from planning failures by identifying root causes and taking preventive actions.

There are four chronological phases to LPS, as follows (Hamzeh et al. 2012):

1. Master Scheduling is a front-end planning process that produces a schedule describing the work to be carried out over the project duration. Major milestones are identified, and CPM is used to determine the overall project duration.
2. Phase Scheduling generates a schedule covering each project phase, such as foundation, structural frame, overhead, in-walls, or finishing. In a collaborative planning setup, the project team defines these phases and their various activities and uses pull planning to schedule the activities backward from the milestones.
3. Lookahead planning is the first step in production control (i.e., executing the work) and it usually covers a six-week time frame. At this level, activities are broken down into the level of production processes, constraints are identified, operations are designed, and assignments are made ready.

4. Weekly work planning is the most detailed plan in the system and covers the particulars of work to be performed each week.

(Oakland and Marosszeky 2017) indicated that work teams who used LPS in their weekly planning processes increase their rate of reliable commitments on a weekly basis from 50% up to 85%.

2.1.3.2. Takt-Time Planning

Kenley and Seppänen (2006) indicated that there are two main methodologies for scheduling work: *activity-based* and *location-based*. Location-based scheduling methods explicitly consider location as a dimension in the production process. A project can be modeled as a series of locations in which activities flow through different units in turn. Thus, in each location, activities are linked through a logical relationship network (Soini et al. 2004).

2.1.3.2.1. Activity-Based Methodology

While the term *activity-based* methodology was first coined by (kenley 2004) as a way to contrast it to *location-based* methodology, the concepts and methods underlying this methodology date back to the 1950s (Kenley and Seppänen 2006). Activity-based methods are planning, scheduling and control method that focus on the unit of work to be completed. Work is considered a series of discrete packages which only have a time-based relationship to each other. This methodology does not explicitly account for the physical location and its relationship to the surrounding location. In other words, there is no location-based relationship between activities (Kenley and Seppänen 2006). One activity-based method that dominates the construction industry is the Critical Path Method (CPM) (Shi 1999; Kenley 2004). The term CPM was coined by Kelley and Walker in 195 to highlight the central position that critical activities in a project play in the method (Kelley Jr and Walker 1959; Kenley and Seppänen 2006). The main approach of CPM is to find, calculate, and optimize the critical path of the project. The critical path is defined as the sequence of activities that has the longest duration and thus determine the duration of the project. CPM, thus, only considers two fundamental features: durations of activities and dependencies between activities which are usually vassalized through Gantt Charts (Bølviken et al. 2015). Once the CPM network of activities have been established, and in order to execute the activities according to the schedule, resources must be allocated. Resources leveling is a concept that is closely related to CPM (Wilkens 2006). Resource leveling is an optimization technique to adjust and smooth the schedule by removing peaks and throughs in project resources. CPM and resource leveling are widely adopted by the construction industry and there is a wealth of literature that discusses both concepts as the dominant method for planning, scheduling, and controlling construction project (Kenley and Seppänen 2006; Bølviken et al. 2015). However, researchers, specifically Lean advocates, realized the shortcomings of both concepts and argued that implementation of Lean Thinking in the construction industry requires the development of a new approach to production planning and execution (Kenley 2004). Koskela (1992) who first introduced Lean production to the construction industry, indicated that a production system must consist of continuous flow through networks of trade workers that create value to the customer. He then criticized CPM and explained that this conventional concept violates the core principle of Lean – flow: the CPM network determines the start and end date of an activity but does not plan the flow itself (neither the flow of teams nor the flow of materials). Therefore, this traditional activity-based planning methods fails to support the planning of work flow and, thus, leads to non-optimal flows and an increase of non-value-adding activities (Koskela 1992). Other researchers such as (Kenley 2004; Kenley and Seppänen 2006; Ghosh and Reyes 2017a) argued that activity-based methods ignore the dynamics and interdependencies of construction activities and focus only on the “Transformation-view” of production by optimizing each activity individually. Various researchers discussed major drawbacks of using CPM including: inability to cope with non-precedence constraints, difficulty in plan evaluation and communication, and inadequacy for work-face executions, ‘black boxes’ that encapsulate all production details and only show only the total duration of activities, failure to consider fluctuation in production rates, inability to deal with intermediate or fuzzy dependencies (Sriprasert and Dawood 2002; Koskenvesa et al. 2010; Brioso et al. 2017; Sacks et al. 2017).

Given the failure of activity-based methods to consider flow, new methods that model dependencies between activities and ensure continuous flow are needed. When considering continuous flow, it is important to determine the rate of the flow – i.e. how fast should the flow move (Yassine et al. 2014). A key technique in achieving continuous flow is the concept of Takt-Time (Womack and Jones 1997). This concept is explained in section 2.2.2.3. The new planning techniques that aim to achieve continuous flow must consider the concept of Takt-Time, and thus the focus shifted from activity-based to location-based methodology.

2.1.3.2.2. Location-Based Methodology

Originally developed in manufacturing, location-based methods were adopted for construction. Location is at the core of the *Location-Based Methodology* where the relationship between the location of the work and the unit of work to be done is the main focus. The term *location-based* schedule was proposed by (Kenley 2004) and illustrate the flow of workers, materials, and equipment through fixed location units as contrasted with manufacturing where production units flow through the fixed resources. Location-based planning methods aim to achieve continuous workflow and reduce work in process (WIP) (Biotto et al. 2017). The consideration of location (space) and the concept of Takt-Time led to the introduction of Takt-Time Planning, a location-based method that gained momentum in the construction industry.

2.1.3.2.3. Takt-Time Planning Methodology

The traditional view of construction considers a project as a conglomeration of various tasks and focuses on optimizing the process by which each task transforms its inputs into outputs. The shortcoming of this view is its lack of consideration for the dynamics and interdependencies of construction tasks (Ghosh and Reyes 2017b).

Ballard and Howell (1998) stressed the importance of considering space as a resource when planning construction projects. One space planning method that has been previously explored by academicians and professionals is Takt-Time planning.

Takt is a German word which means 'beat' or 'rhythm.' With the industrial revolution, Takt was integrated into many production approaches, such as Fordism and TPS (Haghsheno et al. 2016). It became a key element of Just-in-Time as it sets the pace of production to match the rate of customer demand and is therefore considered the heartbeat of a lean system (Womack and Jones 1997). It is applied to Lean Production to establish flow and is considered to be the heart of one piece-flow (Liker 2004). Implementing Takt into processes prevents overproduction, reduces lead times and inventory, stabilizes processes, optimizes workflow, and improves production capacity (Haghsheno et al. 2016).

The first American employee and later manager at Toyota, John Shook explained the purpose of Takt-Time as 'first and foremost, to serve as a management tool to indicate at a glance whether production is ahead or behind', thus providing instant feedback to any discipline that is overproducing or causing delays so that they can alter their production to maintain flow (Oakland

and Marosszeky 2017). John further explained that Takt Planning ‘serves as an alignment tool: aligning proceeding with following processes, aligning resource requirements with demand, align corporate functions with real-time production needs’ so that all parts of the value stream align around the same rhythm (Oakland and Marosszeky 2017).

Production route in manufacturing is fixed as production moves from machine to machine, worker to worker. However, construction industry does not have a physical assembly line and its production routes are flexible (Antunes and Poshdar 2018). Therefore, one might wonder if the concept of Takt-Time can still apply to construction. In construction the crews are the units that move at a set pace rather than the product.

Within Lean Construction, ‘Takt-Time’ is the unit of time in which a product must be produced (i.e. supply rate) to match the rate at which the product is needed (i.e., demand rate) (Frandson et al. 2013). Takt-time planning thus breaks work down into individual, manageable, chunks and determines their demand and supply rates (Tommelein 2017). In a Takt-Time-balanced workflow construction process, work teams follow each other, close coupled like carriages on a train, to progressively complete a building, area by area (Oakland and Marosszeky 2017). Takt-Time Planning aims to reduce the variability in the downstream processes themselves by pacing the production rate of standard activities across right-sized geographic areas within distinct work phases (Linnik et al. 2013). This is achieved by fixing the durations and varying the crew sizing of standard activities performed by the various trades in succession. The end objective is a steady stream of predictable work, performed in the proper sequence, across the defined geographic areas, and, with appropriately planned crew sizes (Figure 5). This disciplined planning approach aligns not only the workflow at the site, but also the overall flow of materials and information through the supply chain starting in design and moving into detailing, fabrication and delivery processes required to support the Takt sequence (Emdanat et al. 2016).

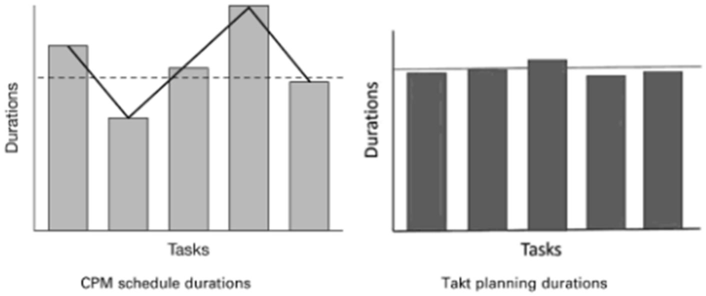

Figure 5 Balanced Workflow using Takt-Time Planning
(Oakland and Marosszeky 2017)

The implementation of Takt-Time Planning in construction has shown up more recently in literature, starting with home building in the United States (Wardell 2003; Velarde et al. 2009) and highway construction in Ecuador (Fiallo and Howell 2012). More recently Takt-Time was used to develop schedules for production on a hospital project in California (Frandson et al. 2013; Linnik et al. 2013; Ebrahim et al. 2017) and to standardize work on a residential construction project in Brazil (Mariz et al. 2013). Yassine et al. (2014) implemented Takt-Time on an infrastructure project. Consequently, various researchers have presented various methodologies to implement takt-time planning in construction.

Fiallo and Howell (2012) illustrated the use of Takt-time planning on an infrastructure project in the Ecuador. The project team, consisting of superintendent, controller, administrator, and resident engineer, divided the project into 4 sectors along the route and the divided each sector into 4 other sections. The following methodology was used to implement Takt-time planning:

1. Identify the project demand rate: the project team identified the dates and milestones of each sector and established a demand rate of 115m/week.

2. Identify tasks to be done: six major tasks were identified as necessary to complete the project (pavement removal, excavation for structure, concrete duct, refill with outside materials, refill with base, and pavement).
3. Estimate production rates for each task: using previous projects, production rates (m/week) were established for each task
4. Identify bottleneck: The task with the lowest production rate was identified as the bottleneck task. To improve the whole system, the project team needs to improve the productivity of the bottleneck task
5. Make Throughput equals demand rate: While the demands rate was set at 115 m/week, the throughput (i.e. the rate of the bottleneck task) was 36 m/week. The team discussed multiple solutions and agreed on one to improve the flow process.
6. Structure the work in continuous flow process: A value stream mapping of the current state was drawn and then then analyzed and improved.

Frandson et al. (2013) described Takt-time planning as an interactive six-step process:

1. Data gathering: Trades meet individually with planners to identify what work is to be performed where. The last planner of each trade (i.e. foreman) are heavily involved in this process as they are the individuals who understand the details of the work the best. Last planners use colored marker to highlight a certain floor plan to illustrate their production, such as highlighting how much work they can perform in one day. Planners act as facilitator to help the trades throughout the process. The output of this step is a set of “colorups” – an essential input in the Takt-time planning process.
2. Zone definition: Takt-Time is defined as the time a trade can afford to complete their work in a zone. Ideally, the project will be divided into zones of equal time – i.e. it takes

all trades the same amount of time to complete their work in all the zones. Initial zones are developed from the information collected in the first step.

3. Trade sequence generation: All parties responsible for executing a task hold collaborative planning meetings. The information obtained from the Pull Planning phase is used as a reference in this step. The objective is to identify the parties that need to perform work in a certain zone, discuss the sequence of the work (who come after who), specify how many passes each trade will need to complete their work in the zone.
4. Workflow balancing: Bottleneck tasks are identified, and the project team works to improve their production rates. The fastest tasks are also identified, and the project team takes measure to slow them down.
5. Individual trade duration: The time needed for each trade is determines.
6. Production Planning: Plan according to the Takt-Time and control over improves process to take actions in case of variation from the established Takt-Time.

Frandson et al. (2013) applied this six-step process to the exterior cladding system of a Sutter Medical Center in California. A four-day Takt-Time was used to develop production plans. The results showed that the implementation of Takt-time planning provides a clear daily goal for each activity, increases productivity of workers, enhances problem solving, aligns construction with fabrication production, has the potential to improve project cost control due to the detailed level of production achieved. In addition to the aforementioned benefits, this case study highlighted the need for clear communication and a high degree of planning for each activity. The project under study was completed in five months rather than elevens months (a 55% time saving) by implementing the Takt-time planning methodology.

Frandson et al. (2014) indicated that Takt-time planning is a work structing method and (Ballard 1999) explained that work structuring differs from the traditional Work Breakdown Structure (WBS) as it attempts to answer the following questions:

1. In what chunks or units will work be assigned to specialist production units (Pus), i.e. groups of workers?
2. How will work chunks or units be sequenced through various PUs?
3. How will work chunks or units be released from one PU to the next?
4. Will consecutive PUs execute work chunks in a continuous flow process, or will their work need to be decoupled?[2]
5. Where will be decoupling buffers be needed and how should they be sized?
6. When will the different chunks or units of work be done?

According to (Linnik et al. 2013), Takt-time planning is based on location breakdown structures aims to achieve continuous work flow. The authors investigated the implementation of Takt-time planning in non-repetitive work, namely in the interior framing phase of a healthcare project. The interior framing phases was divided into four sub-phases (overhead phase, framing phase, drywall phase, and finishes phase) and the following Takt-time planning process was implemented in each sub-phase:

1. Identify the trades that will work in the phase and how their task will be grouped together. In doing so, the trades are in a way specifying takt areas which represent the location breakdown structure of the work.

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[2] Taken from The Last Planner Production System Workbook released in 2007 based on Tsao et al. 2000.

2. Gather Information from the trades. The foreman of each trade specifies their scope of work, identified their preferred sequence to perform their work, and uses the floor plans to highlight their daily production (i.e. what work the crew of a certain trade can perform each day).
3. Sequence trade groups and the trades within groups, identify bottleneck trades in each group, and roughly estimate their achievable production rates within the takt area.
4. Balance work flow in each sub-phase to match the Takt-Time. Takt areas specified earlier are then adjusted as needed.
5. Use Takt-Time strategy to plan for resources, material, and information.

The authors found that implementing Takt-time planning does not require dividing the project into repetitive and non-repetitive work. The study also suggested that full BIM models can enable faster quantity takeoffs and provide more exact determination of the Takt-Time and location breakdown structures. This experiment also revealed the following expected benefits of Takt-time planning: reduced project costs and durations, increased transparency, increased predictability of work flow, increased ability to define and deliver work packages of information and materials when needed, and improved design of operations of trades.

Frandson and Tommelein (2016) conducted a case study of the implementation of Takt-time planning for the interior phase of a healthcare facility in California. The authors studied the process underlying the development of a Takt-time plan and the challenges encountered by the team during the execution of the plan. The Takt-time planning process used in this case study is the six-step process explained by (Frandson et al. 2013). The authors highlighted that a Takt-time plan is executed accurately only when all the aspects of the production system are aligned. In other words, a balanced production system in the field requires that the entire production system (including the capability of the project team to make work ready) is balanced as well.

Vatne and Drevland (2016) examined a practical application of Takt-time planning by a Norwegian company on a large project. The methodology employed in this project is similar to the interactive six-step Takt-time planning process described by (Frandson et al. 2013). This study concluded that Takt-time planning can reduce the total completion time of a project and ultimately reduce project costs. The results also showed that workers were conformable implementing this technique as it provided them with a predictable work day.

Oakland and Marosszeky (2017) suggested the following approach to Takt-Time Planning:

- Each floor is broken up into areas with similar amount of scope;
- Each discipline has one cycle (X days) to complete each area;
- Only one trade can occupy an area at once;
- Materia is delivered directly to each crew's work area;
- Crews plan and monitor progress towards completion of their tasks daily;
- All disciplines complete and move to the next are at the end of each cycle.

The focus is to ensure that each crew is moving at the same speed, following each other through the project in a coordinated fashion. Oakland and Marosszeky (2017) added that each trade crew should optimize their resources to fit the production plan and achieve a stable workflow and resource demand.

von Heyl and Teizer (2017) described Takt-time planning as a top-down approach that requires reliable plans and a deep understanding of the structure, the construction process as well as the supply chain. Therefore, last planners are key participants in developing a Tat plan. In order to maintain a reliable production plan, information should be constantly adjusted to reflect up-to-date and correct information. When these requirements are met, Takt-time planning becomes a powerful method to increase the stability and reliability of production (von Heyl and Teizer 2017).

2.1.4. Integration of Last Planner® System and Takt-Time Planning – The Introduction of Production Strategy

As noted by (Ballard and Tommelein 2016), LPS does not presuppose any specific work structure. The authors indicated that work structuring happened before project control – i.e., before lookahead planning could occur. However, location-based work structures like Takt-Time planning have been successfully integrated with LPS. Frandson et al. (2014) demonstrated the complimentary nature of Takt-time planning and LPS, noting that Takt-Time planning introduces a standard, continuous flow of work that the LPS then is able to control, and LPS allows the flow of work to remain when obstacles emerge and must be adapted to. Frandson and Tommelein (2014) explained that developing a Takt-Time plan translates the construction schedule – i.e. the Master Schedule of LPS, into a schedule for production. The authors indicated the Takt-Time Planning foster collaboration as it engages project participants early in conversations that focus on the details of how work can and will be performed.

Faloughi et al. (2015) introduced a new layer to LPS – production optimization. This newly added phase is a transitional step between the Please planning phase (step 2 of LPS) and the Lookahead Planning phase (step 3 of LPS). During the production optimization phase, the production team works collaboratively with the trades to identify improvement opportunities and develop a Takt-time plan before moving to the make-ready lookahead planning phase. Takt-time planning is at the core of production optimization. The Takt-time planning methodology developed by (Linnik et al. 2013) was used in this case study. This research endeavor also highlighted two types of work that are included in the production optimization phase: 1) work that can be planned using the Takt-time planning methodology and is easy to balance the workflow among the different trades, and 2) work in some areas where the density of the work makes it difficult to allocate resources under the regular sequence.

Frandson et al. (2014) listed the following benefits for using Takt-Time Planning with the LPS:

- Increased focus and standardization of the lookahead process
- Increased common understanding, which is considered the 8th flow that augments the 7 flows identified by (Koskela 1999)
- Increased urgency for make ready analysis
- Reduced scope of pull planning
- Enabled distinction between 'schedule noise'(temporal movement of a task within a given Takt-Time sequence that does not affect the completion of the corresponding Takt-Time sequence) and 'schedule variance' (temporal movement of a task within the given Takt-Time sequence that shifts into another Takt-Time sequence).

(Emdanat et al. 2016) extended on the work of (Frandson et al. 2014) and developed a tracking tool – the vPlanner® Production Tracker – that integrates Takt-time planning, LPS, and labor tracking.

Ebrahim et al. (2017) presented a framework of a production system that incorporates five cohesive streams: production planning, material flow, Built-in Quality (BIQ)/Information flow, tracking flow, and safety flow. The production planning stream consists of the four stages of LPS and an additional stage: Production Strategy. This stage is the third level of implementation and comes after Phase Scheduling and before Lookahead. Its three principal goals are: 1) implementing sequence and flow analyses, 2) defining production areas, and 3) designing production using takt-time principles to achieve stable and predictable construction flows.

A Strategy is defined as a plan of action or policy designated to achieve a major or overall aim. In military setup, a strategy represents a plan for military operations and movements during a war or battle. Applying this definition to the construction industry, a production strategy reflects the plan for construction operations and workflow during execution.

The importance of Production Strategy has been highlighted by (dos Santos 1999) as a critical component of world class companies and a powerful source of competitiveness. Production Strategy can be defined as the collective and coordinated decisions used to formulate and deploy production resources (dos Santos 1999). Production strategy is an integral part of production planning and control as it defines how production processes are structured and designed, and outlines how production will be executed: who will do what work where and how they will do it and how long it will take them.

2.2. Information and Communication Technology

2.2.1. Definition

Information and Communication Technologies (ICTs) – an extension of Information Technology (IT) was defined by (Hamelink 1997) as the array of technologies that enable the handling of information and facilitate different forms of communications 1) among human actors, 2) between human beings and electronic systems, and 3) among electronic systems. Hamelink (1997) pointed that digitization is the most common feature of ICTs which he divided into five divisions:

- Capturing Technologies such as keyboards, touch screens, voice recognition systems that collect and convert information into digital form.
- Storage Technologies such as hard disks and smart cards that store and retrieve information in a digital form.
- Processing Technologies such as the systems and applications software that is required for the performance of digital ICTs.
- Communication Technologies such as cellular phones that transmit information in a digital form.
- Display Technologies such as display screens, virtual reality headsets that display digitized information.

Onyegiri et al. (2011) noted that ICT is an integral part of the lifecycle of a construction project – from when the information is being generated, transmitted, and interpreted to when the information enables the project to be built, maintained, reused, and eventually recycled. Hosseini et al. (2012) defined ICT in construction as the application of decision support tools that use electronic machines and programs to process, store, analyze, control, transfer, and present construction data throughout the lifecycle of a project.

Davenport (1993) grouped the opportunities of IT to support process innovation into the following nine categories:

- Analytical: In a process that involved analysis of information and decision making, IT can bring to bear an array of sophisticated analytical resources that permit more data to be incorporated in and analyzed during the decision-making process.

- Automation: The most common recognized benefit of information technology is its ability to reduce human labor and produce a more structured process.
- Disintermediating: Human intermediaries are inefficient for passing information between parties. IT can eliminate intermediaries from processes that require information exchange.
- Geographical: A process that involves coordination among individuals across distances can benefit from IT to better execute the process.
- Informational: Information Technology can be used within a process to capture process information for purpose of understanding.
- Integrative: Information on various aspects of the process stored in different databases can be consolidated into a single source using IT. IT can be used to coordinate between tasks and processes.
- Intellectual: An employee knowledge and experience are a firm's greatest assets and need to be well managed. This knowledge needs to be captured and distributed more broadly and consistently throughout a process. IT has the potential to capture and distribute such intellectual assets.
- Sequential: IT can enable changes in the sequence of processes and transform a process from sequential to parallel in order to achieve process cycle-time reduction.
- Tracking: Effectively executing a process design requires a high degree of monitoring and tracking.

2.2.2. The Evolution of Information and Communication Technologies in Construction

Ever since humanity started building structures, there have been accompanying methods of drawing, sketching, and planning of these buildings. The two-dimensional (2D) drawings for architectural purposes have been traced back to Ancient Egypt (Babič and Rebolj, 2016), and have evolved over the course of history to keep pace with the advancing complexity and ambition of the built environment.

The most common purpose of 2D construction and architecture drawings is the presentation and visualization of an as-yet unbuilt structure, communication of the designer(s) intentions, and instructions for later on-site work. The earliest known drawings of this type are Egyptian, as previously stated. The next evolution of construction documentation occurred in middle-ages Europe. During that time, construction was overseen in all aspects by a ‘Master Builder’ who would plan, manage, and execute a project for an owner or patron. To communicate the particulars of the design to that patron, the master builder would employ scale models (Kymmell, 2007). The patrons, usually landed nobility, provided the funding for many of the most iconic structures we know today – the castles and fortresses of feudal Europe. However, the term ‘construction documents’ as currently used still did not yet exist. The master builder relayed instructions to the workers verbally or through demonstration, rather than disseminating plans and drawings. Many particularly complex aspects of the project were developed as full-scale mockups on site, using real materials.

In the Renaissance, projects grew larger and more complex, and the master builder spent more time off-site working through engineering problems in the ‘office’. Eventually, early engineering drawings emerged. They served a twofold purpose – to communicate to experienced craftsmen what should be built, and to show a particular detail or section to the patron(s) for their approval (Weisberg, 2008). The consequence of the master builder spending more time off-site was the creation of the superintendent position, as the project still required supervision on-site. Thus, the master builder assumed the new responsibility of coordinating communications between the patron (owner) and the superintendent, while making design changes. As construction continued to grow more complex, the various trades began to specialize – masons, carpenters, joiners, etc.

The Pharaohs of Egypt, the master builders of the middle-ages, the architects of the renaissance, and even constructors today all face a common problem: buildings are three dimensional, but documents are not. Thus, the use of 2D drawings and instructions in a 3D world requires multiple translations – from the initial concept in the designer's head, onto paper, and then into reality. As such, numerous efforts have been made to improve the quality of design drawings. These efforts are motivated by the need to reconcile planned solutions with practical implementations, poor communication between project parties, and inefficient scheduling of construction activities (Chi et al, 2013). Ahmad et al (1995), postulated that the need for teamwork, flexibility, coordination, and communication in construction gave the industry a great potential to integrate Information Technology (IT). Froese has divided the innovations in IT into three eras (Froese 2005; 2010). The first era is comprised of stand-alone tools that improve specific work tasks – Computer Aided Design (CAD), Structural Analysis, Estimating, Scheduling – which are all individual programs that each works on a single facet of the construction process. During the early 1980s, CAD became commonplace in architectural work and soon supplanted the drafting board as the most common method of producing drawings. This is because CAD allows for quick replication with a high degree of accuracy. Eventually CAD also supported 3D design, making it a more attractive and efficient option than hand-drafting (Cunz and Larson, 2006; Cohn, 2010). The second era includes computer-supported communications (i.e. email, web-based messaging), and document management systems. The third era is where construction currently sits – reconciling the first two eras into a unified platform wherein project teams can collaborate to produce a virtual model of all aspects of the construction project. One of the problems with the early iterations of CAD was that while it could represent geometric objects and show the relationship between them in space, it was lacking a precise understanding of how the relationship functioned. For example, it could be communicated that a beam is connected to a column, but the number, size and placement of the bolts to connect it would not be communicated (Howell and Batcheler, 2005). More modern iterations of CAD have included this process, commonly known as Building Information Modeling (BIM).

2.2.3. Building Information Modeling (BIM)

The concept of Building Information Modeling can be traced back to 1962 when Engelbart presented a hypothetical description of computer-based augmentation system (Antunes and Poshdar 2018). Later, (Eastman et al. 1974) recognized the shortcomings of 2D drawings and developed a computer-based Building Description System (BDS) that arranges and connects the geometric, spatial, and property description of the various elements of a building into an actual 3D building. This system serves as a database that provides a single description of each building element and of its relation to other components in the building and can be used during design, construction, and operation. In addition, if change is needed, designers need to make the change to the element once and the drawings will be automatically updated. This system designed by (Eastman et al. 1974) paved the way for the concept of Building Information Models, a term that was first introduced by (Van Nederveen and Tolman 1992).

BIM has transformed the traditional paradigm of construction industry from 2D-based drawing information systems to 3D-object based information systems (Arayici et al. 2011; BIM Alliance n.d.). For more than a decade, BIM has been one of the most important innovation means to approach building design holistically, enhance communication and collaboration among key stakeholders, increase productivity, improve the overall quality of the final product, reduce the fragmentation of the construction industry, and improve its efficiency (Succar 2009; Schweigkofler et al. 2018). One of the greatest benefits of BIM is its ability to represent in an accessible way the information needed throughout a project lifecycle, rather than being fragmented (Carlsén and Elfstrand 2018). BIM serves as a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its lifecycle from inception to commissioning and beyond (Rossini et al. 2017). Li and Yang (2017) defined BIM as a technology that describes an engineering project consisting of intelligent facilities with their own data properties and parameter rules, in which each object's appearance and its internal components and features can be displayed in the form of three-dimensional figures.

BIM has been widely hailed as a successful innovation in the construction industry (Yeutter, 2012), with numerous competing products available on the market today: AutoCAD MEP, Revit® (Autodesk®), BIM 360™ Glue®, Navisworks® (Autodesk®), Sketchup (Trimble®), Synchro Bentley Systems, Graphisoft, and Nemeschek (Howell and Batcheler, 2005; JBKnowledge, 2017).

BIM has also evolved from the 3D modeling (object model) to further dimensions such as 4D (time), 5D (cost), and 6D (as-built operations) (Smith 2014). The evolution in dimensions represents added information that is placed in the model and attached to intelligent objects (O'Keeffe 2013).

2.2.4. The Use of Information and Communication Technology in Planning

Various research efforts have been undertaken in an attempt to capture the current planning techniques and allow for the development of new innovative and automated ways in planning. Embarking on advancements in 3D computer graphics and artificial intelligence, previous and current research efforts attempted to automate the planning process by developing tools to manipulate and process project information, carry out the decision-making, and generate the required actions (Waly and Thabet 2003).

Leinonen et al. (2003) investigated the implementation of the integration of 4D applications (i.e. 3D building geometric data + time) and Virtual Reality (VR) in construction planning through a series of case studies. The authors concluded that accessing product data using VR allows the user to view and edit product data. They also reported that the integration of 4D applications into existing practices enables new and improved planning processes. The benefits of such integration are mainly generated from the improved communication between the parties involved in planning.

Waly and Thabet (2003) presented a framework for a new planning approach that utilizes VR modeling techniques (suing 3D models) coupled with object-oriented technologies to develop an integrated virtual planning tool called the Virtual Construction Environment (VCE). This integrated planning tool assists planners in visualizing, analyzing, and evaluating construction processes at the macrolevel. The developed VCE also allows the project team to perform inexpensive rehearsals of major construction processes and test various execution strategies in a near reality sense, prior to the actual start of construction, thus informing and improving the decision-making process.

2.2.5. Industry 4.0

The Concept of Industry 4.0 is a national strategy led by the German government, industry leaders, researchers, associations and trade unions and was formally put forward in 2011 at the Hannover Fair (Li and Yang 2017; “Platform Industrie 4.0” n.d.). Wagner et al. (2017) stated that Industry 4.0 can be defined as the industrial vision that enables “people and things to be connected anytime, anyplace, with anything, and with anyone, ideally using any path or network and any service”. This concept aims to improve the definition of industry from the centralized production mode to the basic form of decentralized production and control (Li and Yang 2017). The fourth industrial revolution is characterized by a wide range of new Information and Communication Technology that are combining the physical, digital, and biological worlds, impacting all disciplines, sectors, and industries and transforming the status quo (Weyer et al. 2015; Schwab 2016). Kolberg and Zühlke (2015) reported that Industry 4.0 describes the increased integration of ICT into production, providing new solution for combining ICT with Lean Production.

As part of the continuing evolution of the construction industry as a whole, the nine pillars of Industry 4.0 have attracted increasing attention from researchers and practitioners (Amor et al. 2002). Augmented Reality (AR)is one of these nine pillars that has the potential to transform the construction industry (Rüßmann et al. 2015; Sebastian et al. 2018).

2.2.6. Augmented Reality

2.2.6.1. Origins and Definitions

AR originated in 1962 when Morton Heilig, a cinematographer, created a Sensorama, motorcycle simulator with visuals, sound, vibration, and smell. In 1966 Harvard Professor Ivan Sutherland invented the first Head-Mounted-Display (HMD), a device that allows the user to experience computer-fed graphics (Candy 2017).

The term “Augmented Reality” was first coined by Caudell in 1990 and was defined as the technology that is used to “augment” the visual field of the user with information necessary to perform a task (Caudell and Mizell 1992; Ramos et al. 2018). Unlike Virtual Reality (VR), AR amplified the real world with virtual (computer-generated) information instead of substituting it (Wang 2009). There are two definitions of AR commonly referred to in the body of literature. One definition was proposed by (Milgram and Colquhoun Jr. 1999) who described AR from the perspective of the mixture between real and virtual environments. Milgram and Kishino (1994) created the “Reality-Virtuality (RV) Continuum” in which the “real” and “virtual” environments are two ends of the continuum, as shown in Figure 6. Milgram and Colquhoun Jr. (1999) explained that the AR section starts from the real environment end and expands towards the center of RV continuum and then encounter its counterpart originating from the virtual environment end and is called Augmented Virtuality (AV). The term MR encompasses both AR and AV.

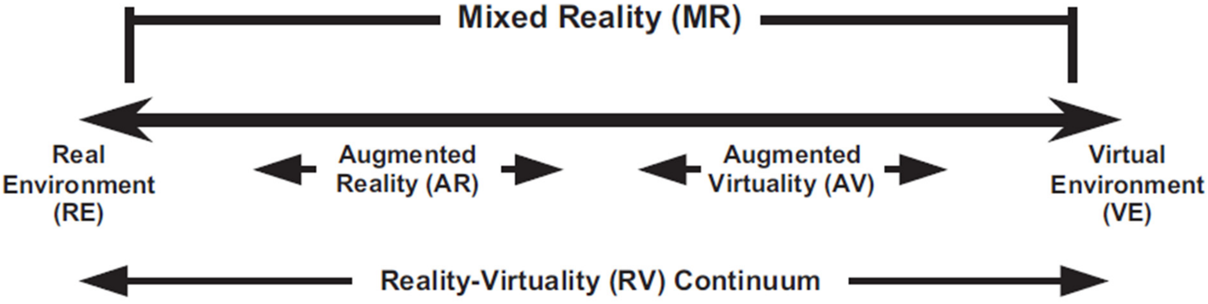


Figure 6 The Reality-Virtuality (RV) Continuum
(Wang 2009)

The second well-known definition of AR was put forward by Azuma who defined AR as any system that has the following three characteristics: 1) combines real and virtual objects, 2) is interactive in real-time, and 3) is registered in 3D (Azuma 1997).This definition refers AR to a class of display systems that comprises some kind of Head-Mounted Displays (HMD) or Head-up Display (HUD) (Milgram and Colquhoun Jr. 1999). It is important to note that the third characteristic identified by Azuma does not consider 2D overlay on live video as a type of AR (Liu 2016). Azuma later modified the third characteristic to only require the real and virtual objects to be registered with each other (Liu 2016).

2.2.6.2. Growth of Augmented Reality

Interest in AR has increased in the past decade. Despite the spike of interest recently, the idea of using AR technology sprouted in the 1960s and the tangible invention has slowly followed. It was not until the 90s that interest became significant enough for the development and implementation of the technology to reach the mainstream markets (Chen et al. 2015). AR implementation has spiked interest and led to economic investment from various companies. AR market leaders include: Atheer, Blippar, Daqri, Google, Gravity Jack, Index AR Solutions, InfinityAR, Meta, Microsoft, Niantic, ODG, Optinvent, PTC, Re'flekt, Scope AR, Seiko Epson, Sony, Total, Ubimax, Upskill, Vuzix, Wikitude, among others (HelpNetSecurity 2016; Nguyen and Blau 2018).

The AR market size at $1.3 Billion in 2016 is anticipated to reach $63 billion by 2021 (Campbell et al. 2017). The increasing scope of applications across different industries, such as manufacturers of industrial products, automotive, aerospace, and high-tech is driving the growth of this technology (Campbell et al. 2017). As a result, many software service providers have emerged to support this demand (more information about these providers can be found in Appendix 1). Figure 7 highlights the industries that are leading the adopting AR.

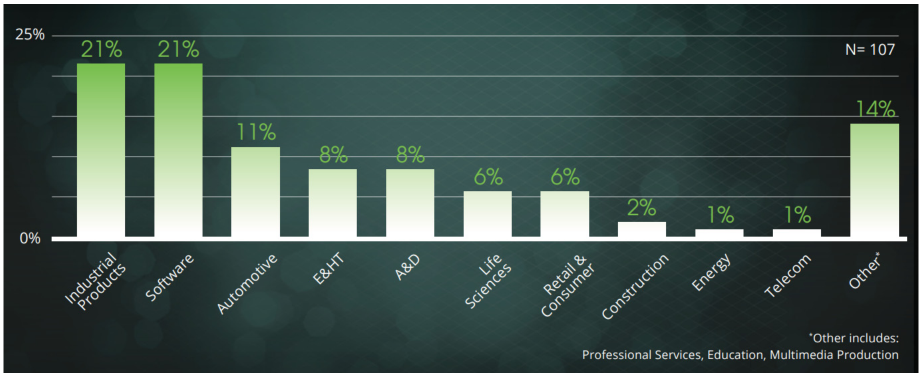


Figure 7 Industries Most Rapidly Adopting AR
N is the number of enterprises surveyed by PTC (Campbell et al. 2017)

2.2.6.3. Applications of Augmented Reality

AR technology has been applied in many application domains including medical, education, manufacturing, gaming and entertainment, and marketing.

2.2.6.3.1. Medical

Nurses, doctors, and surgeons can benefit from AR applications in the medical field. Blackwell et al. (1998) proposed a semi-transparent display for augmentation of orthopedic surgery. Birkfellner et al. (2002) introduced the varioscope AR, an augmented head-mounted operating microscope, for oral implantology. Dey et al. (2018) conducted a systematic review of 43 medical papers on the use of AR and noted that the AR-based research in this field was primarily used in training and simulation where laparoscopy, rehabilitation, and phobia were the topics of primary interest.

2.2.6.3.2. Education

AR has been used in classrooms with ages that range from elementary to secondary education. Subjects in which AR can be applied range from college chemistry, to medical school, to a kindergarten classroom. In combination with a whiteboard, a projector, and a 3D modeling package, elementary school teachers were able to explain the solar system in a more interactive way (Wu et al. 2013). Instead of the real-world 3D model, the AR-based 3D model could be projected in front of students and simulate the orbits of the solar system (Wu et al. 2013). A systematic review of AR application of in educated conducted by (Bacca et al. 2014) showed that AR is being used to explain a certain topic and support students' learning to augment information by providing supplemental material by means of markers placed on printed material that students used to access digital resources. AR is also being used for educational games and to conduct lab experiments.

2.2.6.3.3. Manufacturing

Ong et al. (2008) provided a comprehensive survey of developed and demonstrated AR applications in manufacturing. Their list of application areas included:

- Assembly - AR can be used to display digital assembly information (i.e. textual instruction manuals and drawings or schematics) into the field of view of the operator according to the situation. The augmented assembly information and instructions can also be used for assembly tasks training purposes. In addition, AR can be effectively used in assembly sequence planning and evaluation.
- Maintenance, service, repair, and inspection - AR techniques can be used to display relevant virtual information at the appropriate time and location in the working environments. Remote maintenance can be achieved using AR technologies. AR has also been used for inspection, device diagnostics and maintenance training, such as underground pipe inspection and maintenance.
- Product development - AR can combine physical mock-up of non-reconfigurable parts with 3D graphic prototypes, forming the mixed prototyping approach. Mixed prototyping involves the presentation of virtual prototypes superimposed on the real prototypes in an augmented environment, thus eliminating the need to construct real prototypes (Selim et al. 2000). It allows the users to interactively evaluate synthetic prototypes in the physical environment directly. It also allows the users to perform detailed product assessment, ergonomic validation, assembly sequence validation and, sometimes functional verification.

- Manufacturing layout - using AR, a physically existing production environment can be superimposed with virtual planning objects. Planning tasks can thus be validated without modelling the surrounding environment of the production site. AR-based systems can provide the users with an intuitive way to interact directly with real working environment in manufacturing activities and facilities.

- Telerobotic - in an AR-assisted tele-robotic system, the operator can use a visual image of the remote workspace to guide a real or virtual robot. Relevant annotations of the view or scene that are in front of the operator would be useful. An operator can practice performing the motion path of an end effector using a virtual robot that is augmented on the real shop-floor scene, allowing verification of the motion path in the real environment.

2.2.6.3.4. Gaming and Entertainment

AR can be also applied in the entertainment industry to create games and to increase the visibility of important aspects of games in live sports broadcasting, such as adding the yellow first-down line during football games. AR can also serve advertisers to display virtual ads and product placements (Van Krevelen and Poelman 2007).

Mobile-based gaming has been adapting AR technology in recent years. Most notably, PokémonGo became the first mobile AR game to reach the top of the download charts when it was released in 2016 (Rauschnabel and Ro 2016). Since then, mobile games with AR capabilities have surpassed use in purely entertainment purposes and are being implemented in educational ways. The use of AR based games in education allows students to interact with materials and provide a greater sense of relationships and connections. Games such as Environmental Detectives and Mad City Mystery were developed to support learning outside of classroom environments (Rauschnabel and Ro 2016). These programs aim to create students who are more engaged with their surroundings through AR, as well as students who are more aware of environmental-related factors (Rauschnabel and Ro 2016). Additionally, mobile AR games tend to increase physical activity for users, when compared to traditional console or PC based gaming platforms (Rauschnabel and Ro 2016).

Additionally, AR-based games can increase social interactions. With a greater ability to immerse in the games physically, ‘meet up’ points could be integrated into the game (Rauschnabel and Ro 2016). This opens up the possibility for games to create happiness and positivity in players through physical activity, and the hormones which are released during, as well as social interaction. Game will no longer be looked at as an immobile activity, but instead as an educational, social, and physical form of stress relief. Furthermore, AR gaming is not limited to the traditional mobile technology. Conventional board games, such as Monopoly, have been attempting to adopt a format which supports the implementation of AR (Yuen et al. 2011).

Lastly, AR could be a new way for movies to be experienced. Instead of a 3D or 2D experience in cinemas, AR could allow characters to virtually exit the screen and come into an audience. This would create a more interactive and intense experience for viewers. Using Apple’s ARKit platform, Abhishek Singh was able to bring a character from *The Ring* into a room. The scene becomes more than a screen in front of a viewer, but rather a chilling, interactive experience (Melnick 2018).

Within the gaming and entertainment industry, the possibilities of AR applications range tremendously. This increase in interaction has shown promising growth in how movies, games, and learning can be experienced.

2.2.6.3.5. Marketing

Using AR in the marketing and shopping industry has spiked great excitement within many companies. The technology serves as a platform for customers to engage with products in a way which was impossible before.

With the growth of the internet over the past decade, the growth of online shopping has also increased. Following this boom, shoppers have become more precise and expectant before purchasing a product (Ludwig and Reimann 2005). This has ultimately changed the field of marketing. Currently, IKEA has begun to use AR to allow customers to see what a piece of furniture would look like in their own home (Source). This means shoppers do not need to go to the store, browse, and then test out a product to see if the item may work. They can place in where they would want it and subsequently order it within a matter of minutes. Additionally, this change in shopping changes sales procedures. With less face to face time, companies will be providing more information on an item online. Through AR simulations, this information could be more precise and understandable while presenting the company in an innovatively progressive way (Ludwig and Reimann 2005).

Another area in which AR can be utilized by shoppers is the clothing industry. Without even having to try a garment on, shoppers can see what it would look like on them by placing the virtual simulation on themselves in a ‘virtual mirror’ (Yuen et al. 2011). This approach also works for accessories such as sunglasses, watches, or purses.

2.2.6.3.6. Applications of Augmented Reality through Smart Glasses

Klinker et al. (2018) used the case study research design to investigate service processes to which smart glasses can bring benefits. The authors analyzed and evaluated 76 use-cases in service processes (such as logistics, healthcare, and maintenance), and classified AR into 11 application areas:

- Communication: helps receive or send information to the operation location
- Documentation: provides the possibility to document processes on the fly
- Process guidance: provides guiding information
- Education: uses smart glasses to teach employees
- Alerts: attracts user attention for urgent information or warning
- Data visualization: shows helpful AR information in-situ
- Automatic control: reduces error rates in error-prone processes
- Inventory management and automatic ordering: automatically keeps track of objects and resources to enable optimized consumption, usages and re-ordering
- Resources allocation: manages limited capabilities e.g. time, staff
- Text handling: helps users generate or interpret written language
- Navigation: provides routes and action of sequences

2.3. Augmented Reality in the Construction Industry

2.3.1. Definition

In the context of the construction industry, many researchers who have explored the potential use of AR technology in this industry provided their own definitions, as follows:

Wang and Dunston (2007) defined AR as a technology or an environment where the additional information generated by a computer is inserted into the user's view of a real-world scene. They also noted that AR involves the use of special display and tracking technology that are capable of seamlessly merging digital or virtual contents into real environments.

Helmholt et al. 2009) defined AR as the act of adding an extra layer of information to the real physical works to provide the right information in situ at the right time.

Cleveland Jr. (2010) considered AR the child of virtual reality and provided a simpler definition of AR as augmenting the real world with information from the virtual world.

Wang et al. (2013) deemed AR to be an 'information aggregator' that can collect and consolidate information from individual tools such as BIM, and context-aware sensors. Thus, AR could enable users to define and work with the inter-relationships between products, processes, resources and time to determine and analyze relevant information.

Gartner defines AR is part of the reality-virtuality continuum, in which the user experiences information in real time, in the form of text, graphics, audio and other virtual enhancements integrated with real-world objects (Gartner 2017).

2.3.2. Use-Cases

Webster et al. (1996) developed two AR systems that employ a see-through head-worn display to provide users with visual information that is tied to the physical world. The purpose of these two systems is to improve methods for construction, inspection and renovation of architectural structures. The first AR system, called "Architectural Anatomy", enables users to see portions of a building that are hidden behind architectural or structural finishes and allow them to display additional information about the hidden objects. Their initial experimental AR system shows the location of columns behind a finished wall, the location of rebars inside one of the columns, and a structural analysis of the column. Their experiment was conducted indoors, but they expected that in the future AR's ability to show an "x-ray vision" of systems would allow maintenance workers to avoid hidden features such as buried infrastructure, electrical wiring, and structural elements as they make changes to buildings and outdoor experiments. Overall, maintenance could be sped up and accidental damages to buildings could be reduced. The second AR system addresses spaceframe construction and it is designed to guide construction workers through the assembly of a spaceframe structure to ensure every member is properly placed and fastened. This system can help improve the quality of the work. Inspectors with AR interfaces may be similarly guided through their jobs, allowing them to work without reference to conventional printed construction drawings and ensuring that every item which needs to be checked is in fact inspected.

In 1997, Thomas and Tyerman (1997) expanded the application of AR to outdoor environments and focused on investigating the use of a Wearable Computer with Augmented Realities in an Outdoor Environment (WCAROE) to facilitate collaboration (Thomas and Tyerman 1997). They proposed three scenarios of possible collaboration with the use of a WCAROE system. The first scenario, Maintenance Task, entails the task of a supervisor specifying maintenance work to be performed on a set of buildings, where a journeyman is to perform the specified work later. The second scenario, Data Collection, allows users to collect data in real-time and exchange information previously collected. The third scenario, Location Coordination, enables users to quickly and accurately locate each other allowing them to exchange information and better respond to a given situation.

(Thomas et al. 1998a) developed a wearable computer system with a see-through display to be used a visual navigation aid and was called the “map-in-the-hat” application (Thomas et al. 1998b).

In 1999, Thomas et al. developed an AR wearable computer system to visualize outdoor architectural features (Thomas et al. 1999). This system can allow users to visualize the design of a building, the modification to a building, or the extension to an existing building relative to its physical surroundings. Such a system provides users with a sense of space and feeling of the size and location of the building. Thomas et al. (1999) also recognized the power of AR in helping users visualize hidden or abstract features such as pipe and boundaries. Thomas et al. also highlighted the following benefits of providing information in a 3D form in scale with the surroundings:

1. Objects can be located faster, especially in featureless terrain therefore saving time and costs.
2. Objects can be accurately located.
3. Previously invisible features, for instance boundaries, become visible without the use of physical markers.
4. Various sources and types of information can be displayed, therefore allowing the relationship between objects to be easily determined.
5. Features can be displayed and viewed from orientations that are more appropriate to the task then what a map or a drawing can offer.

Kensek et al. (2000) recognized that AR is a developing field and can have many applications in architecture from visualization to facility management and architectural education. They developed an AR system that uses a see-through display combined with a tracking device to be used as a facility management and maintenance tool. The system allows the user to display information from a database over the view of the user and enables the user to navigate through the information. Kensek et al. (2000) noted that this system can be also used as educational tool providing users with a better understanding of the structure.

Dunston et al. (2000) designed an experimental AR CAD tool to support design activities for mechanical contractors. The AR CAD concept involves the addition of an AR assistant viewer to standard CAD, thus adding the benefits of a more intuitive and liberal interaction with 3D design models. The tool can be also used to support the development and execution of construction plans.

Klinker et al. (2001) discussed the potential use of AR in three phases of a construction projects.

1. Design and Marketing, where AR provides a unique opportunity to integrate the design into the real world and allow customers to evaluate its function and esthetics and how it will look like in its final setting.
2. During Construction, where AR can be used to visualize whether a certain element or structure is built according to the design, to generate and review work plans after a design change has been made, and to visualize and evaluate the impact of potential design changes before they are approved.
3. Maintenance and renovation where AR can be used to visualize hidden information such as wires, pipes, beams and non-graphical information for instance heat and pressure of pipes, maintenance schedules and records, to visualize potential redesigns of the interior and the exterior of the structure and evaluate their compatibility with the existing structure, and to place new structures onto existing ones.

Roberts et al. (2002) explored the potential of AR as an aid for subsurface data visualization. AR can be used to visualize historical building, archaeological artifacts, a proposed structure from a specific location, assess environmental impact, and locate underground structures and utilities. This system helps avoid accidents that may damage underground utilities during excavation.

Hammad et al. (2002) developed a Mobile AR System for Infrastructure Field Task (MARSIFT) that allows users to automatically retrieve necessary information in real-time, based on the location and orientation of the user and within the specific task context, and augment this information onto the real environment. This system can provide workers with specific information needed to fulfill their work in the field in a timely manner without distracting them from their tasks. The concept of MARSIFT can be used for visualization, communication, and data input and can therefore, improve the efficiency and safety of workers in infrastructure projects performing field tasks during construction, inspection, maintenance, and repair.

Dias et al. (2003) developed an Information and Communication Technology (ICT) tool and a co-operative design system for the AEC industry called A4D. The objective of A4D is to help the AEC sector to build more efficiently, accurately, with lesser costs, in a manner that is more planned, safer, easier and humanized for all, by developing and introducing AR technologies. A4D system was designed to address issues found in the interface between the design process and the construction planning sub-process.A4D supports multi-user interactive 4D information visualization, design verification and errors detection, enables construction scheduling, planning, and supports intuitive information presentation provided by tangible AR user interaction in indoor settings, supports teamwork, and fosters a culture of innovative collaboration.

Wang and Dunston (2007) highlighted the suitability of using AR for information-intensive tasks that focus on human decisions and subsequent actions. They explored the potential use of AR in heavy construction equipment operator training and developed an AR-based real-world Training System (ARTS) to train novice operators in a real worksite environment augmented with virtual materials and instructions. The operator trained using ARTS will feel an almost real interaction with the virtual displays. This type of training is low cost and safer than real-life training and allows operators to be trained and practice their skills in an unlimited number of scenarios without the pressure of time and cost. They also argued that as the technology matures, standards are developed, and hardware costs decrease, the AR technology will gain momentum in the construction industry.

Kamat and El-Tawil (2007) discussed the feasibility of using AR to superimpose previously stored building information onto a real structure to evaluate earthquake-induced building damages.

Shin and Dunston (2008) developed a map that comprehensively identified AR application areas in industrial construction based on suitability of AR technologies. The research studied 17 classified work tasks in the AEC industry and the comprehensive map showed that only eight of the work tasks can benefit from AR. Those tasks are:

1. Layout - defined as determining, ascertaining, and marking dimensions.
2. Excavation - that is breaking up, turning up, removing, or filling soil.
3. Positioning - which refers to moving heavy objects to certain locations and orientations for installation.
4. Inspection - defined as examining installed workmanship by a professional to verify quality and that the work is installed to the pre-approved drawings and that the work meets all codes.

5. Coordination - that is organizing and determining upcoming work flows or resource allocations.
6. Supervision - defined as seeing if the work is performed as planned.
7. Commenting - which means conveying supplementary information regarding a task.
8. Strategizing - which refers to figuring out the detailed procedures for specified tasks.

Helmholt et al. (2009) identified three major categories of AR applications. The first category is “in-situ experience” where AR can enable the visualization of the virtual project to be constructed superimposed into the real construction site. This allows project stakeholders to gain an understanding of how the desired project fits in with the surrounding by virtually walking through the project on the landscape. The second category is “in-situ verification” where 3D models can be projected on top of a construction project and the inspector can virtually check if the actual work is installed in accordance to the intended design. The Third category is “in-situ warning” where the use of AR can improve the quality and the occupational health and safety management on site by warning workers of unseen dangers. AR can be used to display more alarming, interruptive, and real-time manifested warning to prevent potential accidents.

Behzadan and Kamat (2009) developed a system in which they integrated AR (AR) visualization and the Global Positioning System (GPS) to create real time views of an excavation site in which CAD models of the buried utilities can be accurately superimposed over live video streams of the real world, with the yielding views being displayed to the equipment operator in real time. This AR application enables equipment operators and other site personnel to visualize virtual models of subsurface utility lines at the excavation site. Such an application enhances the operator's perception of the environment in which the actual operations take place and can therefore reduce the risk of damaging hidden utilities.

Golparvar-Fard et al. (2009) proposed the D^4AR model, an alternative image-based approach for progress monitoring using unsorted daily progress photograph logs taken from a construction site. Their approach is based on collecting a series of images of the site and using them to reconstruct a sparse 3D as-built point cloud of that site. This allowed them to visually compare the generated 3D geometric representation of the as-built data with the 3D as-planned data, and therefore, monitor the progress of the project. The D^4AR system is a coordination and communication aid tool for contractors.

Yeh et al. (2012) developed a wearable device, iHelmet, to project construction drawings and related information on the basis of the needs of the user. The iHelmet allows users – engineers – to input their location at the site, and automatically retrieves related information in an image format. This study showed that using AR can significantly reduce difficulties in retrieving information on the jobsite.

Akyeampong et al. (2012) demonstrated the possibility of using AR for training. They designed and developed the Hydraulic Excavator Augmented Reality Simulator (H.E.A.R.S), an AR prototype for simulating hydraulic excavator operator training. The prototype augments the user's view of the workspace with virtual objects that describe the working parts of the hydraulic excavator, providing the user with firsthand information to safely and efficiently complete the excavator operator training.

Kivrak and Arslan (2019) developed an AR system using smart glasses with the objective to improve the efficiency and quality of education and training in a risk-free environment. For example, a construction worker, foreman, operator, or site engineer performing a certain activity can use the smart glasses to watch an informative and comprehensive animation of how to properly perform the activity prior to actually doing the work.

Park and Kim (2013) proposed a framework for a novel safety management and visualization system (SMVS) that integrates building information modeling (BIM), location tracking, AR, and game technologies. A prototype SMVS was developed and was tested with a safety management process of a real accident case scenario. The results of this study showed that the SMVS has a great potential to improve the identification of field safety risks, increase the risk recognition capacity of workers, and enhance the real-time communication between construction manager and workers.

Wang et al. (2013) investigated the potential of BIM and AR and proposed a conceptual framework that integrates BIM and AR for construction use. They identified seven areas where BIM and AR can be integrated and used on-site:

1. As a visualization tool to provide project stakeholders with a better understanding of interdependencies that exist between their own tasks and other tasks.
2. For spatial site layout collision analysis and management. Spatial collision analysis is mainly performed in the design phase using computer software. However, collision may still arise during the actual construction process due to change orders and errors. By using AR, a site manager can address the potential for conflicts and clash detections on-site by retrieving and visualizing all the properties and details related to the building elements from BIM.

3. To link digital information to physical resources. The AR visualization of information contained within BIM can provide on-site personnel with an improved understanding of construction sequencing, which will reduce the incidence of quality failures.
4. To map the as-built and as-planned data in a single digital environment with each component allocated with a status: ordered, procured, delivered, checked, installed, completed, commissioned, and fixed. Being able to visualize the difference between 'as-planned and as-built' progress enables 'current and future' progress to be monitored and therefore facilitates appropriate decision-making.
5. To monitor the progress of construction projects. With AR, a project manager, who is responsible for several projects, can obtain information about activities in different locations.
6. Integration with procurement to track and manage material flow. It is suggested that on-site status monitoring using AR and project documentation related activities could be consolidated and integrated with a pre-fabrication plant. Transparency between construction works and pre-fabrication processes would improve the accuracy of short-term planning, which may lead to reductions in construction duration and delays and a lower demand for material buffering.
7. To visualize design during production. BIM and AR can provide a full 3D interactive solid model of the design, providing subcontractors with visual understanding of details.

Rankohi and Waugh (2013) reviewed 133 articles on AR in the AEC industry and identified seven application areas of AR: 1) visualization or simulation, 2) communication or collaboration, 3) information modeling, 4) information access or evaluation, 5) progress monitoring, 6) education or training, and 7) safety or inspection.

Park et al. (2013) presented a conceptual system framework, AR-based Defect Inspection System, for construction defect management that integrates ontology and AR with BIM. The purpose of this framework is to enable proactive reduction of the defect occurrence during the construction process. This study also suggested that the developed system allows manager and workers to remotely interact with each other and proactively exchange the right information at the right time. Consequently, managers can inspect the jobsite without visiting the workplace.

Chandarana et al. (n.d.) reviewed and identified opportunity areas to integrated AR in three phases of a construction project: design, construction, and post-construction. In the design phase, AR can be used to visualize the design indoor and outdoor in full scale and to perform walkthroughs. AR can assist in clash detection in the early stages of design and construction. AR can be also used overlay 4D virtual content onto physical objects such as traffic flow and wind flow to better understand the relationship between the project and its surrounding environment. During the construction phase, AR can be used to overlay BIM data onto the construction sites. This can allow the users to visualize future work to be constructed, view hidden elements such as buried structures, assist site personnel with the inspection process, allow contractor to monitor the progress of the project, locate material on-site, and display information onto equipment and projects components. AR has also the potential to assist in task support for assembly activities, specifically for prefabrication. AR can be also used for 4D scheduling and site logistic planning. In addition, AR applications can help users navigate a construction project during construction. AR can play an important role in displaying in-situ safety warnings. In the post-construction phase, AR can assist specialists and non-specialists in performing complicated maintenance and repair tasks by integrating real-time graphics with the real environment. AR applications can also help facility managers locate building systems without destructive demolition.

Danker and Jones (2014) surveyed 43 UK construction companies and identified nine key areas of application of AR with BIM. The applications are: 1) clash detections, 2) visualization of services on site, 3) projection of safety routes on site, 4) visualization of construction sequence on site, 5) refurbishment visualization, 6) communication information and details between architects, contractors, and subcontractors, 7) retrieve location information of a component for maintenance and replacement, 8) visualization of building Big Data to produce feedback for architects to improve future designs, and 9) visualization of BIM on site with context in-situ.

Zollmann et al. (2014) presented an approach for using AR for on-site construction site monitoring and documentation. The authors developed a mobile AR interface that uses aerial 3D reconstruction to automatically capture progress information, allowing the user – specifically the client – to directly visualize the progress on the construction project on-site.

Meža et al. (2015) developed a prototype that was tested on a real construction site to evaluate the potential use of AR. Experts in the Architecture, Engineering, and Construction industry assessed the functionality of the prototype through a survey. The results showed that AR has the following potential applications (listed in ordered of usefulness) :

1. Identifying and locating existing building components locations
2. Supervision of compliance with the design
3. Renovations
4. Visualization of 3D models on site

5. Locating construction materials and equipment
6. Locating installation instructions and guidance notes
7. Schedule compliance
8. Production of project documents
9. Operation and Maintenance

The study also confirmed that AR can significantly contribute to the understanding of project documentation in various stages of constructions projects.

An article published by the MIT Technology Review in 2016 discussed how Gilbane Building Company is using augmented mockups. Using the Microsoft HoloLens, the project manager was able to look at the mockup of steel frames that the company planned to order and noticed that the walls of the building were too long to fit the design. Having spotted this issue ahead of time using AR, the company can contact the supplier to adjust the length of the frames, saving the company time and cost that would otherwise have occurred (Woyke 2016).

A video recently posted by Bluebeam, Inc. showed how Martin Bros, a drywall subcontractor in Gardena California, successfully framed a structure only using a Head Mounted Display (the HoloLens) and rendered models without any construction plans (Bluebeam, Inc. 2016).

Ghaffarianhoseini et al. (2016) proposed a methodology to integrate BIM and AR to facilitate construction site coordination. The authors developed a mobile AR-based construction drawing application to improve the efficiency of on-site construction. The results of this study showed that this AR application improves the performance of existing on-site management processes, by allowing the user to review 3D drawings in real-life based on 2D drawings.

The uses of AR technology in the construction phase were also identified by (Heinzel et al. 2017). The authors interviewed two construction companies, BNBuilders and Gilbane Building Company, and a software company, AugmentDEV SAS. According to BNBuilders, stakeholders who are involved in the physical construction process can use AR as a visualization tool to gain a better understanding of the process. Also, AR can help with complicated construction methods where construction works can watch augmented tutorial videos with step-by-step instruction on how to perform a certain task. Gilbane, who has been using AR for almost three years, recognizes the value of using AR where details are critical such as curtain walls and building envelopes. Gilbane also used AR for logistic planning and is exploring how to use AR to improve safety. The believe that AR can have a significant impact on collaboration and communication by enhancing the cognitive ability of project stakeholders to read and understand the drawings and models. From the perspective of a software company, AugmenteDEV SAS stated that the AEC industry are looking to better visualize their projects using AR technologies.

Chalhoub and Ayer (2017) examined the feasibility of using Mixed Reality (MR) as a visualization tool for electrical prefabrication. The researchers conducted an experiment with participants from an electrical construction firm. Participants were asked to build two conduit assemblies, once using the traditional paper documentation used by the construction firm, and again using the HoloLens MR interface developed by the researchers. The results of this study showed that MR is more effective for communicating design concepts, enabled faster construction times than traditional paper plans, improves productivity, and reduces the number of errors in the final built conduit assembly.

2.3.2.1. Life Cycle Phases of a Construction Project

The potential of AR in the AEC industry has been explored by various researchers whose work has identified potential applications of AR throughout the life-cycle of a construction project. The life-cycle of a construction project consists of a series of phases and the literature review showed that there is no single definition for what the phases are. The following are examples of life-cycle phases as defined by several researchers and institutions.

Shin and Dunston (2008) argued that the lifecycle of a construction projects generally consists of six processes that are related: project formulation, planning, engineering and design, construction, use management, and disposal.

Succar (2009) considered that construction projects pass through three major lifecycle phases: design, construction, and operations. The three phases are each divided into three sub-phases. The design phase is divided into conceptualization, programing and cost planning; architectural, structural, and systems design; and analysis, detailing, coordination and specification. The construction phases consist of construction planning and construction detailing; construction, manufacturing, and procurement; and commissioning, as-built and handover. The operations phase includes occupancy and operations; asset management and facility maintenance; and decommissioning and major re-programming.

The project lifecycle as studied by (Meadati 2009) includes five stages: planning, design, construction, operation and maintenance, and decommissioning. The construction stage is further divided into pre-construction, actual construction, and post-construction.

The lifecycle phases of a construction project described by (Guo et al. 2009) are as follows: planning, design, construction, commissioning, utilization, maintenance, and decommissioning.

Danker and Jones (2014) considered the project lifecycle to consist of four phases: design, delivery, maintenance, and demolition.

Dawood and Vukovic (2015) hypothesized that the lifecycle of construction projects includes the following three stages: 1) inception, design, and production, 2) use and maintenance, 3) refurbishment, alteration, and re-commissioning, and 4) decommissioning and demolition.

The Construction Industry Institute (CII) defines eight phases of the project lifecycle: feasibility, concept, detailed scope, detailed design, procurement, construction, commissioning and startup, and handover and closeout (CII 2019).

Autodesk defines five phases for the lifecycle of a facility: concepts, operational design, construction, operation, and demolition.

The stages of the lifecycle adopted in this research are formulated by John Nelson (Nelson 2015) and are described as follows: we start with the making stage, then the constructed project goes into three different stages: an operating stage, a changing stage, and a using stage. All of these three stages occur concurrently, and they are in one circle of time over the majority of the life of the project. Finally, the project is either retired or put into some form of reuse. This lifecycle is an illustration of the cradle to cradle concept. Figure 8 depicts that overall lifecycle of a construction project.

In this research, the making stage is divided into five phases: Conceptual Planning, Design, Pre-Construction Planning, Construction, and Commissioning. This study will also include two other phases: Operation and Maintenance and Decommissioning. As this research is not focused on the use of AR from the perspective of end users or customer, the using and changing stages will not be studied.

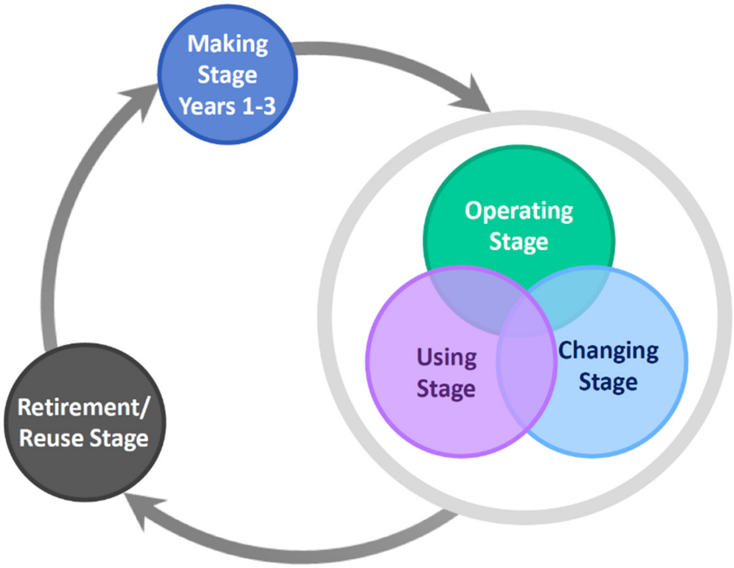


Figure 8 Nelson's Definition of Overall Lifecycle of a Construction Project
(Nelson 2015)

The aforementioned use-cases of AR in the AEC industry (identified from the literature review) were categorized into the following phases: Conceptual Planning, Design, Pre-Construction Planning, Construction, Commissioning Operation and Maintenance, and Decommissioning.

The AR applications identified earlier are mapped into the seven project phases as shown in Table 1.

Table 1 Applications of AR throughout the Lifecycle Phases of a Construction Project

Use-Cases	**References**
Conceptual Planning	
Real-time visualization of conceptual projects	(Thomas et al. 1999; Helmholt et al. 2009)
Overlaying 4D content into real world (or physical objects) such as traffic flow, wind flow, etc.	(Roberts et al. 2002; Chandarana et al. n.d.)
An understanding of how the desired project connects with its surroundings	(Thomas et al. 1999; Roberts et al. 2002; Helmholt et al. 2009)
Design	
Overlay of 3D models over 2D plans (i.e. Design (or project) visualization in the office over 2D plans)	(Chandarana et al. n.d.; Heinzel et al. 2017)
Design (Project) visualization at full scale onsite	(Helmholt et al. 2009; Wang et al. 2013; Danker and Jones 2014; Heinzel et al. 2017)
Virtual tours for clients while on site or in the office (AR walk-through)	(Thomas et al. 1998; Helmholt et al. 2009; Heinzel et al. 2017)
Real-time design change (interactive) (material selection, design functionalities)	(Dias et al. 2003; Wang et al. 2013)
Pre-Construction Planning	
Clash detection	(Dias et al. 2003; Wang et al. 2013; Danker and Jones 2014; Meža et al. 2015)

Use-Cases	**References**
Early identification of design errors	(Dias et al. 2003; Wang et al. 2013; Danker and Jones 2014; Meža et al. 2015)
Constructability Reviews during design	(Dias et al. 2003; Wang et al. 2013)
Full-scale site logistics (virtually locate equipment, trailers, laydown areas, storage, etc.)	(Wang et al. 2013; Heinzel et al. 2017)
Space Validation and Engineering Constraints Checks (collaboratively locate and operate virtual construction equipment, such as cranes)	(Helmholt et al. 2009)
Virtual planning and sequencing	(Dias et al. 2003; Rankohi and Waugh 2013; Wang et al. 2013)
Safety orientation (do safety orientation in an augmented virtual environment)	(Wang and Dunston 2007; Rankohi and Waugh 2013)
AR-simulation based safety training programs for workers	(Wang and Dunston 2007; Akyeampong et al. 2012; Kivrak and Arslan 2019; Park and Kim 2013; Rankohi and Waugh 2013)
Construction	
Off site	
Visualizing layout and integration of prefab components in the shop	(Wang et al. 2013; Meža et al. 2015; Chalhoub and Ayer 2017)
On site	
Site layout without physical drawings	(Shin and Dunston 2008; Bluebeam, Inc. 2016)

Use-Cases	References
4D Simulations on site (augmented simulated construction operations)	(Golparvar-Fard et al. 2009; Wang et al. 2013; Danker and Jones 2014; Heinzel et al. 2017)
Monitoring progression of workflow and sequence	(Shin and Dunston 2008; Rankohi and Waugh 2013; Wang et al. 2013)
Visualization of augmented drawings in the field	(Dunston et al. 2000; Yeh et al. 2012; Danker and Jones 2014; Meža et al. 2015; Ghaffarianhoseini et al. 2016)
On-site inspections	(Webster et al. 1996b; Hammad et al. 2002; Shin and Dunston 2008; Helmholt et al. 2009; Park et al. 2013; Rankohi and Waugh 2013)
Remote site inspection	(Park et al. 2013; Rankohi and Waugh 2013)
Visualization of underground utilities	(Webster et al. 1996b; Thomas et al. 1999; Roberts et al. 2002; Behzadan and Kamat 2009; Meža et al. 2015)
Visualization of the proposed excavation area	(Shin and Dunston 2008; Behzadan and Kamat 2009; Meža et al. 2015)
Visualization of the construction systems/work (i.e. MEP, structural, etc.)	(Shin and Dunston 2008; Meža et al. 2015)
Planning the positioning and movement of heavy/irregular objects/equipment	(Shin and Dunston 2008; Meža et al. 2015)
Real-time support of field personnel	(Hammad et al. 2002)

Use-Cases	**References**
On-site safety precautions (site navigation and in-situ safety warning)	(Helmholt et al. 2009; Park and Kim 2013; Danker and Jones 2014)
Augmented Mock-ups	(Woyke 2016)
Construction progress visualization and monitoring	(Shin and Dunston 2008; Golparvar-Fard et al. 2009; Danker and Jones 2014; Zollmann et al. 2014; Meža et al. 2015)
On-site material tracking	(Chandarana et al. n.d.; Wang et al. 2013; Meža et al. 2015)
Create design alternatives on-site	(Wang et al. 2013; Danker and Jones 2014)
Visualization of augmented work instructions/manuals/procedures in the field	(Dunston et al. 2000; Kivrak and Arslan 2019; Rankohi and Waugh 2013; Wang et al. 2013; Meža et al. 2015)
Real-time visualization, review and analysis of data associated with a particular worker, equipment, construction system, etc.	(Yeh et al. 2012; Chandarana et al. n.d.; Wang et al. 2013)
Commissioning	
On-site inspection/Punchlists	(Webster et al. 1996b; Hammad et al. 2002; Shin and Dunston 2008; Helmholt et al. 2009; Rankohi and Waugh 2013)
Remote site inspection	(Rankohi and Waugh 2013)
Operation and Maintenance	

Use-Cases	References
Availability of Maintenance information	(Kensek et al. 2000; Hammad et al. 2002; Meža et al. 2015)
Locate building systems that need maintenance without destructive demolition or further survey work	(Chandarana et al. n.d.; Danker and Jones 2014; Meža et al. 2015)
Refurbishment visualization	(Chandarana et al. n.d.; Danker and Jones 2014)
Real-time support of engineers and technicians	(Hammad et al. 2002)
Training for maintenance and repair	(Chandarana et al. n.d.)
Decommissioning	
Remodeling visualization	(Chandarana et al. n.d.; Danker and Jones 2014)
Evaluation of the new facility/installations over the existing one	(Chandarana et al. n.d.; Danker and Jones 2014; Meža et al. 2015)

2.3.3. AR Benefits

The wide range of AR use-cases in construction highlighted the beginning of a new era in this industry (Kivrak and Arslan 2019). Various research endeavors have discussed the potential benefits for implementing AR in construction. Dong and Kamat (2013) suggested that AR can benefit the Architecture, Engineering, and Construction (AEC) industry in at least three aspects: visualization, information retrieval, and interaction. The integration of the real world can significantly mitigate the efforts to create and render contextual models for virtual scenes and can provide a better perception of the surroundings than virtual reality alone (Visualization). AR also supplements a user's normal vision with context-related or georeferenced virtual objects (Information Retrieval). Furthermore, authentic virtual models can be deployed to evaluate physical condition of real objects (Interaction).

Piroozfar et al. (2017) claimed that the integration of AR systems throughout the lifecycle of a construction project has the potential to improve health and safety of the work environment, reduce cost caused by inefficient time management, allow stakeholders to perform iterative processes in an easy, cost effective, and safe environment.

16 AR potential benefits were identified from the literature and are listed in Table 2.

Table 2 List of AR Potential Benefits in the Construction Industry

AR Potential Benefits	References
Improving real-time visualization of project	(Dong and Kamat 2013; Heinzel et al. 2017)
Providing additional resources for problem solving	(Wang and Dunston 2013)
Enhancing decision-making	(Wang et al. 2013; Oesterreich and Teuteberg 2017)
Enhancing spatial cognition	(Wang and Dunston 2013; Carlsén and Elfstrand 2018; Chu et al. 2018)
Improving productivity	(Wang and Dunston 2013)
Improving collaboration and communication	(Wang and Dunston 2013; Heinzel et al. 2017)

Improving safety	(Thiel and Thiel 2014; Algohary 2015; Oesterreich and Teuteberg 2017; Ahmed 2018)
Reducing wastes, defects, and construction rework	(Kamat et al. 2010; Wang and Love 2012; Algohary 2015; Agarwal 2016)
detecting design errors	(Agarwal 2016)
Improving quality	(Kamat et al. 2010; Wang et al. 2013; Agarwal 2016; Ahmed 2018)
Educating the workforce (improve their understanding of the project)	(Ahmed 2018)
Improving owner's engagement	(Wang et al. 2013; Agarwal 2016)
Improving corporate image	(Heinzel et al. 2017; Oesterreich and Teuteberg 2017)
Improving the quality of planning and scheduling	(Golparvar-Fard et al. 2009; Khalid et al. 2013)
Allowing real-time data collection	(Agarwal 2016)
Improving growth and success by creating new business models	(Oesterreich and Teuteberg 2017)

2.3.4. AR Obstacles

Researchers have also stated that there are AR obstacles that need to be overcome before reaping the benefits of AR. Numerous researchers have highlighted the technical and technological challenges encountered when building and integrating AR systems into the existing practices of the construction industry. Heinzel et al. (2017) interviewed two general contractors and a software developer about their use of AR. The data analyzed from the interviews showed that cost of implementation, immaturity of the technology, the lack of standard in-field AR applications, and unsureness about the technology's value and benefits are among the challenges that the three companies reported as obstacles for implementing AR in construction.

A total of 22 AR obstacles were extracted from the literature and grouped into five categories: Financial, Human, Organizational, Technological, and Others as shown in Table 3.

Table 3 List of AR Obstacles in the Construction Industry

AR Obstacles	Category	References
Integration with existing technology	Technological	(Wang 2009)
Data privacy and security	Technological	(Ahuja et al. 2009; White et al. 2014)
Maturity of the technology	Technological	(Chandarana et al. n.d.; Cleveland Jr. 2010; Van Krevelen and Poelman 2007; Mekni and Lemieux 2014; Carlsén and Elfstrand 2018)
Hardware compliance with safety standards	Technological	(Chandarana et al. n.d.)
No AEC industry standard for hardware	Technological	(Chandarana et al. n.d.)
No AEC industry standard for software	Technological	(Heinzel et al. 2017)
Lack of management support	Organizational	(Irani et al. 2006)
Uncertain of its benefits	Organizational	(Heinzel et al. 2017)

Cultural resistance	Organizational	(Chandarana et al. n.d.; Carlsén and Elfstrand 2018)
Disruption to the rest of the organization	Organizational	(King and Schrems 1978; Irani et al. 2006)
Lack of skilled personnel	Human	(Pratama and Dossick 2019)
Lack of IT resources	Human	(Carlsén and Elfstrand 2018)
Resistance to change	Human	(Van Krevelen and Poelman 2007; Chandarana et al. n.d.; Mekni and Lemieux 2014)
The need for specialists' assistance	Human	(Mekni and Lemieux 2014)
Discomfort with prolonged use (headset tightness, dizziness, etc.)	Human	(Wang and Dunston 2013)
Cost of implementation	Financial	(King and Schrems 1978; Irani et al. 2006; Chandarana et al. n.d.; Oesterreich and Teuteberg 2017)
Cost of maintenance	Financial	(King and Schrems 1978; Irani et al. 2006; Oesterreich and Teuteberg 2017)
Time and cost required to train existing staff	Financial	(King and Schrems 1978; Irani et al. 2006; Chandarana et al. n.d.; Oesterreich and Teuteberg 2017; Carlsén and Elfstrand 2018)
Unawareness of actual in-field applications	Financial	(Carlsén and Elfstrand 2018)

The fragmented nature of the construction industry	Others	(Shrestha and Kumaraswamy 1995; Alsafouri and Ayer 2018)
Lack of standards (to describe data and support interaction and collaboration)	Others	(Sanna and Manuri 2016; Carlsén and Elfstrand 2018)
Lack of existing BIM workflow to augment	Others	(Wang 2009; Carlsén and Elfstrand 2018)

2.4. Cross-Pollination between Lean and Information and Communication Technology

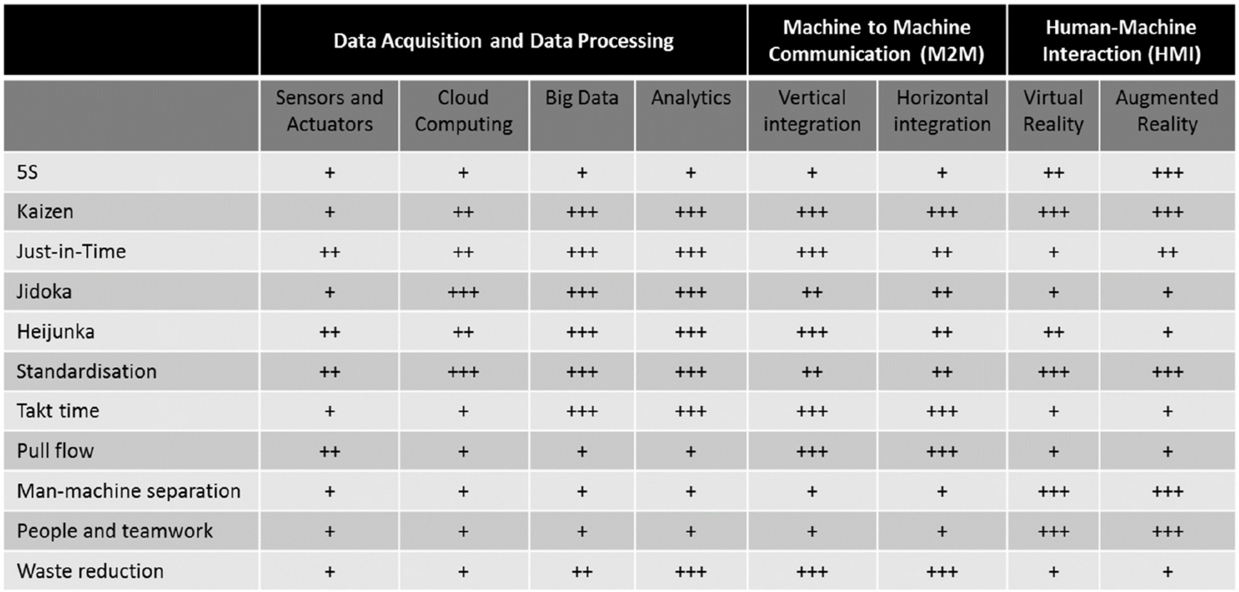
2.4.1. Manufacturing

(Riezebos et al. 2009) suggested that IT can facilitate the implementation of the principles and practices of Lean Production. Moyano-Fuentes et al. (2012) considered IT a powerful instrument to support Lean production and increase efficiency of operations.

(Hernández and Fast-Berglund 2014) explored how the implementation of ICT tools can support Lean Principle 6: standardized tasks are the foundation for continuous improvement and employee empowerment. The results of this study showed that the use of ICT tools (such as web applications) has a positive impact in Lean Production as it reduces wastes such as unnecessary motion (i.e. go and search for information) and provides an easier and faster platform to update standardized work and share the new knowledge.

Wagner et al. (2017) studied the integration of Industry 4.0 with existing Lean Production systems of industrial companies. The authors developed a conceptual framework that outlines the impact of Industry 4.0 technologies on Lean Production systems. The Industry 4.0 matrix in Figure

9 outlines the opportunities for integrating ICT with Lean Production systems. This study also suggested that the implantation of Industry 4.0 has the potential to increase the transparency and stability of lean principles.



	Data Acquisition and Data Processing				Machine to Machine Communication (M2M)		Human-Machine Interaction (HMI)	
	Sensors and Actuators	Cloud Computing	Big Data	Analytics	Vertical integration	Horizontal integration	Virtual Reality	Augmented Reality
5S	+	+	+	+	+	+	++	+++
Kaizen	+	++	+++	+++	+++	+++	+++	+++
Just-in-Time	++	++	+++	+++	+++	++	+	++
Jidoka	+	+++	+++	+++	++	++	+	+
Heijunka	++	++	+++	+++	+++	++	++	+
Standardisation	++	+++	+++	+++	++	++	+++	+++
Takt time	+	+	+++	+++	+++	+++	+	+
Pull flow	++	+	+	+	+++	+++	+	+
Man-machine separation	+	+	+	+	+	+	+++	+++
People and teamwork	+	+	+	+	+	+	+++	+++
Waste reduction	+	+	++	+++	+++	+++	+	+

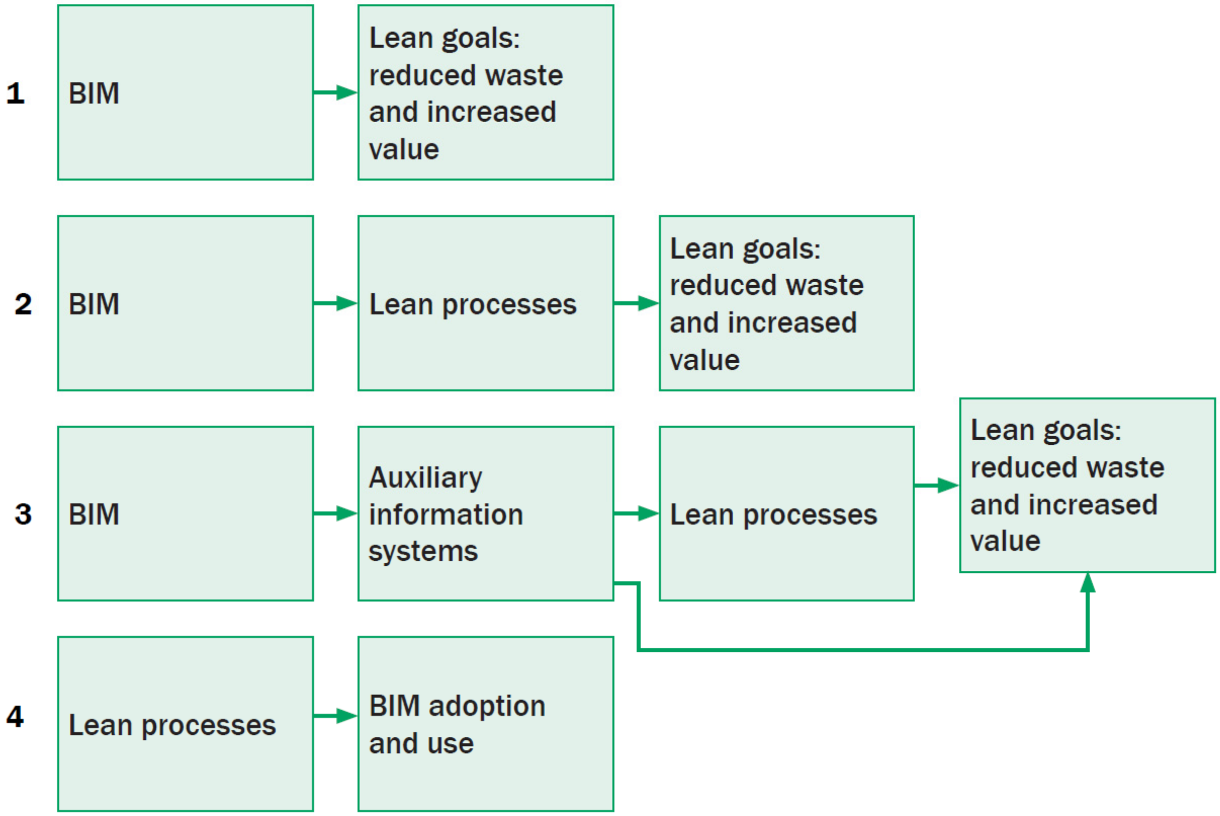
Figure 9 Industry 4.0 Impact Matrix on Lean Production Systems
(Wagner et al. 2017)

It can be concluded from Figure 9 that AR has a great potential to be integrated with Lean practices, namely, Just-in-Time, Standardization, Takt-Time, Pull flow, people and teamwork, and waste reduction. These practices are highlighted because they are components of the production strategy process.

2.4.2. Construction

Lean Construction and ICT (namely BIM) are two initiatives that are radical in and of themselves, and their impacts on construction have been far reaching and documented by multiple researchers. The synergies between Lean and BIM have been also explored and investigated by

(Dave et al. 2013) who discussed four major mechanisms for the interaction of Lean and BIM, as illustrated in Figure 10.



Note

1 BIM contributes directly to Lean goals.
2 BIM enables Lean processes, which contributes indirectly to Lean goals.
3 Auxiliary information systems, enabled by BIM, contribute directly and indirectly to Lean goals.
4 Lean processes facilitate the adoption and use of BIM.

Figure 10 Conceptual Connections between BIM and Lean
(Dave et al. 2013)

Sriprasert and Dawood 2002) developed a porotype called LEWIS that explores the next generation production planning and control system through a synergy of 1) innovative construction project management paradigm namely Lean Construction and 2) advanced information technology named web-based information management and 4D visualization.

Sacks et al. (2009) implemented two prototypes to facilitate process flow within the context of BIM systems. Their work demonstrated aspects of the synergy between BIM and Lean Construction and highlighted the importance of BIM-based visualization interfaces for providing process transparency.

Sacks et al. (2010a) analyzed possible interactions between 24 principles of Lean Construction and 18 BIM functionalities. They identified 54 points of direct interaction, 50 positive and only 4 negative. They found that the following three Lean principles had the most interactions with BIM functions: 1) get quality right the first time (reduce product variability), 2) focus on improving upstream flow variability (reduce production variability), and 3) reduce production cycle durations. The first two principles are grouped under the 'Reduce Variability' principle and the third principle is categorized under 'Reduce Cycle Time'. The three Lean principles belong to the 'Flow Process' area. The authors concluded that implementing BIM and Lean alongside each other was optimal, as the functionality of BIM improved Lean processes significantly. Oskouie et al. (2012) built upon the work of (Sacks et al. 2010a) and explored new interactions between BIM and Lean. The authors investigated two new Lean principles (*increase relatedness and collaboration* and *tightly coupling of learning with action*) and three new BIM functionalities (*support the make ready process*, *facilitating real-time construction tracking and reporting*, and *support AR*). The latter BIM functionality enhances the understanding of construction progress, increases the precision and accuracy of constructed elements by superimposing as-built and as-planned models. Integrating BIM with AR allows project managers to better detect defects and enables them to effectively make control decisions (Oskouie et al. 2012). The results of this study showed that integrating BIM with AR has a positive interaction with the following lean principles: reduce variability, verify and validate, and go and see for yourself.

Sacks et al. (2010b) developed KanBIM, a BIM-enabled system to support production planning and day-to-day production control on construction sites. The software was developed based on seven areas: 1) process visualization, 2) product and method visualization, 3) computation and display of work package and task maturity, 4) support for planning, negotiation, commitment, and status feedback, 5) implementation of pull flow control, 6) establishment and maintenance of workflow and plan reliability, and 7) formalization of experimentation for continuous improvement. The key contribution of KanBan is the visualization of the production process. The software builds upon LPS and provides the information structure to reduce the granularity of planning coordination from weekly to daily. KanBan also fosters negotiation between parties and provide real-time updates of any changes.

Lagos et al. (2017) explored the improvement of the level of implementation of LPS with the use of IT. The authors identified 16 LPS criteria, each containing n sub-criteria. The level of implementation of each sub-criterion of each of the 16 criteria was evaluated on a four-point Likert scale and the level of implementation of a criterion was obtained as the average of the sub-criteria. Data was collected from 18 projects, 10 of which had IT support. The results showed that when IT systems are integrated on a project to support LPS, a greater level of implementation is achieved for the following five criteria: standardization of the planning and control process; use of indicators to assess compliance with planning; critical analysis of information; using an easy-to-understand and transparent master plan; and analysis and systematic removal of constraints.

Tezel and Aziz (2017) recognized the important efforts of Lean construction and construction automation to improve the performance of the construction industry. The authors explored how emerging ICT can replace or facilitate existing conventional visual management systems and Lean tools in construction. The interaction matrix is presented in Table 4.

Table 4 Emerging Technologies to Support Conventional VM Systems and Tools (Tezel and Aziz 2017)

	BIM	**Context aware systems**	**Mobile computing (& wearable devices)**	**AR systems**	**Surface scan (Laser scanning, photogrammetry)**	**AutoID (RFID, NFC)**	**The Internet of Things (IoT)**
5S	x	x	x	x		x	
Visual Performance Boards	x	x	x		x		x
Standard Operating Procedures		x	x	x		x	
Internal Marketing		x	x	x		x	x
One-Point-Lessons		x	x	x		x	
The A3 methodology		x	x			x	
The Last Planner meeting boards	x	x	x	x	x	x	x
Project production control systems	x	x	x	x	x	x	x
Andon system	x		x			x	x
Heijunka boards	x		x			x	x
Kanban System	x	x	x			x	x
Poka Yokes		x	x			x	x

Antunes and Poshdar (2018) developed a theoretical framework for an information integration system for construction as shown in Figure 11. The proposed framework is divided into planning, monitoring, controlling, and executing groups. Each group includes a cluster of technologies to track both the project product and production.

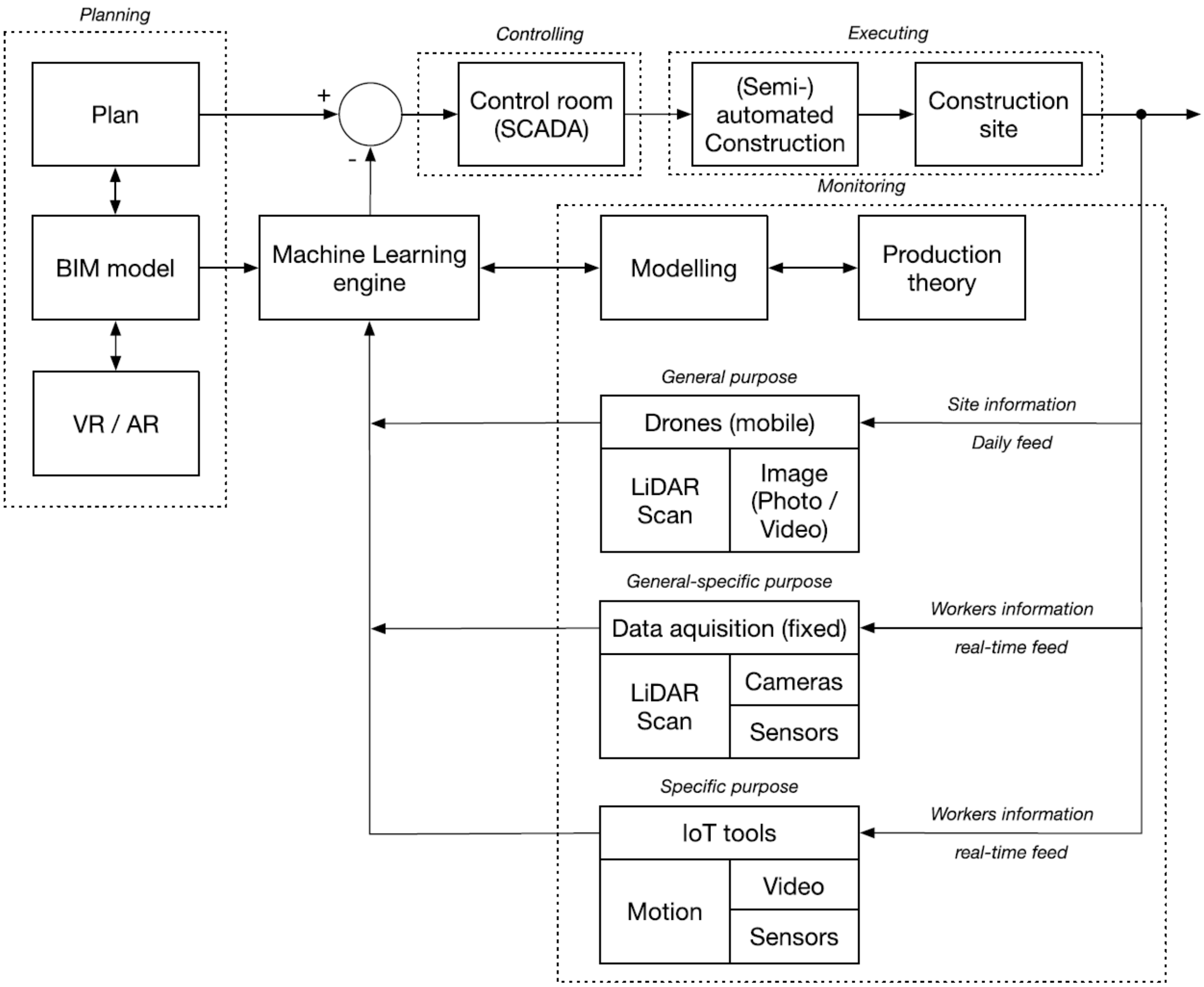


Figure 11 Theoretical Framework for an Information Integration System for Construction (Antunes and Poshdar 2018)

Section II

Chapter 3: Objective A Methodology and Data Collection

Augmented reality (AR) is an emerging technology within construction, and there is still little existing data about its uses, benefits, challenges, and successes. The preceding chapters have introduced the research, its motivation, and two primary objectives (A and B), and presented a review of existing literature and previous research endeavors. This chapter outlines the methodology used to achieve the first objective of this research: Investigate the potential of AR in the Construction Industry: A Holistic Approach.

3.1. Objective A – Research Methodology

To achieve the first objective of this study, the research was divided into five distinct phases: (1) literature review of AR in construction, (2) survey development, pilot testing, and data collection, (3) summary of data characteristics, (4) data analysis, and (5) conclusions.

To better understand the perception that the construction industry has of the potential of AR, an extensive survey was developed and distributed to the construction industry. Data collected from the survey was then analyzed to identify current and future trends of AR in the industry. The survey consisted of two major sections. Due to the emerging state of the technology, a diversity of thoughts in responses is crucial; therefore, the first section entitled 'Respondent Information' asks a series of questions about the respondent and their companies. The second section entitled 'Augmented Reality' includes a series of questions to assess the current and future states of AR in the construction industry. The 43 AR use-cases, 16 potential benefits, and 22 obstacles identified from the literature review were also included in the survey.

The AR section of the survey can be further divided into 8 sub-divisions as follows:

- Knowledge and Experience using AR

- Perceived usage of the 43 AR use-cases (variable 1)
- Perceived impact of the 16 AR benefits (variable 2)
- Perceived impact of the 22 obstacles to implementing AR in construction (variable 3)
- Perceived usage of construction stakeholders of AR (variable 4)
- Perceived usage of AR in the seven phases of a construction lifecycle (variable 5)
- AR statements (variable 6)
- Timeline for AR adoption

The questions in the ‘Augmented Reality’ section are mainly qualitative as they are answered in accordance to the opinion of the respondent. The scale used for each question is described when the question is analyzed.

3.2. Pilot Testing, and Data Collection

Following the thorough survey development stage, and to ensure that the survey would be effective, easy to complete, and would capture the necessary information, the survey was pilot tested by industry experts. The feedback of 12 industry experts was collected and the survey was refined accordingly. The pilot testing offered insights form the perceptive of the respondents and helped finalize the survey before moving to the full-scale data collection stage. The resulting survey allowed for a comprehensive industry-driven assessment of AR in the construction industry.

3.3. Data Characteristics

The results presented in this section and in the following chapter are obtained from a *sample* dataset of 128 observations collected from the survey. Since the *population* dataset, i.e., the dataset that contains all individuals working for all types of companies within the construction industry, is not available, true values are not known and the variability in the sample dataset needs to be accounted for. Therefore, standard error is used to represent variability in estimates of a parameter (here proportion) and to compute a 95% Confidence Interval (CI) that defines a range of values that contains the population parameter[3].

$$Standard\ Error\ (SE) = \sqrt{\frac{p(1-p)}{n}}$$

where:

- p is the sample proportion calculated as $p = \frac{X}{n}$ with X denoting the number of successes out of a sample of size n
- n is the sample size

The general form of a confidence interval is:

$$point\ of\ estimate \pm z\alpha/_2 SE$$

where:

- $point\ of\ estimate$ is the sample proportion p

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[3] Here the population parameter is the population proportion π, and the sample proportion is denoted as p.

- $z\alpha/_2$ is the z-score

From the standard normal distribution, for a 95% CI, α equals 0.05 and therefore,

$$z\alpha/_2 = z_{0.025} = 1.96 = 2$$

Thus, the 95% CI is obtained by:

$$p \pm 2SE$$

All of the graphs presented have error bars to represent the variability of the corresponding data. It is important to note that standard error are not statistical tests. In order to investigate the difference between groups, formal statistical analysis must be performed.

3.3.1. Geographic Distribution

A total of 128 responses were collected throughout the survey. The bulk of the respondents (around 96%) were located in the United States of America, other respondents were located in Canada, United Kingdom, and Netherlands as illustrated in Figure 12. Within the USA, the majority of responses were collected from Wisconsin, California, Illinois, and Minnesota.

Location	Responses
United States of America (27 states)	123
United Kingdom	2
Canada	2
Netherlands	1

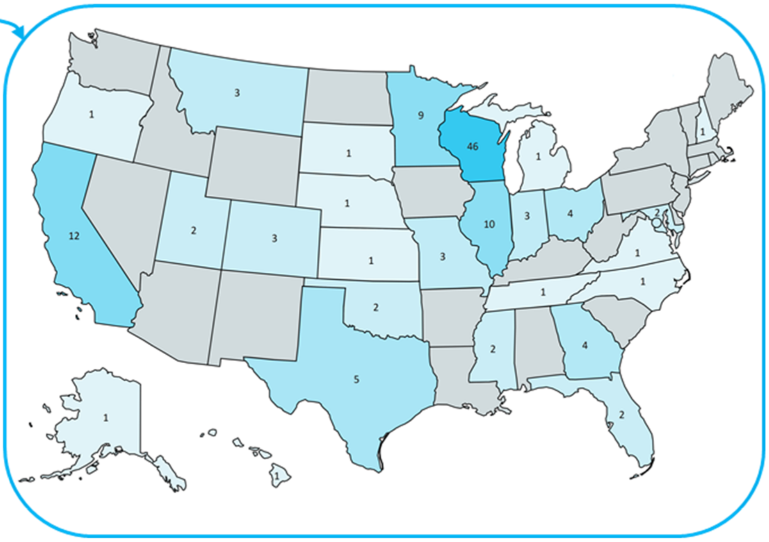

Figure 12 Geographic Distribution of the Respondents
Note: The numbers shown on the map represents the number of responses collected from each state.

3.3.2. Types of Companies

Respondents were asked to identify the type of their company among the following options: Owner, Owner's Representative (OR), Architect/Engineer (A/E), General Contractor/Construction Management (GC/CM), Mechanical Contractor, Electrical Contractor, Sheet Metal Contractor, Plumbing Contractor, Fire Protection Contractor, Structural Steel Contractor, Facility Manager, and Other. The collected data was recategorized into the five types as illustrated in Figure 13.

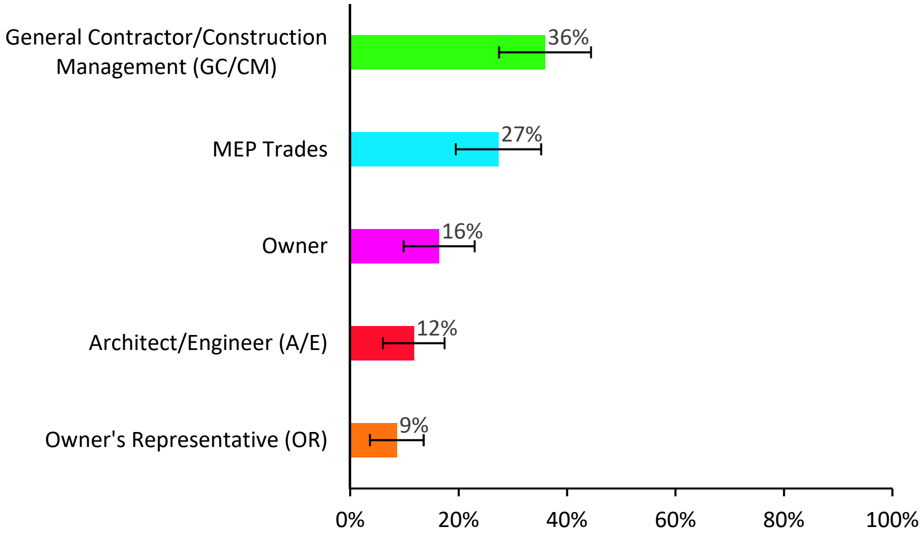

Figure 13 Breakdown of Respondents by Company Type

3.3.3. Respondent Age

Respondents were asked to select their age group from the following ranges: [18-24], [25-34], [35-44], [45-54], [55-54], and [65 and above]. Figure 14 shows the breakdown of respondents by age.

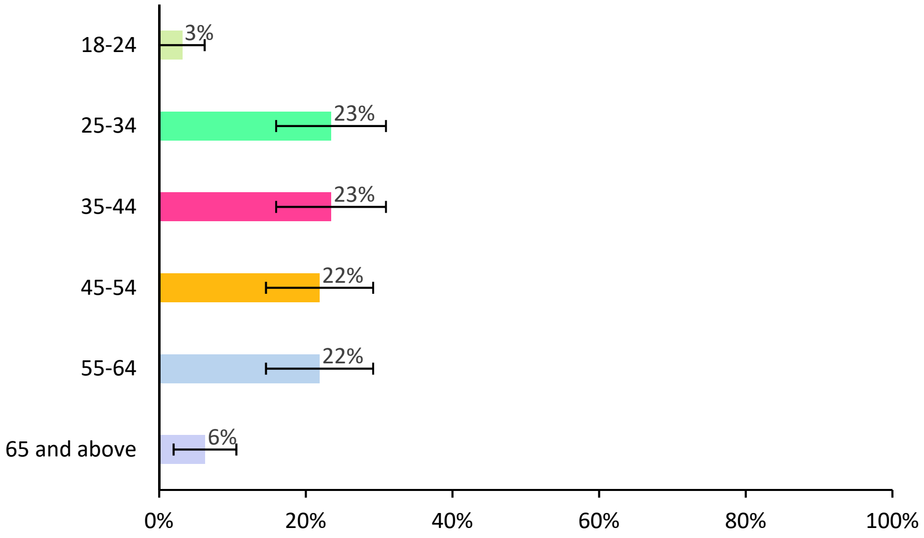

Figure 14 Breakdown of Respondents by Age

Respondents were equally distributed among the following four age groups: [25-34], [35-44], [45-54], and [55-64]. The 2017 Labor Force Statistics reported by the Bureau of Labor Statistics for Construction showed that the population of the construction industry is broken down by age as indicated in Figure 15.

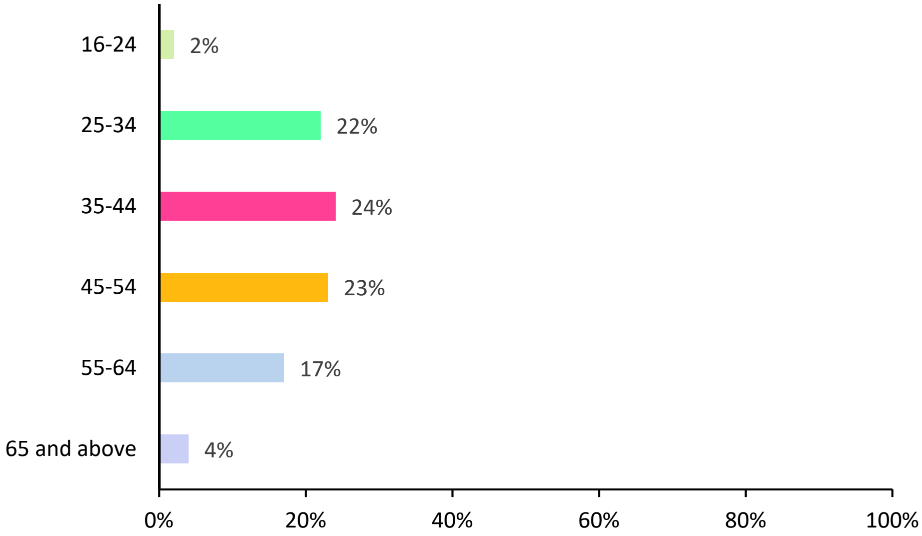

Figure 15 Bureau of Labor Statistics' Breakdown of the Construction Population by Age Reproduced using data from the Bureau of Labor Statistics4

The confidence interval shown in Figure 14 show that the data collected has a similar distribution to that collected by the Bureau of Labor Statistics, indicating that the survey is representative of the construction industry.

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[4] https://www.bls.gov/cps/cpsaat11b.htm

3.3.4. Respondent Occupation

Respondents were asked to provide their job titles. Their responses were then categorized into one of the following occupations: Technologist, Field, and Top Management. Figure 16 shows the distribution of the respondents based on their occupation.

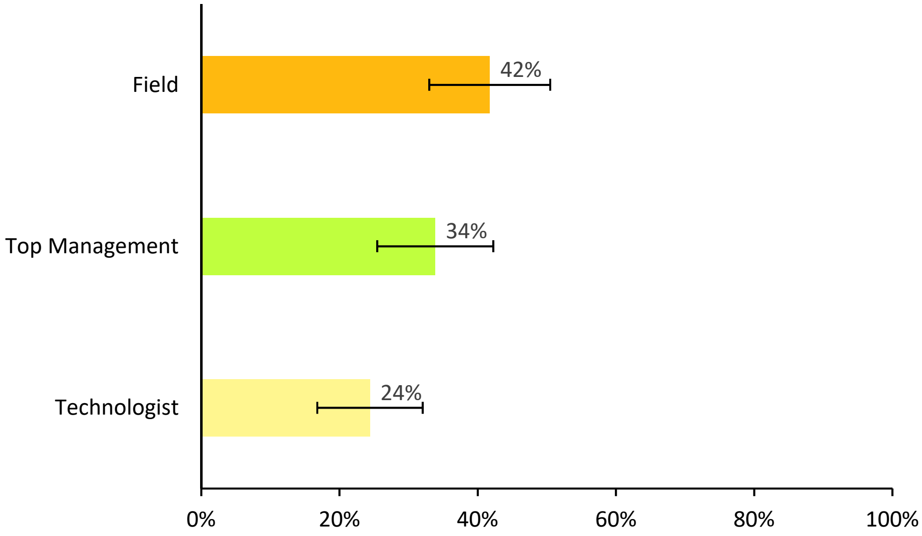


Figure 16 Breakdown of Respondents by Occupation

Chapter 4: Data Analysis

This chapter will discuss the statistical analysis that was conducted to explore AR use-cases, potential benefits, obstacles, stakeholders, and phases in which AR will be integrated. The current state of AR in construction is investigated through a series of questions that asked respondents to report on their current use of the technology in construction. Finally, insights into the potential future state of AR and its future adoption are discussed.

4.1. Variables

From the literature review, 43 AR use-cases were identified (variable 1), along with 16 potential benefits (variable 2) and 22 obstacles (variable 3). To better understand the potential of AR over the project lifecycle, the 43 collected use-cases were grouped into the seven phases of a project life-cycle: Conceptual Planning, Design, Pre-Construction Planning, Construction, Commissioning, Operation and Maintenance, and Decommissioning. The 22 AR obstacles were also grouped into five categories: Financial, Human, Organizational, Technological, and Others. In addition to exploring AR use-cases, benefits, and obstacles, it was important to understand and investigate who benefits the most from AR and where the technology is most useful. Therefore, the potential usage of AR among 10 stakeholders in the construction industry (variable 4) and in the seven phases of a construction project lifecycle (variable 5) was investigated. Respondent’s perception of the technology for each of the five variables was captured on a five-point Likert scale, from very low (1), to low (2), moderate (3), high (4) and very high (5).

Another section of the survey included eight statements (variable 6) describing the future of AR in the construction industry to which respondents reported their level of agreement with each statement using a five-point scale from strongly disagree (1), to disagree (2), undecided (3), agree (4), and strongly agree (5). It is important to mention that the order of the answer options

(AR use-cases, AR potential benefits, AR obstacles, AR stakeholder, AR phases, and AR statements) were randomized to avoid survey bias.

4.2. Statistical Methodology

Due to the qualitative nature of the questions, non-parametric tests were employed to analyze the data. Kruskal-Wallis test is the non-parametric version of ANOVA (Analysis of Variance) and is performed to compare samples of equal or different sizes and indicate if at least one sample stochastically dominates one other sample. This test provides a p-value: the smaller the p-value, the stronger the statistical evidence that at least one sample is statistically different than one other sample.

If Kruskal-Wallis results in a significant p-value, post-hoc tests – namely the Conover-Iman non-parametric test – is used to compare all possible pairs and identify which group is significantly different than the other.

In addition, Kendall's tau-b is used to measure the strength and direction between two ordinal or continuous variables. Kendall Tau-b is a nonparametric measure used to find associations between two variables. An example of this test in this research is comparing two Likert scale questions with each other. Kendall's tau-b hypothesis test produces two statistical metrics: The first metric is a p-value which can be thought of as the probability of having no statistical correlation between the two variables that are being studied. the smaller the p-value, the stronger the evidence of statistically significant correlation between the two variables. The second metric is the correlation coefficient, τ_b. This coefficient measures the ordinal association between the two variables and ranges from -1 to 1. A positive τ_b indicates a direct relationship between the two variables: as variable A increases, variables B increases as well, and vice versa. The higher the value of τ_b, the stronger the correlation. On the other hand, a negative τ_b indicates an inverse relationship between the two variables being analyzed: as variable A increases, variables B decreases, and vice versa. In this case, the lower the value of τ_b, the stronger the direct relationship. Finally, a τ_b of zero indicates that there is no ordinal association between the two variables under consideration.

The relationship between 1) the respondents' perception of each of the six variables and respondents' familiarity with AR and 2) the respondents' perception of each of the four variables and respondents' usage of AR was evaluated using Kruskal-Wallis H test and Kendall's Tau-b. The results indicated that the respondents' perception of each of the four variables depends on their level of familiarity and usage of AR in the context of the construction industry. Therefore, a mathematical model was developed for each variable to adjust the original respondents' perception by accounting for respondents' familiarity and usage of the technology. The model is described in detail for the AR use-cases.

Finally, once the original respondents' answers for each of the first five variables were adjusted using the corresponding mathematical model, *k*-means cluster analysis was performed on the first three variables to identify the AR use-cases that have the highest usage potential, the AR benefits that have the highest potential, and the obstacles that have the highest impact. Cluster analysis is a statistical method used to group data by comparing each candidate AR use-case for example to the other AR use-cases already in the cluster. If the difference between the candidate AR use-case and the other AR use-cases already in the cluster is significant, then the candidate AR use-case is assigned to a different cluster.

4.3. Respondents Knowledge and Experience with AR

4.3.1. Familiarity with Augmented Reality on a Personal Level

4.3.1.1. Distribution of Respondents' Familiarity with Augmented Reality on a Personal Level

Respondents were asked about their level of familiarity with AR in their personal lives. As shown in Figure 17, only 6% indicated that they have not heard of AR before, 12% said that they have vaguely heard of the term before, 32% reported that the have a basic understanding of AR, 28% have a good understanding of AR, and 22% mentioned that they have a very good understanding of AR.

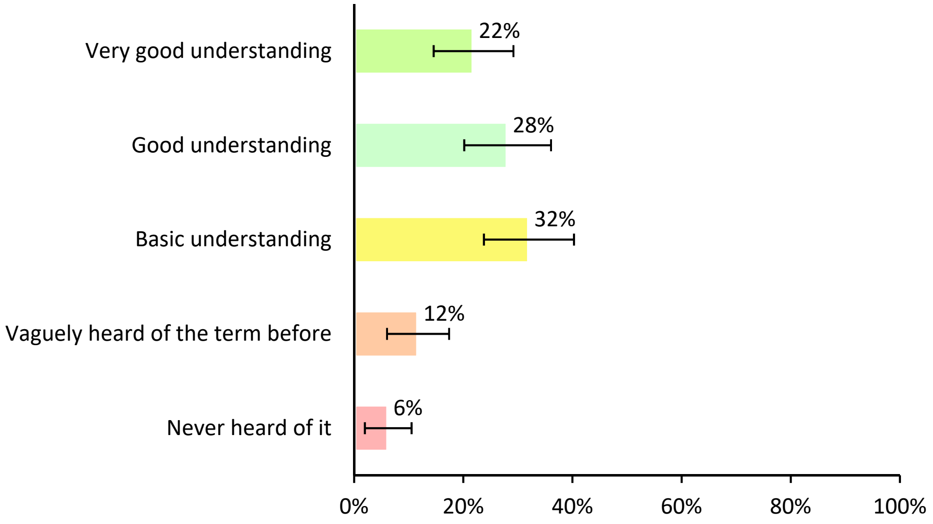


Figure 17 Breakdown of the Respondents' Familiarity with AR on a Personal Level

4.3.1.2. Respondents' Familiarity with Augmented Reality on a Personal Level vs Age Group

Age groups [18-24] and [65 and above] had few responses, therefore they were aggregated with age groups [23-34] and [55-64], respectively, resulting in the distribution shown in Figure 18. This aggregation creates more uniform groups, which facilitates further analyses.

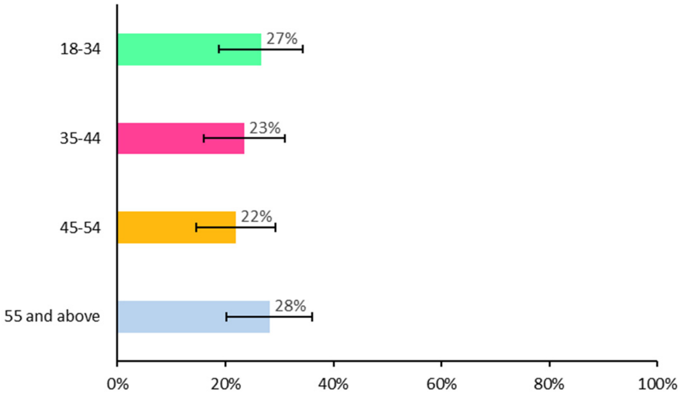


Figure 18 Breakdown of Respondents by Age

4.3.2. Usage of Augmented Reality on a Personal Level

4.3.2.1. Distribution of Respondents' Usage of Augmented Reality on a Personal Level

Respondents were asked to specify their level of usage of AR in their personal lives. As depicted in Figure 19, 35% of the respondents who answered this question have never used AR, 28% have tried it a few times, 15% infrequently use AR, 14% use it on a semi-regular basis, and 8% use AR regularly.

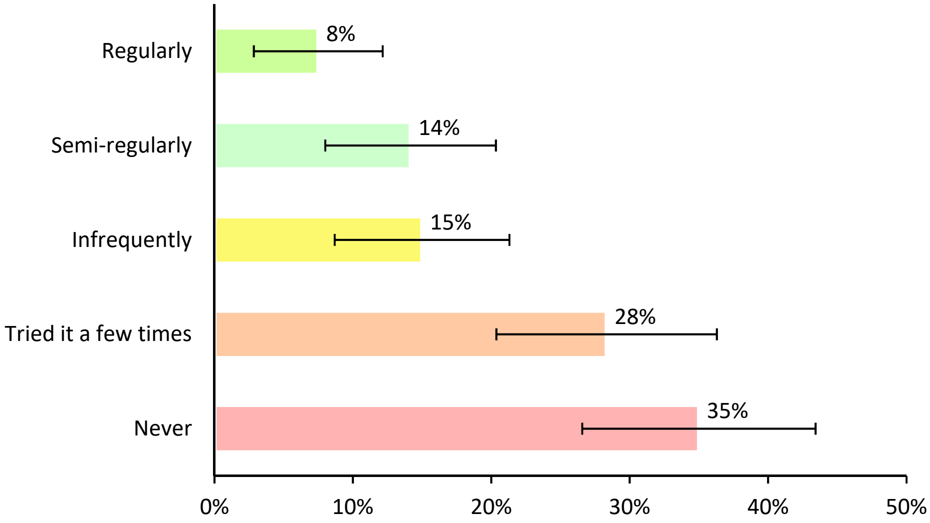


Figure 19 Breakdown of the Respondents' Usage of AR on a Personal Level

4.3.2.2. Usage of AR Platforms on a Personal Level (Hands-On Experience)

Out of the 65% of respondents (i.e. 78 respondents) who reported that they have experience using AR (either Tried it a few times, Infrequently, Semi-regularly, Regularly) , 90% have interacted with AR using Mobile (phone and tablet) Consumer Applications such as Snapchat™ and Pokémon Go™, and 87% have interacted with AR using wearable technologies such as the Microsoft HoloLens (Figure 20).

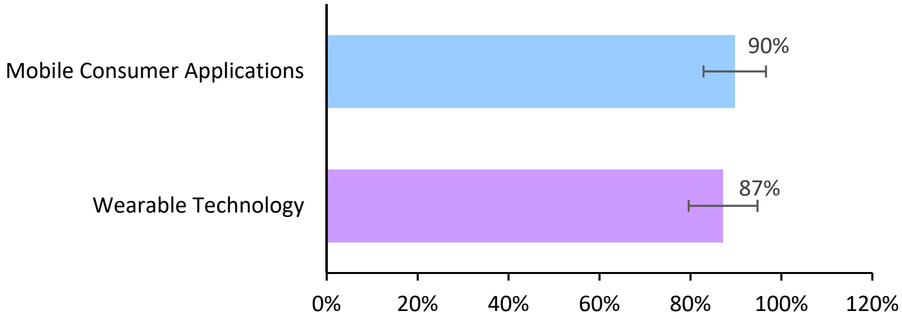


Figure 20 Breakdown of AR Platform Used by Respondents on a Personal Level

4.3.2.3. Familiarity with Augmented Reality Wearables

All 128 respondents were then asked about their familiarity with the following AR wearables: HoloLens, Daqri, Meta, Google Glass, and Magic Leap. The results displayed in Figure 21 show that respondents are the most familiar with Google Glass (70%), followed by HoloLens (55%) and are least familiar with Meta (16%).

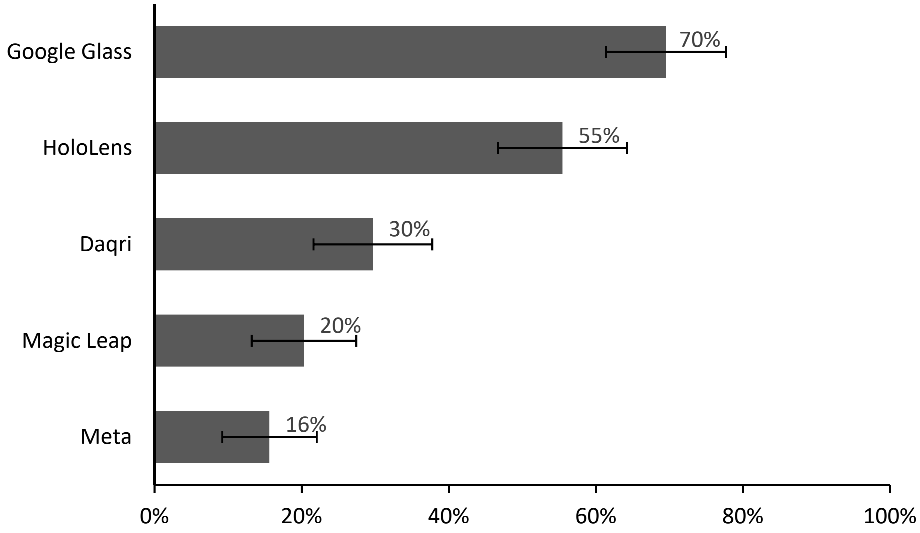


Figure 21 Respondents’ Familiarity with AR Wearables

4.3.3. Familiarity with Augmented Reality on a Professional Level

4.3.3.1. Distribution of Respondents’ Level of Familiarity with AR on a Professional Level

Respondents were asked about their level of familiarity with AR in their professional lives. As shown in Figure 22, 15% indicated that they are not at all familiar with AR, 24% said that they are slightly familiar with AT, 16% reported that they are somehow familiar, 27% are moderately familiar with the technology, and 17% mentioned that they are extremely familiar with AR.

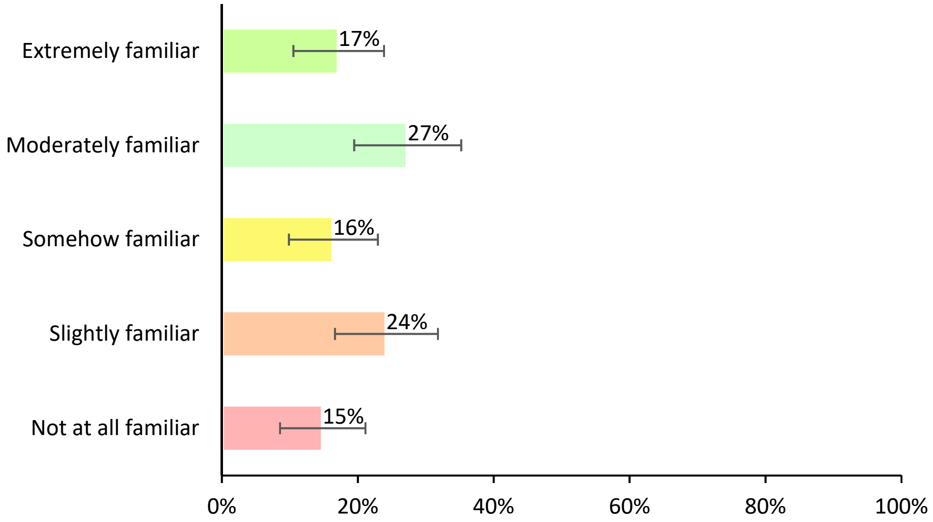


Figure 22 Breakdown of the Respondents' Familiarity with AR on a Professional Level

4.3.3.2. Familiarity with AR on a Professional Level vs Type of Company

The level of familiarity of AR on a professional level was measured across the different company types. Figure 23 shows that the level of familiarity of the technology varies across company types, with C/CM having, on average, a higher level of familiarity with AR in the context of the construction industry than other types of company.

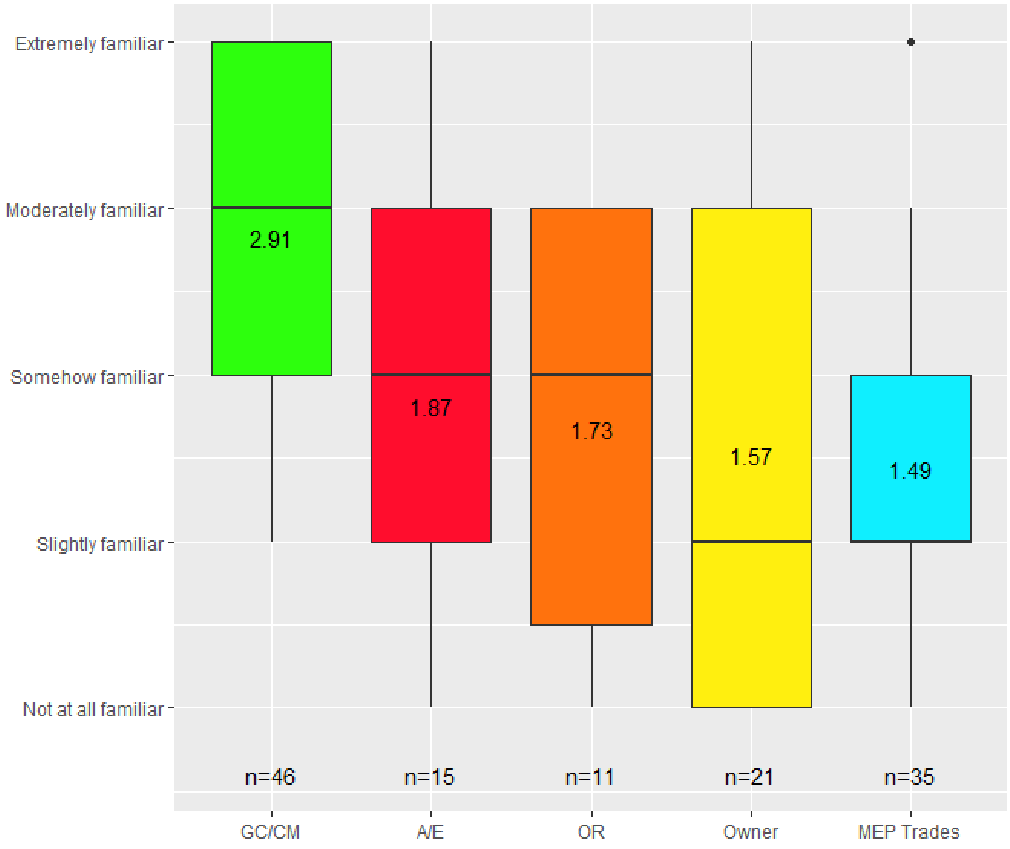


Figure 23 Comparing the level of AR Familiarity on a Professional Level among the Different Company Types

The difference in the level of familiarity among the different types of company was statistically tested first using Kruskal-Wallis and followed then by Conover-Iman test, as shown in Table 5. The Kruskal-Wallis test resulted in a significant p-value of 0.00000885. This provides a statistical evidence at more than 99% confidence level to reject the null hypothesis and conclude that the level of familiarity of AR on a professional level is dissimilar across the five types of company in the construction industry. The results from the post hoc Conover-Iman tests show that GC/CM have, on average, a statistically higher level of familiarity with AR in the context of the construction industry than A/E, OR, Owner, and MEP Trades which have a homogeneous level of familiarity with the technology.

Table 5 Results of Kruskal-Wallis and Conover-Iman Tests for Level of Familiarity of AR on a Professional Level against Type of Company

Statistical Test		P-value	Significance at 95% Confidence Level
Kruskal Wallis		0.00000885	Significant
Conover-Iman			
GC/CM	A/E	0.0410	Significant
GC/CM	OR	0.0394	Significant
GC/CM	Owner	0.0004	Significant
GC/CM	MEP Trades	0.0000	Significant
A/E	OR	1.000	Not Significant
A/E	Owner	1.000	Not Significant
A/E	MEP Trades	1.000	Not Significant
OR	Owner	1.000	Not Significant
OR	MEP Trades	1.000	Not Significant
Owner	MEP Trades	1.000	Not Significant

4.3.3.3. Familiarity with AR on a Professional Level vs Occupation

The level of familiarity of AR on a professional level was measured across the different occupations. Figure 24 shows that Technologists have, on average, a higher level of familiarity with AR in the context of the construction industry than individuals working in the Field and Top Management.

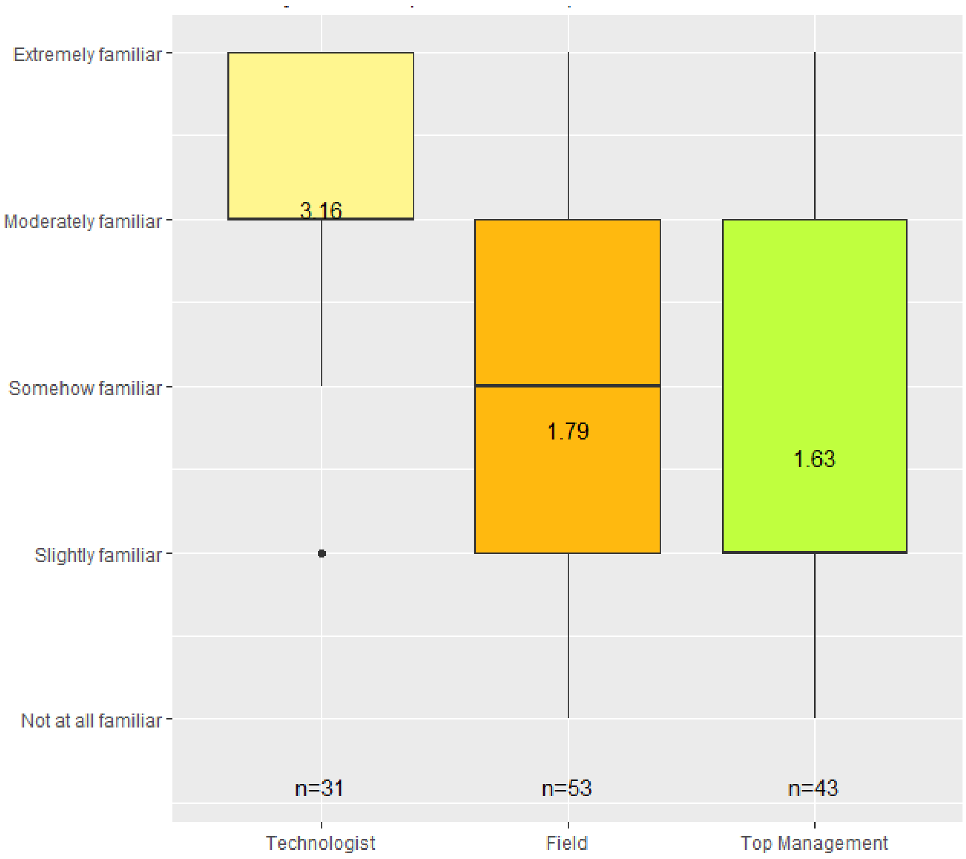


Figure 24 Comparing the Level of Familiarity with AR on a Professional Level among the Different Occupations

The difference in the level of familiarity among the different types of occupation was statistically tested first using Kruskal-Wallis followed then by Conover-Iman test, as shown in Table 6. The Kruskal-Wallis test resulted in a significant p-value of 0.00038. This provides a statistical evidence at more than 99% confidence level to reject the null hypothesis and conclude that the level of usage of AR on a professional level is dissimilar across the three types of occupation. The results from the post hoc Conover-Iman tests show that technologists have, on average, a statistically higher level of usage of AR in the context of the construction industry than individuals who work in the Field and Top Management.

Table 6 Results of Kruskal-Wallis and Conover-Iman Tests for Level of Usage of AR on a Professional Level against Occupation

Statistical Test		**P-value**	**Significance at 95% Confidence Level**
Kruskal Wallis		0.00000099	Significant
Conover-Iman			
Technologists	Field	0.0000	Significant
Technologists	Top Management	0.0000	Significant
Field	Top Management	1.0000	Not Significant

4.3.4. Usage of Augmented Reality on a Professional Level

4.3.4.1. Distribution of Respondents' Usage of AR on a Professional Level

Respondents were asked to specify their level of usage of AR in their professional lives, i.e. in the context of the construction industry. As depicted in Figure 25, only 8% of the respondents indicated that they have not used AR and they are not interested in the technology, 47% have not experienced AR before, but are interested in the technology, 19% explored or are exploring AR applications, 13% have tested or are testing AR applications for future use, and 15% have used AR on at least one project.

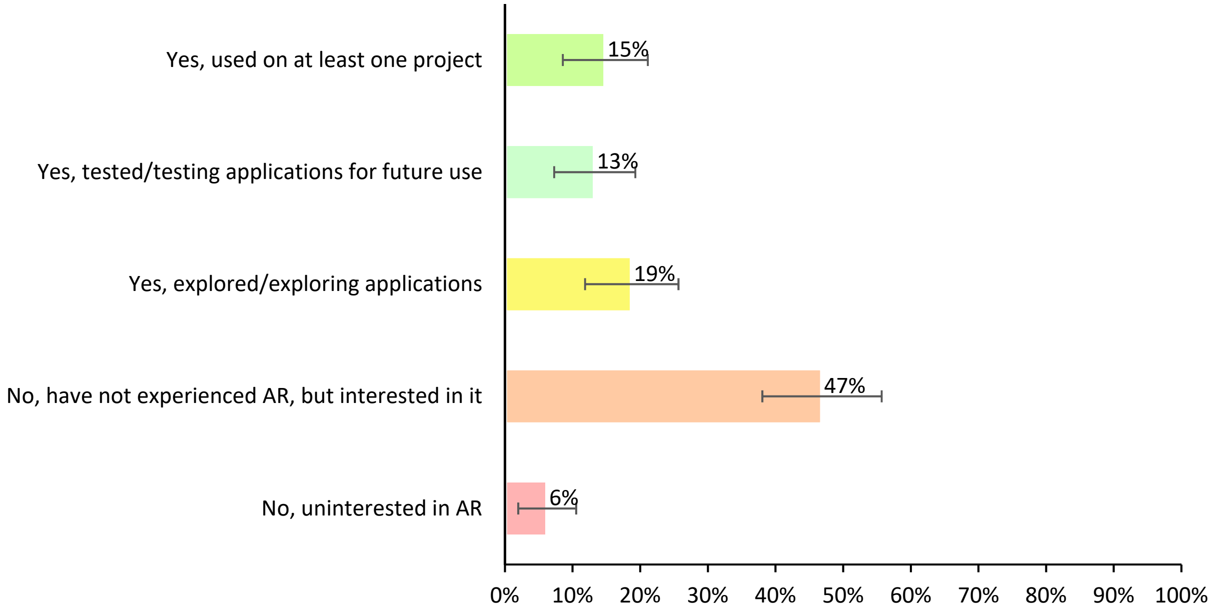


Figure 25 Breakdown of the Respondents' Usage of AR on a Professional Level

4.3.4.2. Usage of AR on a Professional Level vs Type of Company

The usage of AR on a professional level was also measured across the five types of companies. Figure 26 shows that employees who work for GC/CM have, on average, a significantly higher level of usage of AR in their professional lives than those who work for A/E, OR, Owners, or MEP Trades.

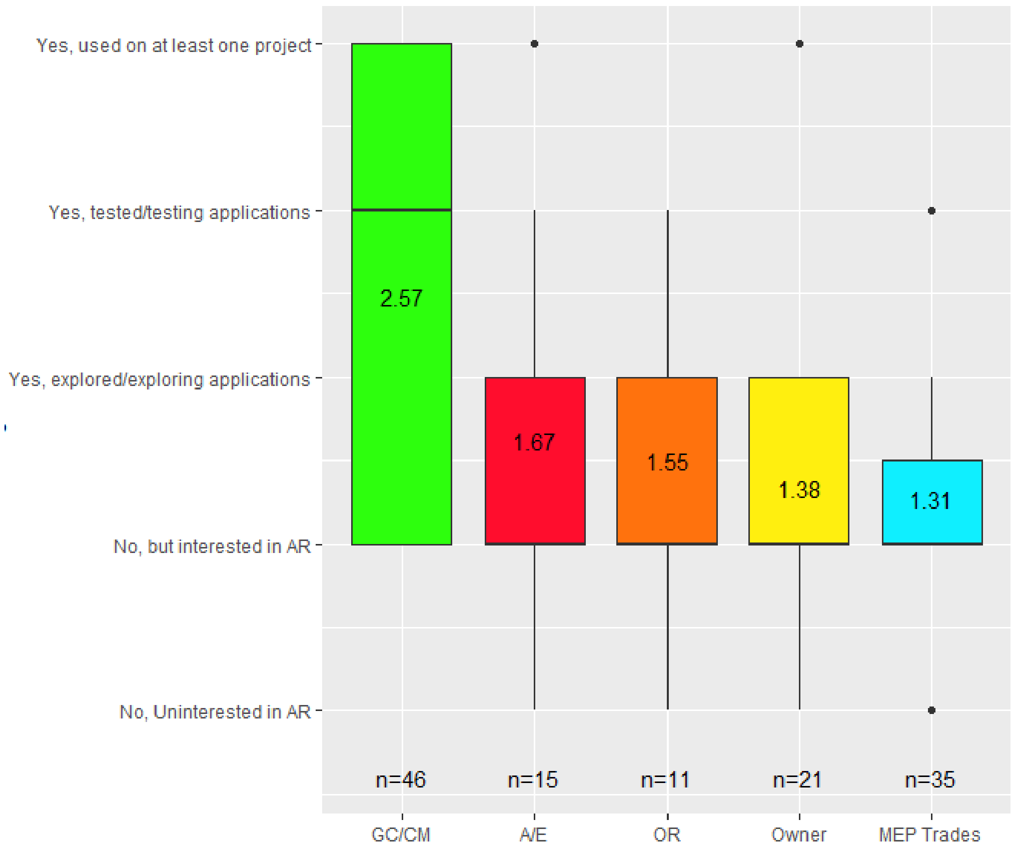


Figure 26 Comparing usage of AR on a Professional Level among the Different Company Types

The difference in the level of usage of AR among the different types of company was statistically tested first using Kruskal-Wallis followed then by Conover-Iman test, as shown in Table 7. The Kruskal-Wallis test resulted in a significant p-value of 0.0000227. This provides a statistical evidence at more than 99% confidence level to reject the null hypothesis and conclude that the level of familiarity of AR on a professional level is dissimilar across the five types of company in the construction industry. The results from the post hoc Conover-Iman tests show that employees who work for GC/CM have, on average, a significantly higher level of usage of AR in their professional lives than those who work for MEP trades and Owners.

Table 7 Results of Kruskal-Wallis and Conover-Iman Tests for Level of Usage of AR on a Professional Level against Type of Company

Statistical Test		**P-value**	**Significance at 95% Confidence Level**
Kruskal Wallis		0.0000227	Significant
Conover-Iman			
GC/CM	A/E	0.0817	Not Significant
GC/CM	OR	0.1181	Not Significant
GC/CM	Owner	0.0003	Significant
GC/CM	MEP Trades	0.0000	Significant
A/E	OR	1.000	Not Significant
A/E	Owner	1.000	Not Significant
A/E	MEP Trades	1.000	Not Significant
OR	Owner	1.000	Not Significant
OR	MEP Trades	1.000	Not Significant
Owner	MEP Trades	1.000	Not Significant

4.3.4.3. Usage of AR on a Professional Level vs Occupation

The level of usage of AR on a professional level was measured across the different occupations. Figure 27 highlights that individuals who are technologists have, on average, a significantly higher level of usage of AR in their professional lives that those who work in the Field or Top Management.

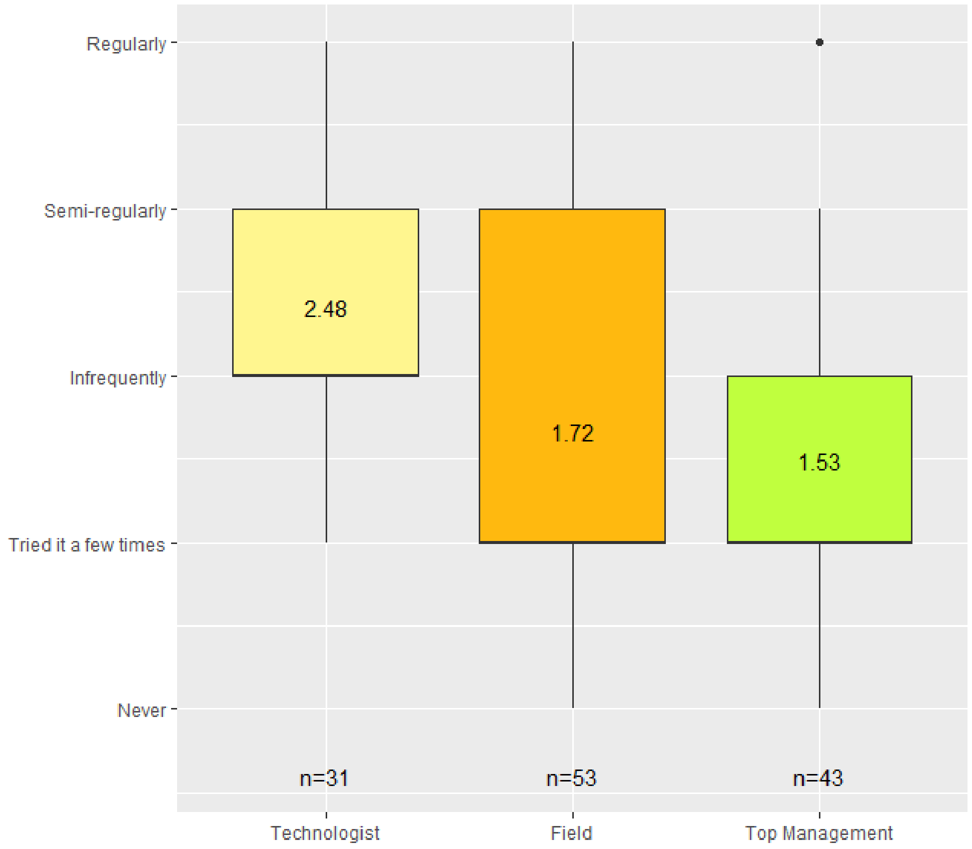


Figure 27 Comparing the usage of AR on a Professional Level among the Different Occupations

The difference in the level of usage of AR among the different types of occupation was statistically tested first using Kruskal-Wallis followed then by Conover-Iman test, as shown in Table 8. The Kruskal-Wallis test resulted in a significant p-value of 0.00038. This provides a statistical evidence at more than 99% confidence level to reject the null hypothesis and conclude that the level of usage of AR on a professional level is dissimilar across the three types of occupation. The results from the post hoc Conover-Iman tests show that technologists have, on average, a higher level of usage of AR in the context of the construction industry than individuals who work in Top Management.

Table 8 Results of Kruskal-Wallis and Conover-Iman Tests for Level of Usage of AR on a Professional Level against Occupation

Statistical Test		**P-value**	**Significance at 95% Confidence Level**
Kruskal Wallis		0.0038	Significant
Conover-Iman			
Technologists	Field	0.1155	Not Significant
Technologists	Top Management	0.0021	Significant
Field	Top Management	0.2981	Not Significant

4.3.4.4. Usage of AR Platforms on a Professional Level (Hands-On Experience)

Out of the 47% of respondents (i.e. 60 respondents) who specified that they have had experience using AR in the construction industry (Explored/Exploring applications, Tested/Testing applications, and Used on at least one project), 65% indicated that they have used wearable technology to interact with AR and 62% specified that they have used mobile phones and tablets to interact with AR (Figure 28).

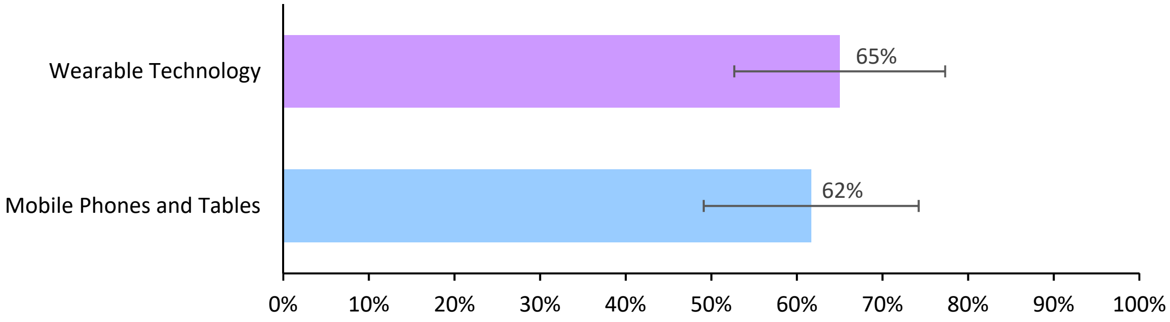


Figure 28 Breakdown of AR Platform Used by Respondents on a Professional Level

4.3.4.5. Project Phases in which AR has been Used (Hands-On Experience)

The 60 respondents reported that they have employed AR in 5 phases of the lifecycle of a construction project. The majority specified that they have used AR during the construction phase (70%), design phase (67%), and pre-construction phase (60%). Few respondents have also used

AR in the Operation and Maintenance (O&M) phase (12%), and commissioning phase (5%). None of the respondents reported any use of AR in either the planning or decommissioning phases. The breakdown of the respondents' experience with AR in each phase of the lifecycle of a construction project is illustrated in Figure 29.

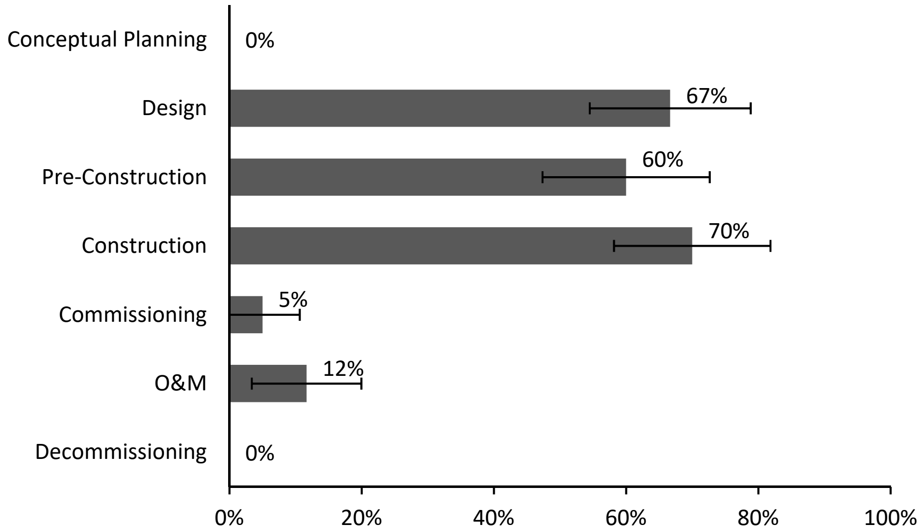


Figure 29 Breakdown of the Respondent's Experience with AR in Each Phase of the Lifecycle of a Project

4.3.4.6. Hands on Experience using AR in Construction

Respondents who indicated that they had hands-on experience using AR were asked to elaborate on their experience and use of the technology. This section summarizes the input of the respondents by company type.

- Architects/Engineers

Respondents who work for A/E reported that they have used AR to leverage 3D visualization and enhance the client experience when exploring the design of the facility. Using the HoloLens, the 3D BIM model of the project was project in a conference room and clients were able to walk around, visualize the project in real time and discuss the design with the A/E.

In addition, clients were able to interact with the project content and turn on and off layers such as structural steel, MEP, facade, and design options. Another use-cases of AR is the creation of coordination models in the HoloLens for complex mechanical spaces so that the end users and facility managers can better understand the spaces that they will be expected to operate and raise their opinions about clearances and access requirements. Others reported the use of AR for planning purposes and engaging the client in the design process.

- General Contractors/Construction Managers

The experience of GC/CM respondents were divided into in-house experience, and experience with other stakeholders such as designers, owners, and suppliers.

Some respondents reported using Trimble Connect for HoloLens to improve Quality Control (QC) processes by allowing the user to compare the planned versus the installed systems. One particular case was the use of AR for quality control and inspection of pre- and post-concrete pours. Others used the HoloLens for field layout and verification of the installation of the MEP systems on site and coordination with concrete penetrations. Another respondent reported that their company has used AR to visualize virtual mockup of a project. The use of AR to look at mockups provides a safe environment to review construction models, verify the design, and suggest and implement changes immediately. Another AR use-cases was the full-scale visualization of projects and overlays of planner systems onto the real structures. Respondents commented that AR fills in the gap between office (design work) and field (placing work) as it helps communicate the design and supports real time decisions that field personnel can make without having to go back to the office and look at a model. Another respondent described their use of the HoloLens to install in-wall blocking in the field while. A number of respondents indicated the use of AR for project proposal and presentations and pre-construction planning without expanding on the applications. Additionally, one respondent indicated that they have developed proof-of-concept applications for the HoloLens and have evaluated off the shelf applications for the last 3 years. However, the respondent did not provide further detail regarding their use of the technology. Moreover, GC/CM respondents reported using AR to review designs with A/E and walk the owner and users through their new space prior to building it. Finally, GC/CM have also worked with their suppliers and vendors to strategize how AR could be integrated into construction by listening to their needs. No details were provided regarding specific use-cases of AR.

- MEP Trades

MEP respondents did not elaborate much on their use of the technology as the majority of their hand-on experience was at conference and during showcases, where they had the opportunity to demo the HoloLens and DAQRI for a few minutes. Although MEP respondents did not have any formal use of AR, they did indicate that the technology has a promising future in the construction industry.

- Owners

Owners reported that they have mainly used AR to review designs and physically walk through their future projects, such as touring the planned expansion of a property.

- Owner's Representatives

Owner's representatives indicated that they have used AR to gain owner buy in by allowing them to physically walk through the facility and to provide contractors with a better understanding of the projects.

4.3.4.7. Usage of Augmented Reality Wearables in Construction

The 60 respondents who indicated that they have experience with AR in the construction industry were asked to select the AR wearable(s) that they have tried or used. The results illustrated in Figure 30 show that the HoloLens headset by Microsoft is the device that is most commonly used in construction with 68% of the "experienced" respondents reporting that they have used it for their AR application. Meta and Magic Leap were found to be the headsets that respondents are the least used in the construction industry.

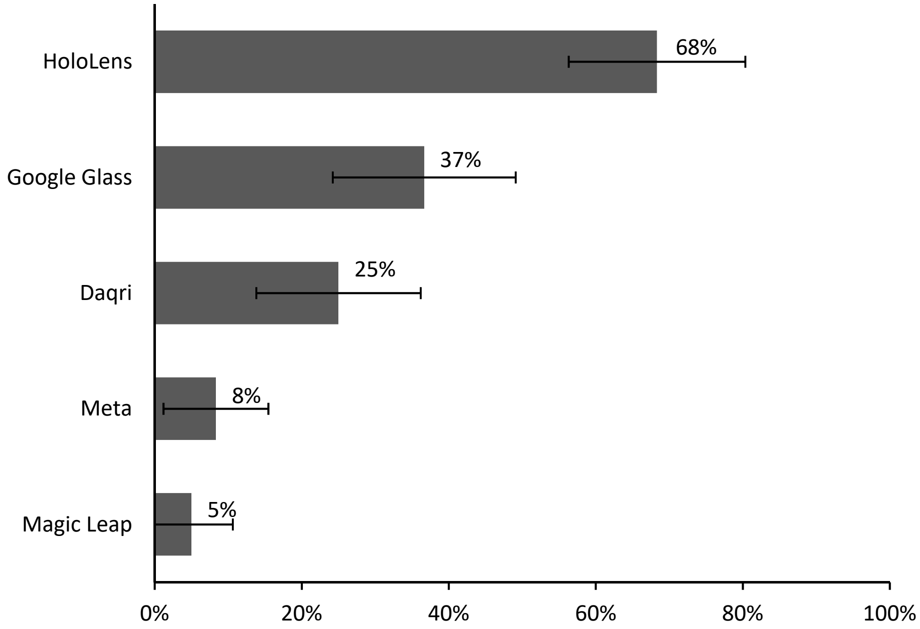


Figure 30 Breakdown of the Usage of the Various AR Wearables in Construction

4.3.4.8. Concerns using AR Wearables in the Construction Industry

Respondents who indicated that they have used AR warbles in construction were asked to identify any negative feedback they experienced from the use of the Head-Mounted-Display. As illustrated in Figure 31, respondents reported that *Safety Concerns* (39%) was their most frequent deterrent from using AR wearable, followed by *Discomfort* (29%)*, Inaccuracy* (29%), and *Motion Sickness* (27%). *Headache* was reported to be the least frequent concern (8%). In additions to these five concerns provided in the survey, some respondents specified other concerns including: narrow field of view and unclear vision when the device is used outside in the daylight.

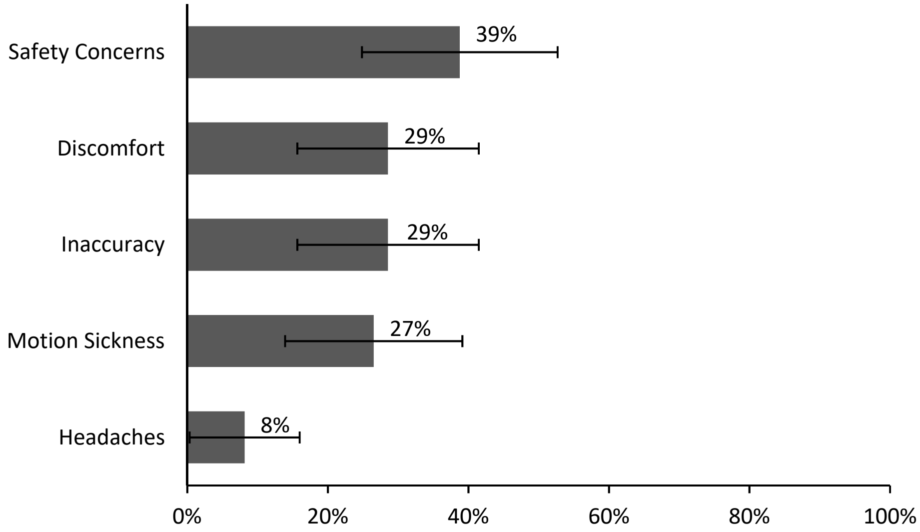


Figure 31 Concerns from the Use of AR Wearables

4.3.4.9. Use of Augmented Reality on Construction Projects

Figure 32 indicates that the majority of respondents believe that AR will be used on Healthcare and Industrial projects and only 25% think that AR will be used in Residential.

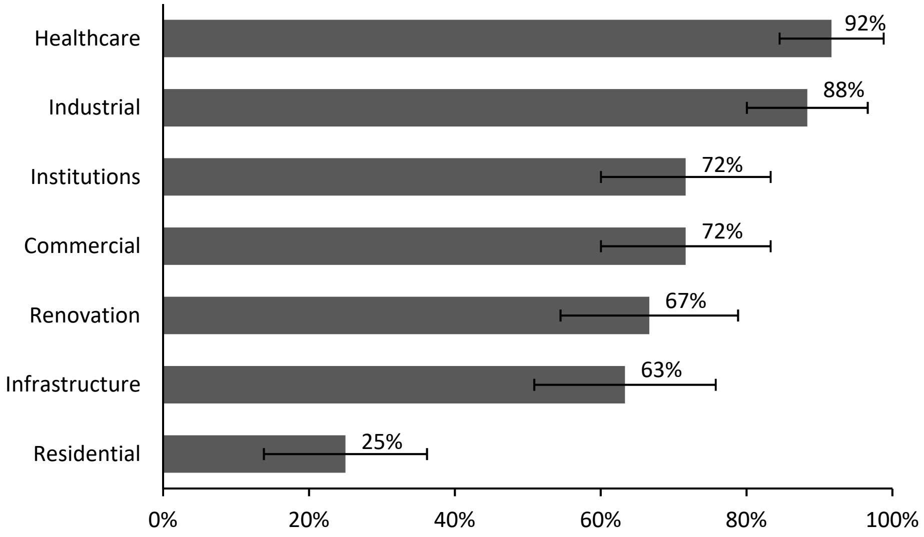


Figure 32 Distribution of Project Types Based on their Potential Use of AR

4.4. Usage Potential of Augmented Reality

The 43 AR use-cases identified form literature and grouped into the seven phases of the life-cycle of a construction project (planning, design, pre-construction planning, construction, commissioning, operation and maintenance, and decommissioning) were included in the survey. Respondents were asked to specify their perceived level of usage of each AR application in the construction industry. Between 2% and 8% of respondents felt that these AR applications will not be used, while the rest believed that the AR use-cases are relevant to the construction industry (shown in Figure 33).

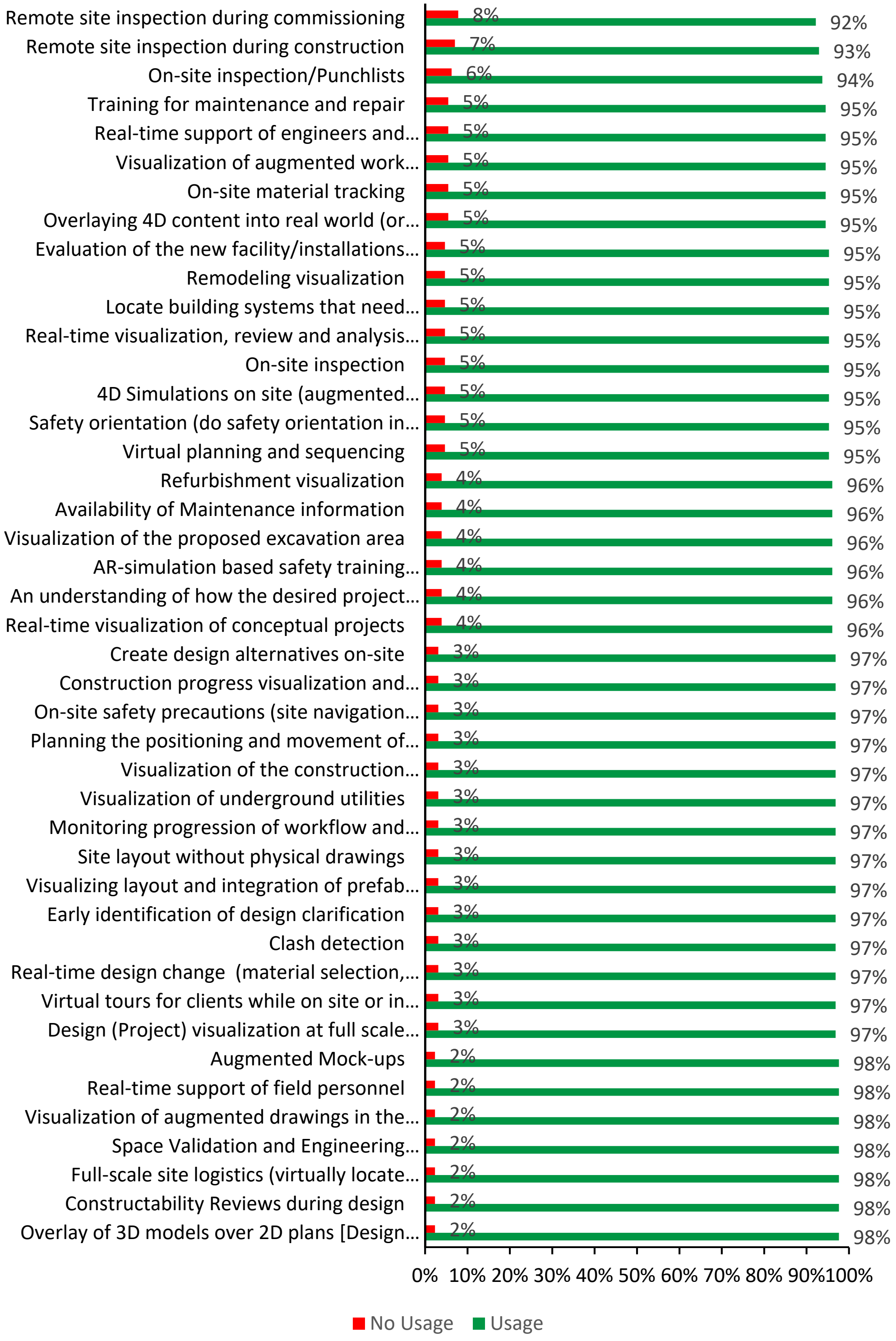


Figure 33 Usage/No Usage Distribution of AR Use-Cases

Respondents who indicated that an AR use-case has potential rated their perceived level of usage of the AR use-case on a scale from 1 (very low) to 5 (very high). However, this variable is subjective by nature and differs among respondents. Performing Kruskal-Wallis and Kendall's Tau b between 1) each AR use-case and respondent's level of familiarity with AR on a professional level and 2) each AR user-case and respondent's level of usage of AR on a professional level resulted in significant p-values. This indicates that a respondent's rating of the perceived level of usage of an AR use-case depends on the respondent's level of familiarity and usage of the technology. Therefore, to reduce the influence of this subjectivity, the perceived possible use of an AR use-case j obtained from the survey is subsequently weighted based on two variables: familiarity with AR and usage of AR in the context of the construction industry. These two variables are combined into one variable, namely the response weight (w_i), which is used to weigh the perceived possible use of an AR application corresponding to respondent i.

The following section introduces the mathematical model developed to adjust the original respondent's perceived level of usage of an AR use-case.

4.4.1. Mathematical Model

The model computes for each AR use-case j a corresponding Usage Potential, UP_j. UP_j is based on the evaluation of the weighted perceived possible use of an AR use-case j corresponding to respondent i collected from the survey.

The Usage Potential of AR of use-case j is defined as:

$$UP_j = \sum_{i=1}^{I} w_i x_{ij} \tag{1}$$

where: I denotes the number of respondents,

X_{ij} denotes the original perceived possible use of an AR use-case j corresponding to respondent i, where $X_{ij} \in \{1, 2, 3, 4, 5\}$. And,

w_i is a response weight assigned to respondent i, with $\sum_{i=1}^{I} w_i = 1$.

w_i is computed based on the following four variables, A_i, B_i, and u_i, where:

A_i is the AR familiarity of respondent i, with $A_i = \{0, 1, 2, 3, 4\}$, and

B_i is the AR usage of respondent i, with $B_i = \{0, 1, 2, 3, 4\}$

It is important to account for the input of each respondent i; therefore, the original values of each of A_i and B_i were first modified by adding 1, and then normalized. As a result, the following variables are defined:

a_i is the adjusted AR familiarity of respondent i, where $a_i = (A_i + 1)/5$, so $a_i \in \{0.2, 0.4, 0.6, 0.8, 1\}$, and

b_i is the adjusted AR usage of respondent i, where $b_i = (B_i + 1)/5$, so $b_i \in \{0.2, 0.4, 0.6, 0.8, 1\}$.

The variables a_i, and b_i are then combined into a new variable, d_i, which represents the "*expertise factor*" of respondent i. d_i is calculated as the geometric mean of a_i and b_i, i.e.

$$d_i = \sqrt{a_i b_i}.$$

As shown in Figure 34 the geometric mean (right) gives a smaller weight to respondents with lower expertise in comparison to the arithmetic mean (left).

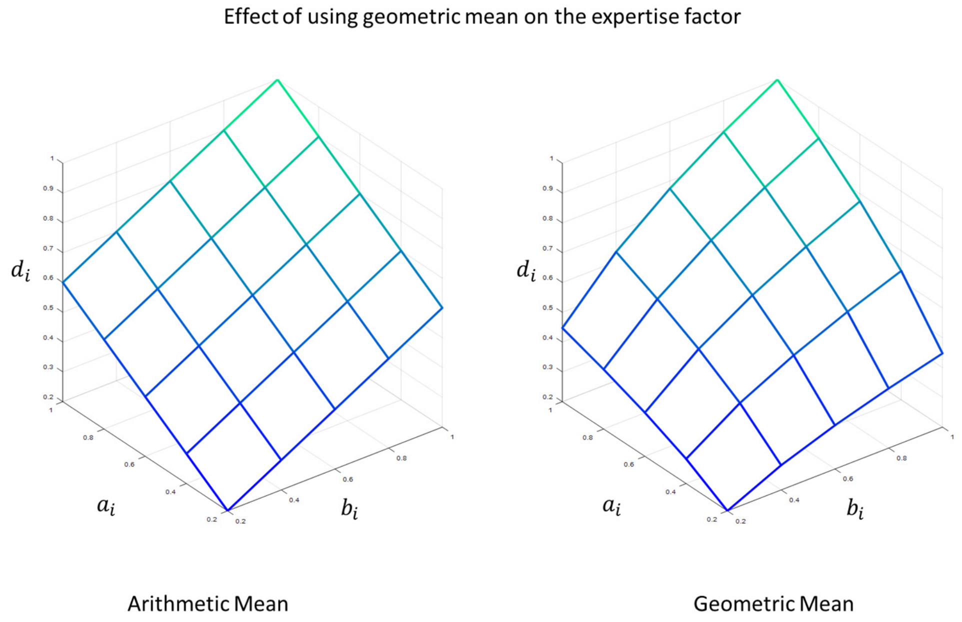


Figure 34 Effect of Using Geometric Mean on the Expertise Factor, d_i, for $a_i = 1$

For each respondent i, w_i is then assumed to be proportional to u_i (their economic impact) and d_i (their expertise factor). Therefore:

$$w_i = \alpha d_i$$

α is then calculated by:

$$1 = \sum_{i=1}^{I} w_i = \alpha \sum_{i=1}^{I} d_i.$$

Thus,

$$\alpha = \frac{1}{\sum_{i=1}^{I} d_i}$$

and,

$$w_i = \frac{d_i}{\sum_{i=1}^{I} d_i} = \frac{\sqrt{a_i b_i.}}{\sum_{i=1}^{I} \sqrt{a_i b_i.}} \qquad (2)$$

Consequently,

$$UP_j = \sum_{i=1}^{I} \frac{\sqrt{a_i b_i}}{\sum_{i=1}^{I} \sqrt{a_i b_i}} X_{ij} \tag{3}$$

Appendix B includes a numerical example explaining the steps used to calculate the UP_j an AR use-case j.

4.4.2. Validation of the Mathematical Model

The objective of the mathematical model is to reduce the subjectivity of the data by adjusting the answers of the respondents based on their level of familiarity and usage of AR in construction. An important question arises as to how to prove that the methodology employed to develop the model is effective. Simulations provide a powerful technique for answering this question (Hallgren 2013). A simulation study was designed to evaluate the mathematical model developed and to compare it to competing approaches, i.e. using arithmetic mean instead of geometric. The objective of the simulation is to prove that the values computed from the model are more representative than the observed, raw data collected from the survey. In other words, the goal is to demonstrate that the proposed model generates a dataset that has a smaller deviation from an assumed *true* dataset than the deviation in the directly observed dataset. Figure 35 – Figure 38 outline the various steps of the simulation and this section provides an overview of the procedure involved in designing and running the simulation.

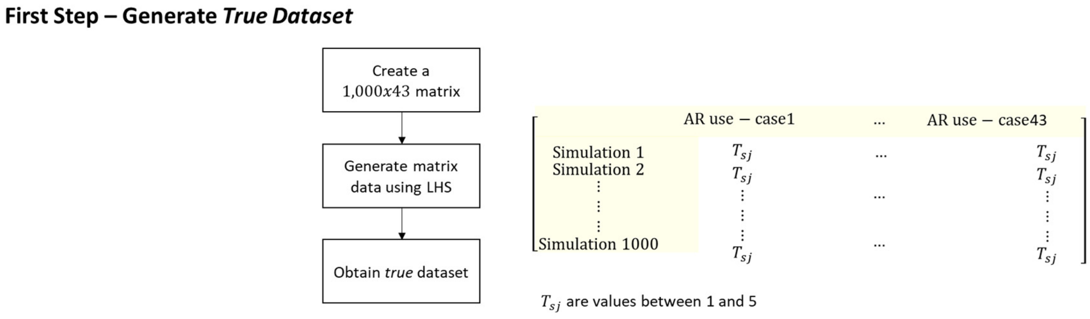


Figure 35 First Step – Generate True Dataset

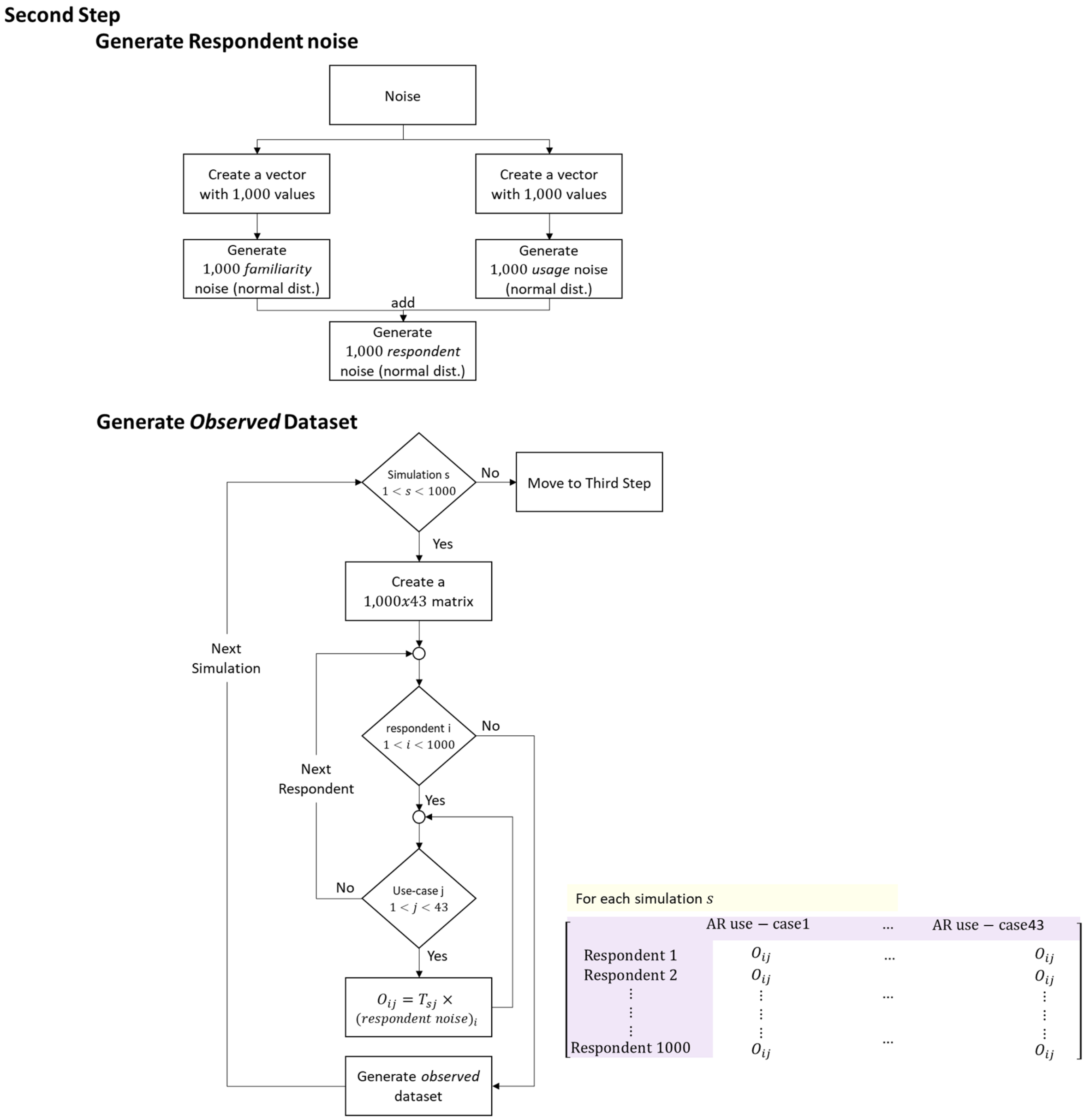


Figure 36 Second Step – Generate Respondent Noise and Observed Dataset

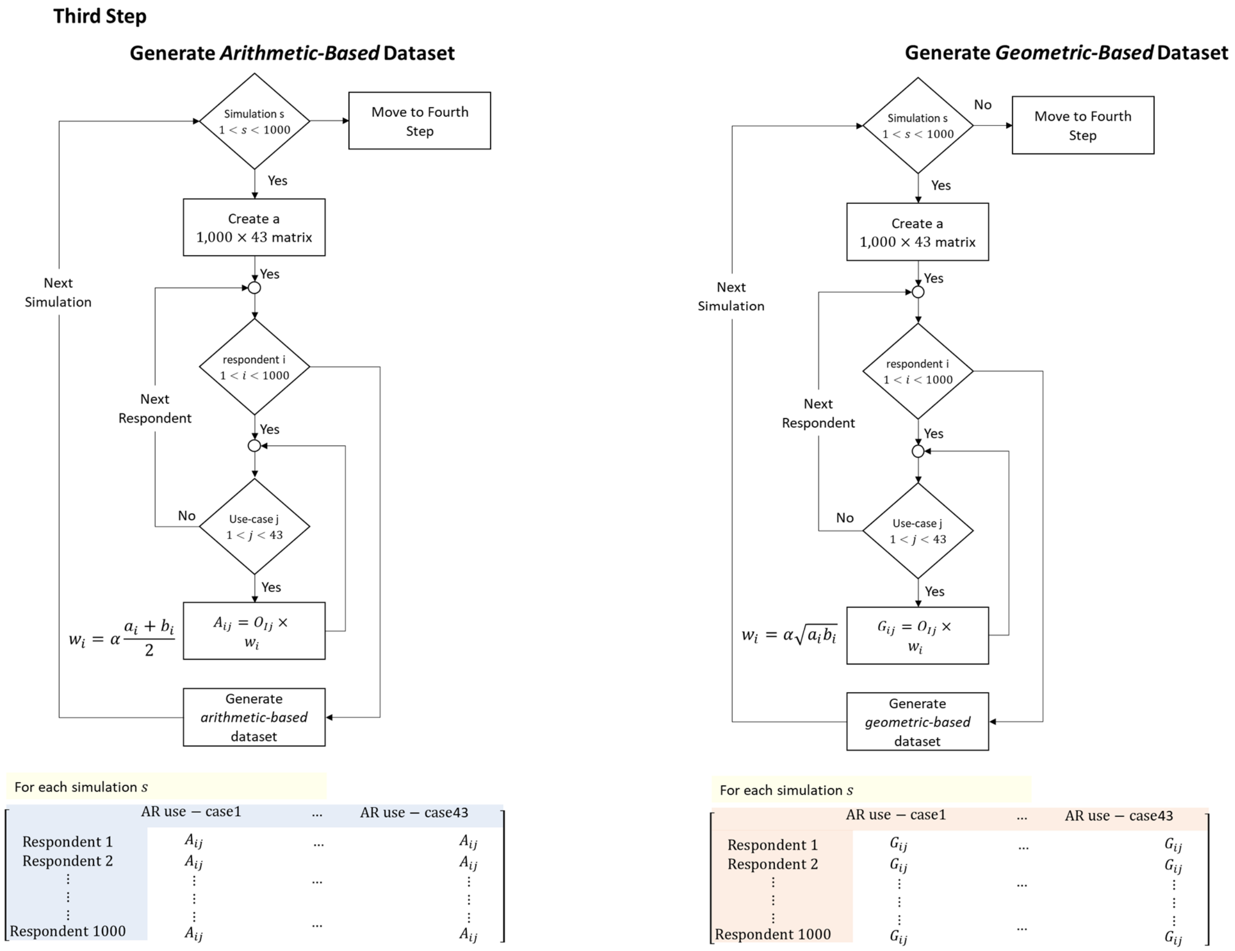


Figure 37 Third Step – Generate Geometric and Arithmetic-Based Datasets

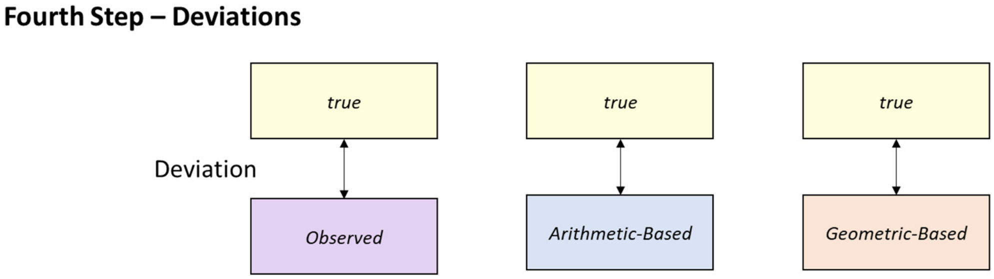


Figure 38 Fourth Step - Deviations

Four datasets are generated in this simulation: the assumed *true* dataset, the *observed* dataset, the *arithmetic-based modeled* dataset, and the *geometric-based modeled* dataset. The *true* dataset represents the expected reference responses and will be used as a datum to evaluate the results of the models. The *observed* dataset is obtained by simulating human responses through the introduction of random noise to the *true* dataset for each response. Furthermore, the two *modeled* datasets are generated by applying the corresponding mathematical weighting model to each response in the *observed* dataset. In addition to the four datasets, two variables are also generated in this study: *familiarity of AR* and *usage of AR*. These two variables are then used to compute the *expertise* factor on which the weights are based. This simulation was run 1,000 times in a Monte Carlo fashion. The steps of the simulation are explained next.

The first step in designing the simulation is generating the *true* dataset which represents the assumed *true* Usage Potential of each AR use-case. This dataset consists of 43 columns in which each column represents an AR use-case. The rows of the true dataset are the 1,000 simulation runs whose values were generated using the Latin-Hypercube Sampling (LHS) experimental design technique using Python, and were set to be between 1 and 5. The values represent the five-point Likert scale used in the survey.

The next step is to compute the *observed* dataset. This dataset is generated to represent of the data of the respondents collected from the survey. For each *true* dataset of the 1,000 simulation runs, an *observed* dataset was created with a sample size of 1,000 representing the number of respondents. In every run, the value of each respondent for a particular use-case was obtained by adding a random noise to the true value of the corresponding column of the use-case. The randomness in the answers of the respondent is assumed to be due to the levels of familiarity of respondent with and usage of AR. Therefore, for a particular respondent, the correspondent *respondent noise* is obtained by adding the noise associated with the familiarity of the respondent and usage of AR. The *familiarity and usage noises* follow a normal distribution between 0 and 0.5 each. Consequently, the *respondent noises* are normally distributed and take values between 0 and

1. The *observed* dataset of each run was then generated by multiplying the *true* values and *respondent noises*.

The observed datasets were then used to generate two other datasets: the first is based on the arithmetic mean (the *arithmetic-based modeled* dataset) and the second is based on the geometric mean (*geometric-based modeled* dataset). The main difference between the two models is the equation used to compute the expertise factor, d_i. For the *arithmetic-based* model, $d_i = \frac{a_i + b_i}{2}$, while for the *geometric-based* model, $d_i = \sqrt{a_i b_i}$, where a_i and b_i are the adjusted AR familiarity and AR usage of respondent i. The values of a_i were computed from the *familiarity noise* and b_i where computed from the *usage noise*. The values of a_i and b_i are inversely proportional to their noises, where higher noises lead to lower level of familiarity and usage, i.e., lower values of a_i and b_i. Based on the 1,000 simulation runs with a sample of 1000 respondents each, the values of the *arithmetic-based modeled* dataset and a *geometric-based modeled* dataset were generated by multiplying the values of each *observed* dataset by the corresponding weight, w_i, with $w_i = \alpha d_i$ and d_i is computed differently for each model.

After generating the two modeled datasets, the Usage Potential of each AR use-case was obtained by summing the 1,000 respondents of each run. As for the *observed* dataset, the values were averaged over all respondents for each AR use-cases, resulting in two-dimensional datasets with 1,000 rows corresponding to the number of runs and 43 columns corresponding to the 43 AR use-cases, with the value in each cell corresponding to the averaged *observed* perceived level of usage. The format of the averaged dataset is similar to the *true* dataset which is also based on 1,000 simulation runs of 43 AR use-cases.

In order to evaluate the effectiveness of each model, the squared deviations between 1) *observed* and *true* values, 2) *arithmetic-based modeled* and *true* values, and 3) *geometric-based* *modeled* and *true* values were calculated. Then for each run the sum of squared deviations was obtained for each of the three cases. Finally, single deviation figure was computed for each case by averaging the squared deviations over all simulation runs.

Since a large number of cases were simulated to reduce the dependency on the randomness, the deviations were normalized. Thus, the averaged squared deviation between:

- *observed* and *true* equals 1
- *arithmetic-based modeled* and *true* equals 0.77
- *geometric-based modeled* and *true* equals 0.64

Paired t-test performed in order to test 1) if the deviation between the *geometric-based model* and *true* is statistically significantly less that the other two deviations. The test resulted in a significant p-values at the 95% confidence level, indicating that the deviation between *geometric-based model* and *true* is statistically smaller than the deviations between *observed* and *true* and between *arithmetic-based modeled* and *true*, indicating the geometric model is closer to the truth.

It is important to mention that models with different coefficients for familiarity and usage were also simulated. The best results were achieved when the two variables had equal coefficient.

4.4.3. Cluster Analysis of AR Use-Cases

A Usage Potential, UP_j, was calculated for each of the 43 AR use-cases. Table 9 presents the UP_j of the AR use-cases, with the use-cases ranked in a descending. Column (1) in the table represents a description of AR use-case j, Column (2) is the phase of a project lifecycle which includes AR use-case j, Column (3) reports the values of UP_j calculated using equation *(3)*.The rightmost column of Table 9 shows which Cluster an AR use-case belongs into. By dividing the data into clusters, an understanding is gained about which cluster(s) or group(s) of AR use-cases have the highest usage potential in the construction industry. Cluster analysis (single value) is a statistical method used to group data by comparing each candidate AR use-case to the other AR use-cases already in the cluster. If the difference between the candidate AR use-case and the other AR use-cases already in the cluster is significant, then the candidate AR use-case is assigned to a different cluster. The cluster analysis was performed, and the 43 AR user-cases were grouped into three clusters based on their Usage Potential: *Cluster 1* includes 20 AR use-cases, *Cluster 2* encompasses 15 AR use-cases, and *Cluster 3* contains the remaining 8 AR use-cases.

The 20 AR use-cases of Cluster 1 are structured as follows:

- 2 Conceptual Planning use-cases, namely *Real-time visualization of conceptual project* (3.85 – #5) and *Understanding of how the desired project connect with its surroundings* (3.83 – #6).

- 4 Design user-cases, namely *Virtual tours for clients while on site or in the office* (4.11 – #1), *Design visualization at full scale on site* (3.91 – #4), *Overlay of 3D models over 2D plans* (3.71 – #10), and *Real-time design change* (3.67 – #15).

- 6 Pre-Construction use-cases, namely *Clash Detection* (3.93 – #3), *Constructability reviews during design* (3.79 – #8), *Virtual planning and sequencing* (3.68 – #12), *Early identification of early design clarification* (3.68 – #13), *Space validation and engineering constraints check* (3.56 – #18), and *Full-scale site logistics* (3.54 – #19).

- 6 Construction use-cases, namely *Visualization of the construction systems* (4.07 – #2), *Augmented mock-ups* (3.81 – #7), *Visualization of underground utilities* (3.79 – #9), *Visualization of augmented drawings in the field* (3.68 – #13), *Construction progress* *visualization and monitoring* (3.60 – #16), and *Visualization of layout and integration of prefab components in the shop* (3.58 – #17).

- 2 Operation and Maintenance use-cases, namely *Locate building systems that need maintenance without disruptive demolition or further survey work* (3.70 – #11) and *Training for maintenance and repair* (3.50 – #20).

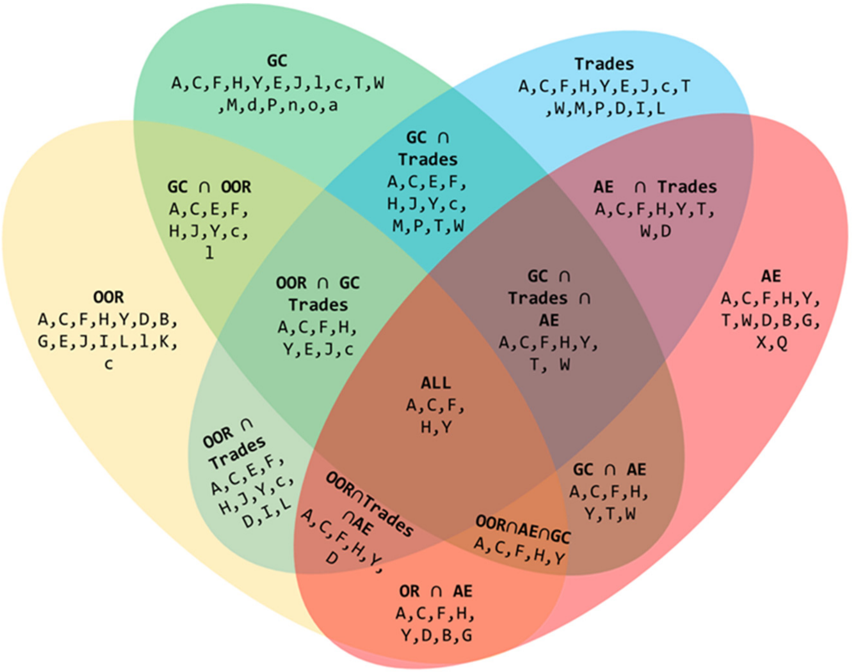
Table 9 Clustered Table of Ranked AR Use-Cases

AR Use-Case Code	AR Use-Case	Phase	Usage Potential	Clusters
D1	Virtual tours for clients while on site or in the office (AR walk-through)	Design	4.11	Cluster 1
Con1	Visualization of the construction systems/work (i.e. MEP, structural, etc.)	Construction	4.07	
PreCon1	Clash detection	Pre-Construction	3.93	
D2	Design (Project) visualization at full scale onsite	Design	3.91	
CP1	Real-time visualization of conceptual projects	Conceptual Planning	3.85	
CP2	An understanding of how the desired project connects with its surroundings	Conceptual Planning	3.83	
Con2	Augmented Mock-ups	Construction	3.81	
PreCon2	Constructability Reviews during design	Pre-Construction	3.79	
Con3	Visualization of underground utilities	Construction	3.79	
D3	Overlay of 3D models over 2D plans	Design	3.71	
O&M1	Locate building systems that need maintenance without destructive demolition or further survey work	Operation & Maintenance	3.70	
PreCon3	Virtual planning and sequencing	Pre-Construction	3.68	
PreCon4	Early identification of design clarification	Pre-Construction	3.68	
Con4	Visualization of augmented drawings in the field	Construction	3.68	
D4	Real-time design change (material selection, design functionalities)	Design	3.67	
Con5	Construction progress visualization and monitoring	Construction	3.60	
Con6	Visualizing layout and integration of prefab components in the shop	Construction	3.58	
PreCon5	Space Validation and Engineering Constraints Checks	Pre-Construction	3.56	
PreCon6	Full-scale site logistics (virtually locate equipment, trailers, laydown areas, storage, etc.)	Pre-Construction	3.54	
O&M2	Training for maintenance and repair	Operation & Maintenance	3.50	
CP3	Overlaying 4D content into real world (or physical objects) such as traffic flow, wind flow, etc.	Conceptual Planning	3.48	Cluster 2
O&M3	Real-time support of engineers and technicians	Operation & Maintenance	3.47	

Con7	Planning the positioning and movement of heavy/irregular objects/equipment	Construction	3.45	
O&M4	Availability of Maintenance information	Operation & Maintenance	3.44	
Con8	Visualization of the proposed excavation area	Construction	3.41	
Decon1	Remodeling visualization	Decommissioning	3.39	
Con9	Site layout without physical drawings	Construction	3.39	
Con10	4D Simulations on site (augmented simulated construction operations)	Construction	3.38	
Con11	Real-time support of field personnel	Construction	3.35	
Decon2	Evaluation of the new facility/installations over the existing one	Decommissioning	3.30	
Con12	Monitoring progression of workflow and sequence	Construction	3.29	
PreCon7	AR-simulation based safety training programs for workers	Pre-Construction	3.24	
Con13	Real-time visualization, review and analysis of data associated with a particular worker, equipment, construction system, etc.	Construction	3.24	
PreCon8	Safety orientation (do safety orientation in an AR environment)	Pre-Construction	3.23	
Con14	Visualization of augmented work instructions/manuals/procedures in the field	Construction	3.23	
Con15	Create design alternatives on-site	Construction	3.20	Cluster 3
Con16	On-site inspection	Construction	3.19	
O&M5	Refurbishment visualization	Operation & Maintenance	3.14	
Con17	On-site safety precautions (site navigation and in-situ safety warning)	Construction	3.11	
Com1	On-site inspection/Punchlists	Commissioning	3.05	
Con18	Remote site inspection	Construction	3.04	
Con19	On-site material tracking	Construction	2.79	
Com2	Remote site inspection	Commissioning	2.78	

4.4.4. Cluster Analysis of AR Use-Cases by Company Type

The Usage Potential of AR was then broken down by company type. It should be noted that since the sample size of Owner's Representative respondent is small (11 respondents) and given that the perspective of an OR is aligned with that of an Owner, the responses from OR were added to those from Owners to form one sample with 31 responses. Figure 39 provides a roadmap for industry practitioners to identify the top AR use-cases that individual from similar company type perceive to have high Usage Potential. The graph also shows interactions and commonalities between different company types. A detailed description of the clustered analysis and usage potential values for each company type can be found in Appendix B.



Key	Description	Key	Description
A	Real-time visualization of conceptual projects	P	Visualizing layout and integration of prefab components in the shop
B	Overlaying 4D content into real world (or physical objects) such as traffic flow, wind flow, etc.	Q	Site layout without physical drawings
C	An understanding of how the desired project connects with its surroundings	T	Visualization of augmented drawings in the field
D	Overlay of 3D models over 2D plans	W	Visualization of underground utilities
E	Design (Project) visualization at full scale onsite	X	Visualization of the proposed excavation area
F	Virtual tours for clients while on site or in the office (AR walk-through)	Y	Visualization of the construction systems/work (i.e. MEP, structural, etc.)
G	Real-time design change (material selection, design functionalities)	a	Real-time support of field personnel
H	Clash detection	c	Augmented Mock-ups
I	Early identification of design clarification	d	Construction progress visualization and monitoring
J	Constructability Reviews during design	l	Locate building systems that need maintenance without destructive demolition or further survey work
K	Full-scale site logistics (virtually locate equipment, trailers, laydown areas, storage, etc.)	n	Real-time support of engineers and technicians
L	Space Validation and Engineering Constraints Checks	o	Training for maintenance and repair
M	Virtual planning and sequencing		

Figure 39 AR Use-Cases Flower Diagram – Analysis by Company Type

4.5. Benefit Potential of Augmented Reality

The 16 AR benefits identified form literature were also included in the survey. Respondents were asked to specify their perceived level of impact of each AR benefit on the construction industry. Between 2% and 4% of respondents felt that these AR benefits do not exist, while the rest believed that the AR will have an impact on the construction industry in terms of the benefits reported in the survey (Figure 40).

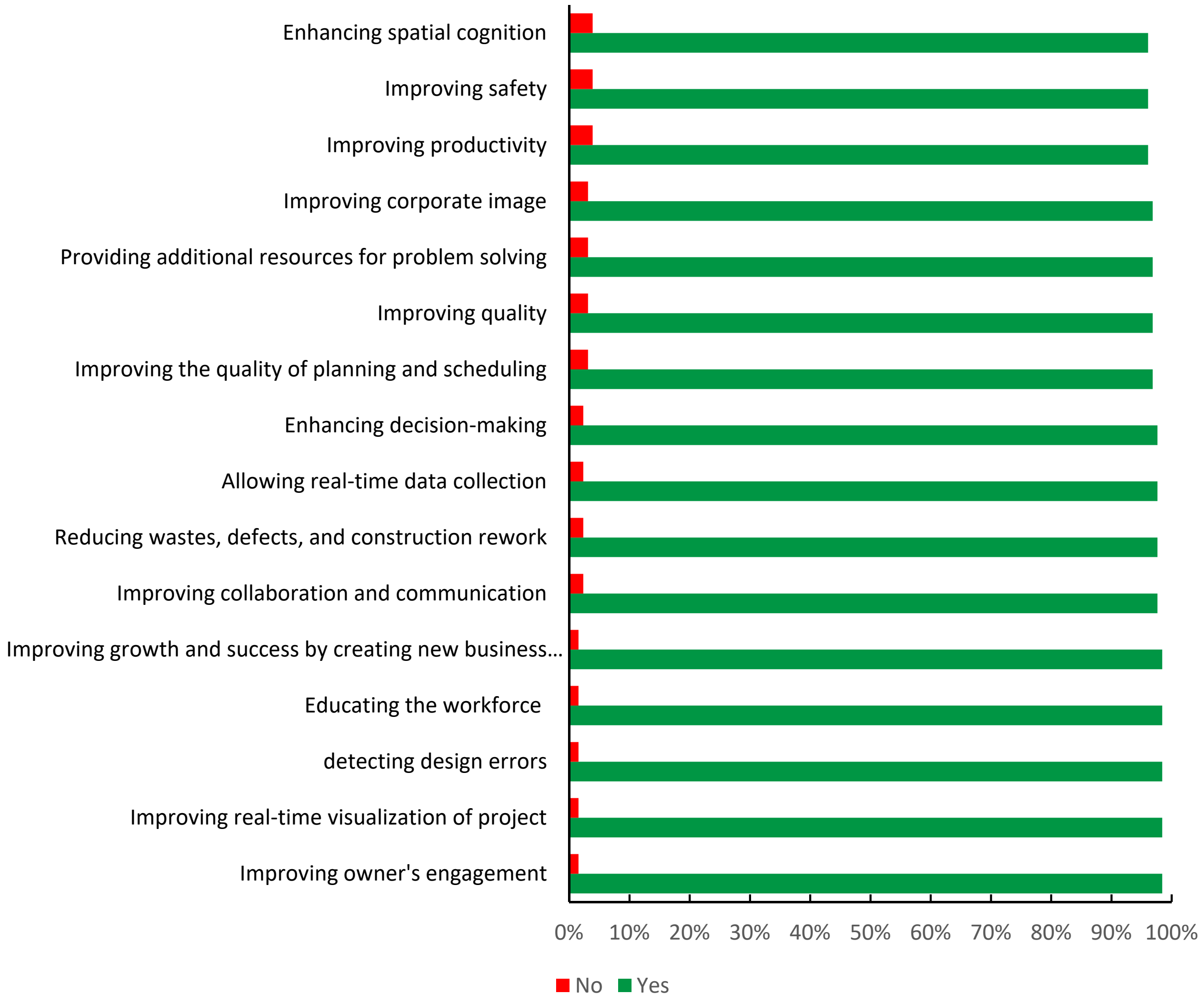


Figure 40 Yes/No Distribution of AR benefits

Respondents who reported the existence of potential benefits to the implementation of AR also rated their perceived level of impact of the identified AR benefits on a scale from 1 (very low) to 5 (very high). Similar to the analysis of the respondent's perceived level of an AR use-case and respondent's perceived level of impact of an AR obstacle, performing Kruskal-Wallis and Kendall's Tau b between 1) each potential benefit and respondent's level of familiarity with AR on a professional level and 2) each potential benefit and respondent's level of usage of AR on a professional level resulted in significant p-values, indicating that a respondent's rating of the perceived level of impact of an AR benefit depends on the respondent's level of familiarity and usage of the technology. Therefore, to reduce the influence of this subjectivity, the perceived potential impact of an AR benefit k obtained from the survey is subsequently weighted based on two variables: familiarity with AR and usage of AR in the context of the construction industry. A mathematical model similar to the Usage Potential and Obstacle Potential models was developed for the AR benefits, and is presented in the following section.

4.5.1. Mathematical Model

The model computes for each AR benefit k a corresponding Benefit Potential, BP_k. BP_k is based on the evaluation of the weighted perceived possible impact of an AR benefit k corresponding to respondent i collected from the survey.

The Benefit Potential of an AR benefit k is defined as:

$$BP_k = \sum_{i=1}^{I} w_i Z_{ik} \qquad (4)$$

where: I denotes the number of respondents,

Z_{ik} denotes the original perceived impact of a benefit k corresponding to respondent i, where $Z_{ik} \in \{1, 2, 3, 4, 5\}$. And

w_i is a response weight assigned to respondent i, with $\sum_{i=1}^{I} w_i = 1$. These weights are the same as those used in equation *(2)*.

Consequently,

$$BP_b = \sum_{i=1}^{I} \frac{\sqrt{a_i b_i}}{\sum_{i=1}^{I} \sqrt{a_i b_i}} Z_{ib} \tag{5}$$

4.5.2. Cluster Analysis of AR Benefits

A Benefit Potential, BP_b, was calculated for each of the 16 AR benefits. Table 10 presents the BP_b of the AR benefits, with the obstacles ranked in a descending. Column (1) in the table represents a description of benefit b, Column (2) reports the values of BP_b calculated using equation *(5)*. The rightmost column of Table 10 shows which Cluster an AR benefit belongs into. By dividing the data into clusters, an understanding is gained about which cluster(s) or group(s) of AR benefits have the highest impact on the construction industry.

The cluster analysis grouped the 16 AR benefits into three clusters based on their Benefit Potential: *Cluster 1* includes 4 AR benefits, *Cluster 2* encompasses 8 AR benefits, and *Cluster 3* contains the remaining 4 AR benefits.

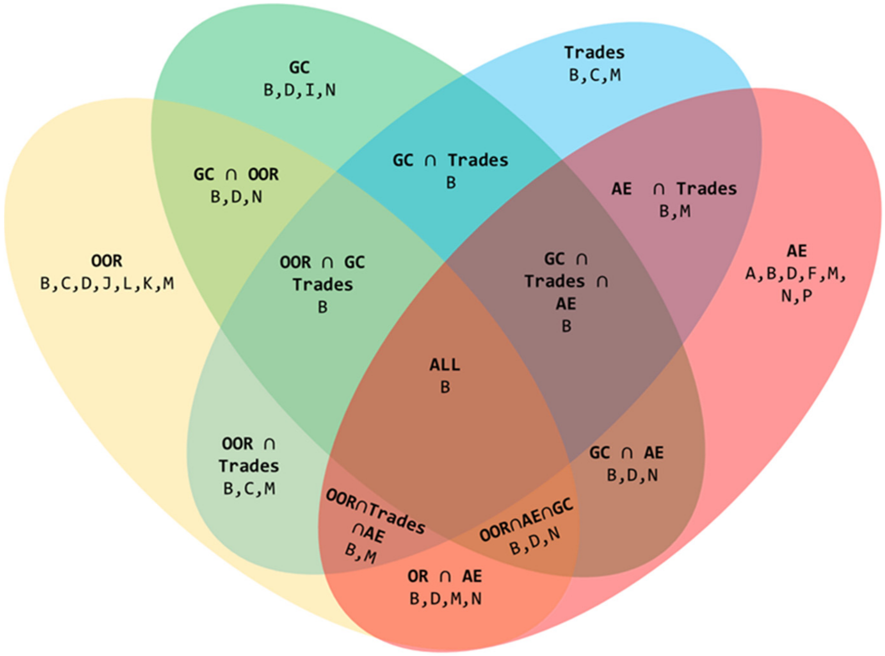
The 4 AR benefits of Cluster 1 have one average a high potential impact on construction and are as follows: Improving real-time visualization of project (4.20), Enhancing decision-making (4.01), Improving collaboration and communication (3.98), and Enhancing spatial cognition (3.96)

Table 10 Clustered Table of Ranked AR Benefits

AR Benefit Code	Title	Benefit Potential	Clusters
B1	Improving real-time visualization of project	4.20	1
B2	Enhancing decision-making	4.01	
B3	Improving collaboration and communication	3.98	
B4	Enhancing spatial cognition	3.96	
B5	Detecting design errors	3.85	2
B6	Providing additional resources for problem solving	3.84	
B7	Improving quality	3.79	
B8	Educating the workforce (improve their understanding of the project)	3.78	
B9	Improving owner's engagement	3.74	
B10	Reducing wastes, defects, and construction rework	3.74	
B11	Improving corporate image	3.70	
B12	Improving productivity	3.65	
B13	Improving the quality of planning and scheduling	3.55	3
B14	Allowing real-time data collection	3.50	
B15	Improving growth and success by creating new business models	3.39	
B16	Improving safety	3.29	

4.5.3. Cluster Analysis of AR Benefits by Company Type

The Benefit Potential of AR was then broken down by company type. Figure 41 provides a roadmap for industry practitioners to identify the top AR benefits that individual from similar company type perceive to have high impact. The graph also shows interactions and commonalities between different company types. A detailed description of the clustered analysis and benefit potential values for each company type can be found in Appendix C



Key	Description
A	Improving owner's engagement
B	Improving real-time visualization of project
C	detecting design errors
D	Improving collaboration and communication
E	Reducing wastes, defects, and construction rework
F	Improving the quality of planning and scheduling
G	Improving productivity
I	Improving quality
J	Educating the workforce (improve their understanding of the project)
L	Providing additional resources for problem solving
M	Enhancing spatial cognition
N	Enhancing decision-making
P	Improving corporate image

Figure 41 AR Potential Benefits Flower Diagram – Analysis by Company Type

4.6. Obstacle Potential of Augmented Reality

The 22 obstacles for implementing AR in the construction industry identified form literature and grouped into five categories (financial, human, organizational, technological, and others) were included in the survey. Respondents were asked to rate the level of impact of each obstacle. Between 1% and 6% of respondents reported that the obstacles don’t have an impact whereas the rest indicated that these obstacles have an impact on the implementation of AR in the construction industry (Figure 42).

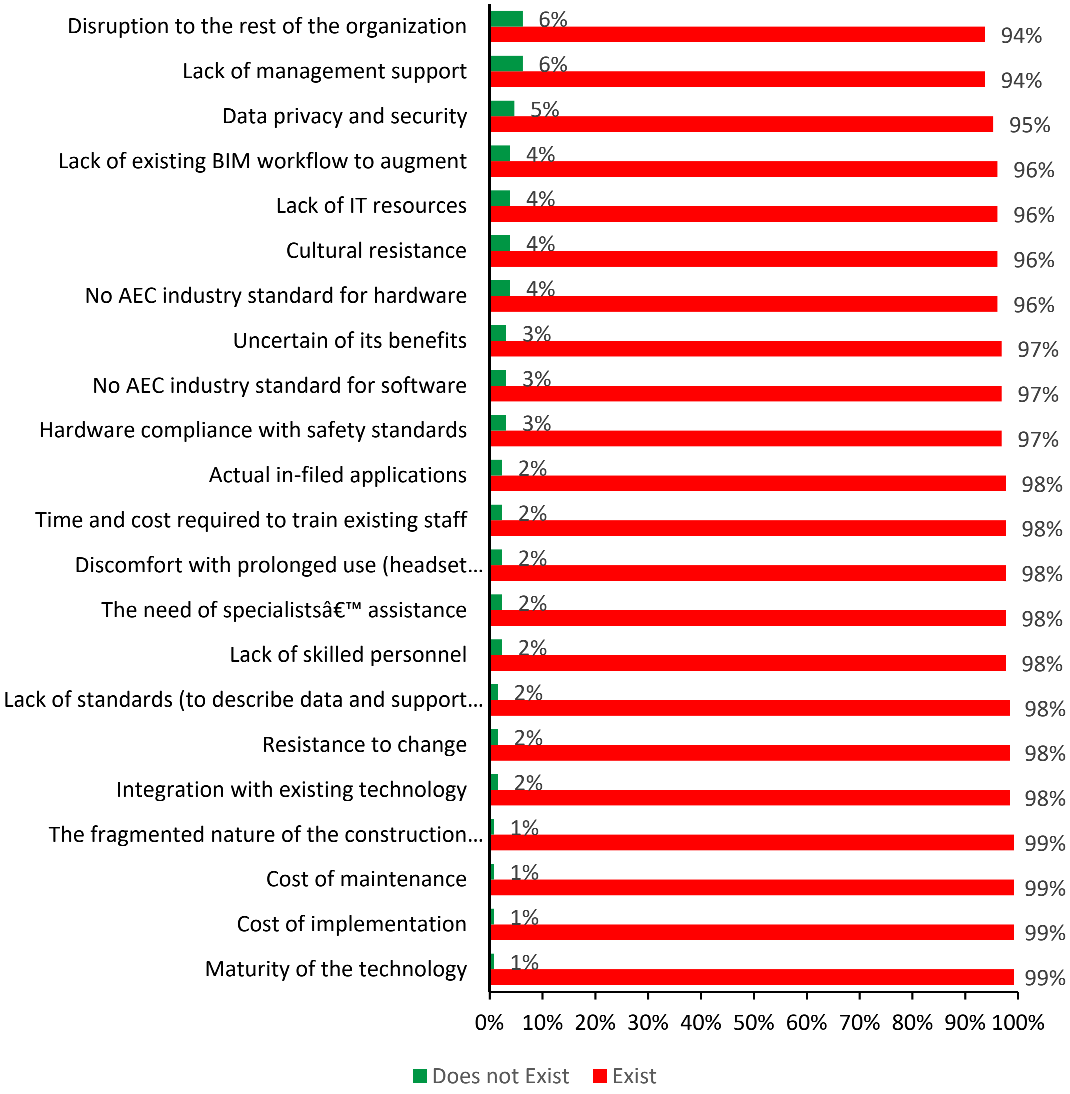


Figure 42 Exist/Does Not Exist Distribution of AR Obstacles

Respondents who indicated the existence of obstacles also rated their perceived level of impact of each AR obstacle on a scale from 1 (very low) to 5 (very high). Similar to the analysis of the respondent’s perceived level of usage of an AR use-case, performing Kruskal-Wallis and Kendall’s Tau b between 1) each obstacle and respondent’s level of familiarity with AR on a professional level and 2) each obstacle and respondent's level of usage of AR on a professional level resulted in significant p-values, indicating that a respondent's rating of the perceived level of impact of an AR obstacle depends on the respondent's level of familiarity and usage of the technology. Therefore, to reduce the influence of this subjectivity, the perceived potential impact of an AR obstacle b obtained from the survey is subsequently weighted based on two variables: familiarity with AR and usage of AR in the context of the construction industry. A mathematical model similar to the Usage Potential and Benefit Potential models was developed for the AR obstacles, and is presented in the following section.

4.6.1. Mathematical Model

The model computes for each AR obstacle l a corresponding Obstacle Potential, OP_l. OP_l is based on the evaluation of the weighted perceived possible impact of an AR obstacle l corresponding to respondent i collected from the survey.

The Obstacle Potential of an AR obstacle l is defined as:

$$OP_l = \sum_{i=1}^{I} w_i Y_{il} \qquad (6)$$

where: I denotes the number of respondents,

Y_{il} denotes the original perceived impact of an obstacle l corresponding to respondent i, where $Y_{il} \in \{1, 2, 3, 4, 5\}$. And,

w_i is a response weight assigned to respondent i, with $\sum_{i=1}^{I} w_i = 1$. These weights are the same as those used in UP_j and BP_k, see equation *(2)*.

Consequently,

$$OP_l = \sum_{i=1}^{I} \frac{\sqrt{a_i b_i}}{\sum_{i=1}^{I} \sqrt{a_i b_i}} Y_{il} \tag{7}$$

4.6.2. Cluster Analysis of AR Obstacles

An Obstacle Potential, OP_l, was calculated for each of the 22 AR obstacles. Table 11 presents the OP_l of the AR obstacles, with the obstacles ranked in a descending. Column (1) in the table represents a description of obstacle l, Column (2) is the category to which AR obstacle l belongs, Column (3) reports the values of OP_l calculated using equation (7). The rightmost column of Table 11 shows which Cluster an AR obstacle belongs into. By dividing the data into clusters, an understanding is gained about which cluster(s) or group(s) of AR obstacles have the highest impact on the implementation of the technology in the construction industry.

The cluster analysis grouped the 22 AR obstacles into three clusters based on their Obstacle Potential: *Cluster 1* includes 10 AR obstacles, *Cluster 2* encompasses 0 AR obstacles, and *Cluster 3* contains the remaining 3 AR obstacles.

The 10 AR obstacles of Cluster 1 are structured as follows:

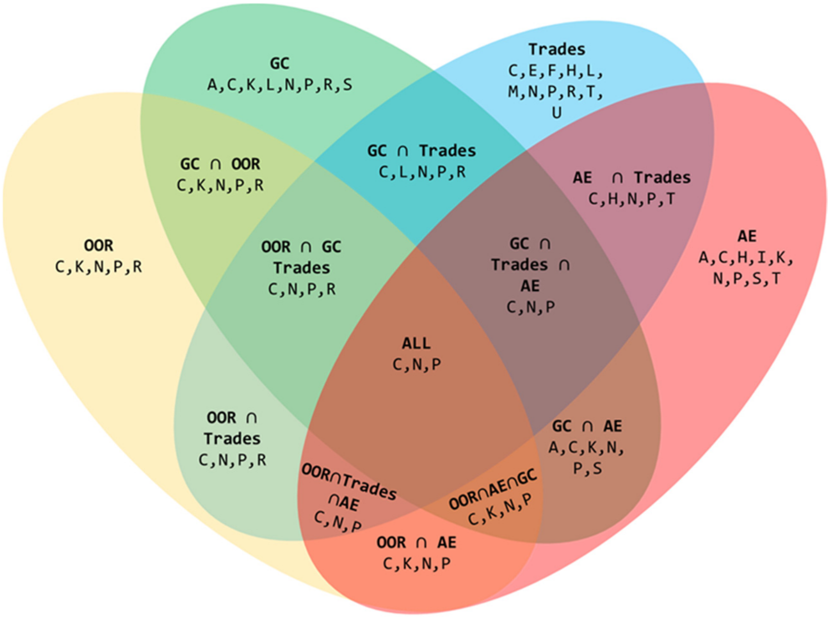
- 3 Financial obstacles, namely *Cost of* implementation (3.63 – #3), *Time and cost required to train existing staff* (3.53 – #4), and *Actual in-field applications* (3.47 – #7).
- 4 Human obstacles, namely *Lack of skilled personnel* (3.64 – #2), *The need for specialists' assistance* (3.53 – #5), *Lack of IT resources* (3.47 – #6), and *Resistance to change* (3.39 – #9)
- 2 Technological obstacles, namely *Maturity of the technology* (3.78 – #1) and *Integration with existing technology* (3.38 – #10)

Table 11 Clustered Table of Ranked AR Obstacles

AR Obstacle Code	Title	Category	Obstacle Potential	Clusters
T1	Maturity of the technology	Technological	3.78	1
H1	Lack of skilled personnel	Human	3.64	
F1	Cost of implementation	Financial	3.63	
F2	Time and cost required to train existing staff	Financial	3.53	
H2	The need of specialists' assistance	Human	3.53	
H3	Lack of IT resources	Human	3.47	
F3	Unawareness/Unsureness of actual in-field applications	Financial	3.47	
Ot1	The fragmented nature of the construction industry	Others	3.40	
H4	Resistance to change	Human	3.39	
T2	Integration with existing technology	Technological	3.38	
O1	Uncertain of its benefits	Organizational	3.33	2
T3	No AEC industry standard for software	Technological	3.30	
O2	Cultural resistance	Organizational	3.28	
Ot2	Lack of standards (to describe data and support interaction and collaboration)	Others	3.26	
Ot3	Lack of existing BIM workflow to augment	Others	3.20	
O3	Lack of management support	Organizational	3.20	
T4	No AEC industry standard for hardware	Technological	3.16	
F4	Cost of maintenance	Financial	3.13	
H5	Discomfort with prolonged use (headset tightness, dizziness, etc)	Human	3.08	
T5	Hardware compliance with safety standards	Technological	2.92	3
T6	Data privacy and security	Technological	2.91	
O4	Disruption to the rest of the organization	Organizational	2.77	

4.6.3. Cluster Analysis of AR Obstacles by Company Type

The Obstacle Potential of AR was then broken down by company type. Figure 43 provides a roadmap for industry practitioners to identify the top AR obstacles that individual from similar company type perceive to have high impact. The graph also shows interactions and commonalities between different company types. A detailed description of the clustered analysis and benefit potential values for each company type can be found in Appendix D.



Key	Description
A	Integration with existing technology
C	Maturity of the technology
E	No AEC industry standard for hardware
F	No AEC industry standard for software
H	Uncertain of its benefits
I	Cultural resistance
K	Lack of skilled personnel
L	Lack of IT resources
M	Resistance to change
N	The need of specialist's assistance
P	Cost of implementation
R	Time and cost required to train existing staff
S	Actual in-filed applications
T	The fragmented nature of the construction industry
U	Lack of standards (to describe data and support interaction and collaboration)

Figure 43 AR Obstacles Flower Diagram – Analysis by Company Type

4.7. Stakeholder Potential

Respondents were provided with a list of 10 stakeholders in the construction industry and were asked to identify the perceived level of usage of AR of each stakeholder. Between 3% and 12% of the respondent believe that the identified stakeholders will not use AR, and the rest identified that these stakeholders will use AR, as indicated in Figure 44.

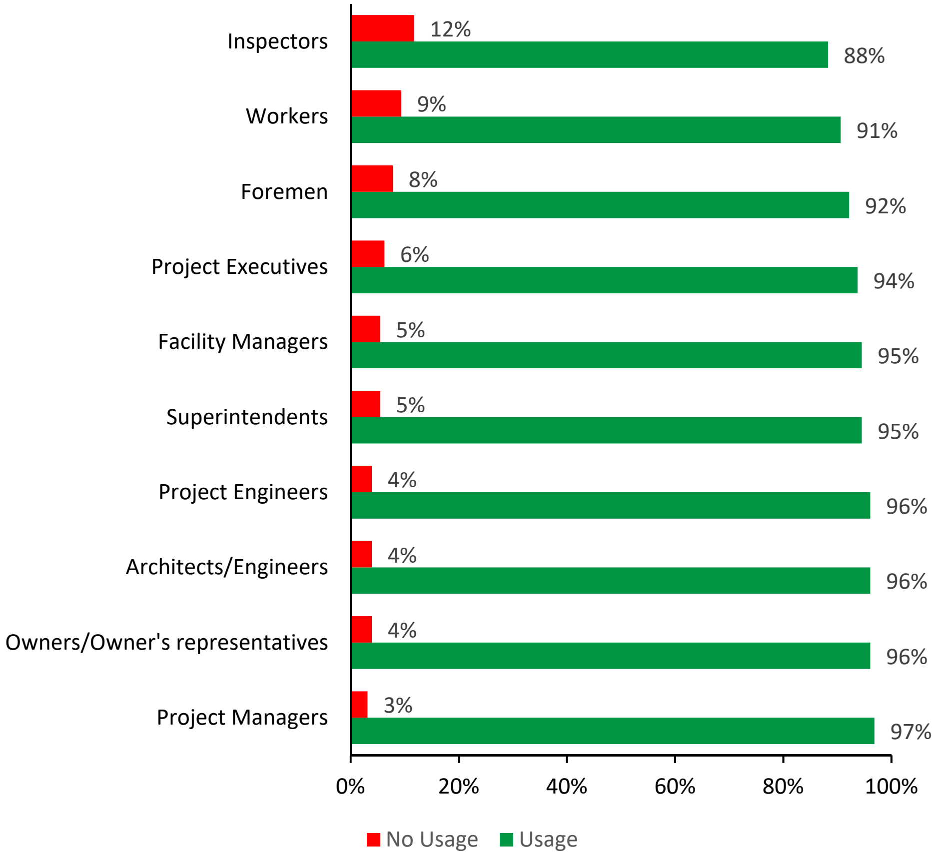


Figure 44 Usage/No Usage Distribution of AR by the Different Users

Respondents who indicated the usage of AR by a stakeholder also rated their perceived level of usage of AR of each stakeholder on from 1 (very low) to 5 (very high). Performing Kruskal-Wallis and Kendall’s Tau b between 1) each stakeholder and respondent’s level of familiarity with AR on a professional level and 2) each stakeholder and respondent’s level of usage of AR on a professional level resulted in significant p-values, indicating that a respondent's rating of the perceived level of usage of AR of each stakeholder depends on the respondent's level of familiarity and usage of the technology. Therefore, to reduce the influence of this subjectivity, the perceived level of usage of AR of each stakeholder s obtained from the survey is subsequently weighted based on two variables: familiarity with AR and usage of AR in the context of the construction industry. A mathematical model was developed for the stakeholders and is presented in the following section.

4.7.1. Mathematical Model

The model computes for each stakeholder s a corresponding Stakeholder Potential, SP_s. SP_s is based on the evaluation of the weighted perceived level of usage of AR of each stakeholder s corresponding to respondent i collected from the survey.

The Stakeholder Potential of a stakeholder s is defined as:

$$SP_s = \sum_{i=1}^{I} w_i Q_{is} \qquad (8)$$

where: I denotes the number of respondents,

Q_{is} denotes the original perceived impact of an obstacle l corresponding to respondent i, where $Q_{is} \in \{1, 2, 3, 4, 5\}$. And,

w_i is a response weight assigned to respondent i, with $\sum_{i=1}^{I} w_i = 1$. These weights are the same as those in equation *(2)*.

Consequently,

$$SP_s = \sum_{i=1}^{I} \frac{\sqrt{a_i b_i}}{\sum_{i=1}^{I} \sqrt{a_i b_i}} Q_{is} \tag{9}$$

4.7.2. Cluster Analysis of AR Obstacles

A Stakeholder Potential, SP_s, was calculated for each of the 10 stakeholders. Table 12 presents the SP_s of the 10 stakeholders, with the stakeholders ranked in a descending. Column (1) in the table lists the stakeholders, Column (2) reports the values of SP_s calculated using (9). The rightmost column of Table 12 shows which Cluster a stakeholder belongs into. By dividing the data into clusters, an understanding is gained about which cluster(s) or group(s) of stakeholders have the highest potential to use AR in the construction industry.

The cluster analysis grouped the 10 stakeholders into three clusters based on their Stakeholder Potential: *Cluster 1* includes 2 stakeholders, *Cluster 2* encompasses 5 stakeholders, and *Cluster 3* contains the remaining 3 stakeholders.

Among the 10 stakeholders, *Architects/Engineers* (4.08) and *Project Engineers* (3.71) are found to have the highest potential to use AR in construction. On the other hand, *Inspectors* (2.87), *Workers* (2.76), and *Project Executives* (2.60) are perceived the have the lowest potential to use AR.

Table 12 Clustered Table of AR Stakeholder Potential

Stakeholder	Stakeholder Potential	Cluster
Architects/Engineers	4.08	1
Project Engineers	3.71	
Superintendents	3.39	2
Project Managers	3.25	
Facility Managers	3.24	
Owners/Owner's representatives	3.18	
Foremen	3.08	
Inspectors	2.87	3
Workers	2.76	

Project Executives	2.60	

4.8. Phase Potential

Respondents were provided with seven phases of a construction project lifecycle and were asked to identify the perceived level of usage of AR in each of the phases. Between 3% and 12% of the respondents reported that they don't think AR will be used in any of the seven phases of a construction project and the rest indicated that AR will be used (as shown in Figure 45).

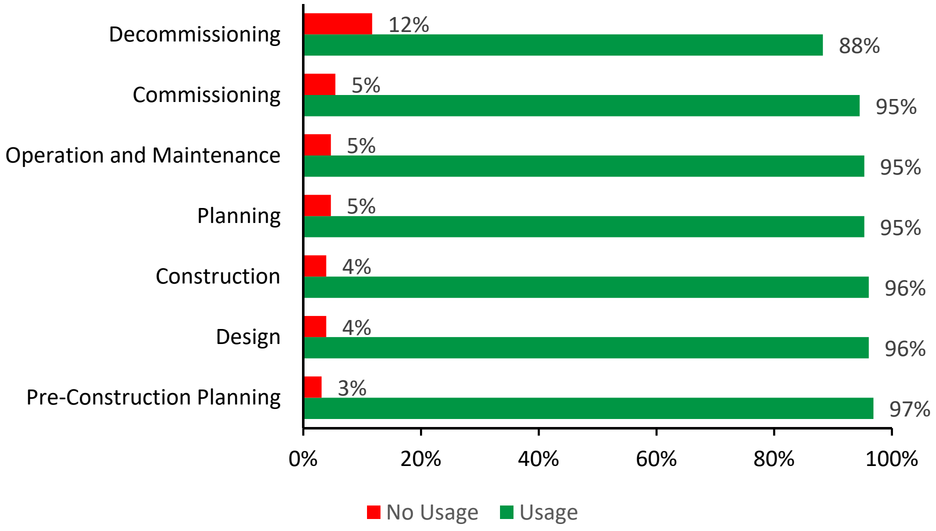


Figure 45 Usage/No Usage Distribution of AR in the Seven Project Phases

Respondents who identified the potential use of AR in a phase where asked to rate perceived level of usage of AR in each phase on a scale from 1 (very low) to 5 (very high). performing Kruskal-Wallis and Kendall's Tau b between 1) each phase and respondent's level of familiarity with AR on a professional level and 2) each phase and respondent's level of usage of AR on a professional level resulted in significant p-values, indicating that a respondent's rating of the perceived level of usage of AR in a phase depends on the respondent's level of familiarity and usage of the technology. Therefore, to reduce the influence of this subjectivity, the perceived level of usage of a phase p obtained from the survey issubsequently weighted based on two variables: familiarity with AR and usage of AR in the context of the construction industry. A was developed for the phases and is presented in the following section.

4.8.1. Mathematical Model

The model computes for each phase h a corresponding Phase Potential, PP_h. PP_h is based on the evaluation of the weighted perceived possible usage of AR in phase h corresponding to respondent i collected from the survey.

The Phase Potential of project phase h is defined as:

$$PP_h = \sum_{i=1}^{I} w_i T_{ih} \tag{10}$$

where: I denotes the number of respondents,

T_{ih} denotes the original perceived possible usage of AR in a phase h corresponding to respondent i, where $T_{ih} \in \{1, 2, 3, 4, 5\}$. And,

w_i is a response weight assigned to respondent i, with $\sum_{i=1}^{I} w_i = 1$ (see equation *(2)*).

Consequently,

$$PP_h = \sum_{i=1}^{I} \frac{\sqrt{a_i b_i}}{\sum_{i=1}^{I} \sqrt{a_i b_i}} T_{ih} \tag{11}$$

4.8.2. Cluster Analysis

A Phase Potential, PP_h, was calculated for each of the seven phases. Table 13 outlines the PP_hvalues of the phases, with the phases ranked in a descending order. Column (1) in the table lists the phases, Column (2) reports the values of PP_h calculated using equation (11). The rightmost column of Table 13 shows which Cluster a stakeholder belongs into. By dividing the data into clusters, an understanding is gained about which cluster(s) or group(s) of stakeholders have the highest potential to use AR in the construction industry.

The cluster analysis grouped the seven phases into two clusters based on their Phase Potential: *Cluster 1* includes 4 phases (design, pre-construction planning, construction, and conceptual planning), and *Cluster 2* contains the remaining 3 phases (operation and maintenance, commissioning, and decommissioning).

Table 13 Clustered Table of Phase Potential

Phase	Phase Potential	Cluster
Design	4.04	1
Pre-Construction Planning	4.03	
Construction	3.90	
Conceptual Planning	3.66	
Operation and Maintenance	2.98	2
Commissioning	2.95	
Decommissioning	2.44	

4.9. Augmented Reality Statements

Respondents were provided with 8 statements and were asked to rate their level of agreement/disagreement on a scale from 1 (strongly disagree) to 5 (Strongly agree). Respondents' answers were also adjusted using the following Level of Agreement (LoA) model:

$$LoA_m = \sum_{i=1}^{I} w_i S_{im}$$

where: I denotes the number of respondents,

S_{im} denotes the original level of agreement of a statement m corresponding to respondent i, where $S_{im} \in \{1, 2, 3, 4, 5\}$. And

w_i is a response weight assigned to respondent i, with $\sum_{i=1}^{I} w_i = 1$. These weights are the same as those used in the previous models.

The results are reported in Table 14. On average, respondents agree that AR has the potential to transform the construction industry, become commonly used though head mounted displays, build upon existing practices, be used on large projects, and be more demanded by clients. Respondents also agree that the construction industry should adopt AR into its current practices and workflow. On the other hand, respondents were undecided regarding the statements that the industry is not yet clear on the suitable applications of AR and that AR is a disruptive technology.

Table 14 Level of Agreement on AR Statements

Statement	**Level of Agreement**
AR has the potential to be a transformative technology to the industry	4.38
AR will become more commonplace in the construction industry with the continued development of Head Mounted Displays such as HoloLens, DAQRI, Google glass, etc.	4.17
AR will build upon lean practices and will reduce wastes in the construction industry	4.02
The construction industry should adopt AR into its current practices and workflow	3.99
In the future, clients will demand AR be used on projects	3.87
AR will be used on large projects more than small projects	3.80
The construction industry is not yet clear on the suitable applications of AR	3.48
Augmented Reality (in the context of the construction industry) is a disruptive technology	3.15

4.10. Timeline for the Adoption of Augmented Reality

4.10.1. Augmented Reality Adoption in Company vs Industry

Respondents were asked to identify the timeline of the common use of AR within their company and the construction industry as well. The timeline was evaluated on an ordinal five-point scale from: *[0-5 years]* coded as 1, *[5-10 years]* coded as 2, *[10-15 years]* coded as 3, *[More than 15 years]* coded as 4, and *[Never]* coded as 5. It can be concluded from Figure 46 that employees believe that the industry is slower to adopt AR while their organization is ahead of the curve than the construction industry as a whole.

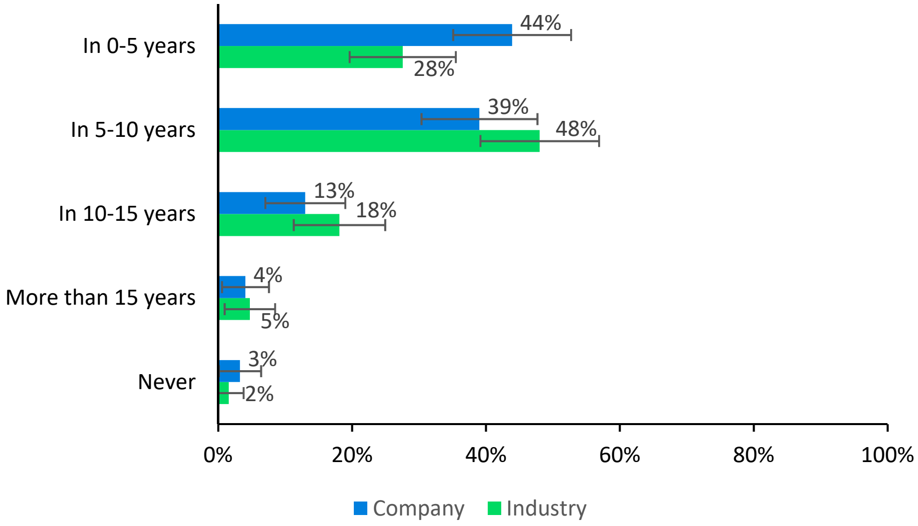


Figure 46 Timeline for Using AR at the Company-Level and Industry-Level

The Mann-Whitney-Wilcoxon (MWW) test was conducted to statistically verify the difference in the AR adoption timeline at the company and industry levels. The low p-values resulted from of MWW test (0.037) provides a statistical evidence at the 95% confidence level indicating that, on average, construction companies are ahead of the curve than the construction industry as a whole.

4.10.2. Augmented Reality Adoption in Company vs Industry: Per Company Type

The timeline of the common use of AR within construction companies was compared across the five types of companies. Figure 47 shows that employees who work for GC/CM believe, on average, a faster rate of usage of AR in their companies than those who work for A/E, OR, Owners, or MEP Trades.

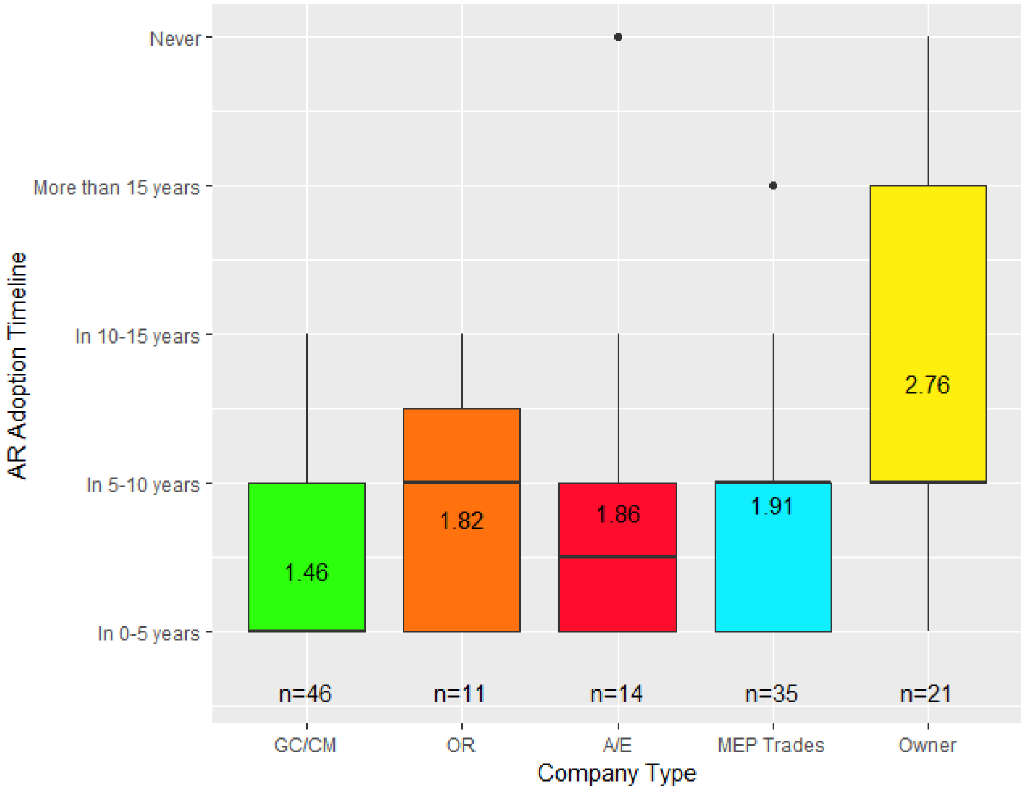


Figure 47 AR Adoption Timeline in Organizations Across Types of Companies

The difference in the level of usage of AR among the different types of occupation was statistically tested first using Kruskal-Wallis followed then by Conover-Iman test, as shown in Table 15. The Kruskal-Wallis test resulted in a significant p-value of 0.00023. This provides a statistical evidence at more than 99% confidence level to reject the null hypothesis and conclude that the timeline for using AR in organizations is dissimilar across the five types of construction companies. The results from the post hoc Conover-Iman tests show that GC/CM are, on average, faster to integrate AR into their organizations than MEP Trades and Owners.

Table 15 Results of Kruskal-Wallis and Conover-Iman Tests for Level of Usage of AR on a Professional Level against Occupation

Statistical Test		**P-value**	**Significance at 95% Confidence Level**
Kruskal Wallis		0.00023	Significant
Conover-Iman			
GC/CM	A/E	1	Not Significant
GC/CM	OR	1	Not Significant
GC/CM	Owner	0.0000	Significant
GC/CM	MEP Trades	0.050	Significant
A/E	OR	1.000	Not Significant
A/E	Owner	0.0867	Not Significant
A/E	MEP Trades	1.000	Not Significant
OR	Owner	0.2905	Not Significant
OR	MEP Trades	1.000	Not Significant
Owner	MEP Trades	0.1788	Not Significant

4.10.3. AR Adoption in Company vs the level of usage of AR in the construction industry

The relationship between the Timeline for using AR in construction companies and Respondents’ usage of AR in construction was investigated. Figure 48 indicates that there is a reverse correlation between the level of usage of AR on a professional level and the adoption timeline of AR. Respondents who have more experience using AR in the construction industry reported that the technology will be used by their companies sooner than those who have less experience with the technology.

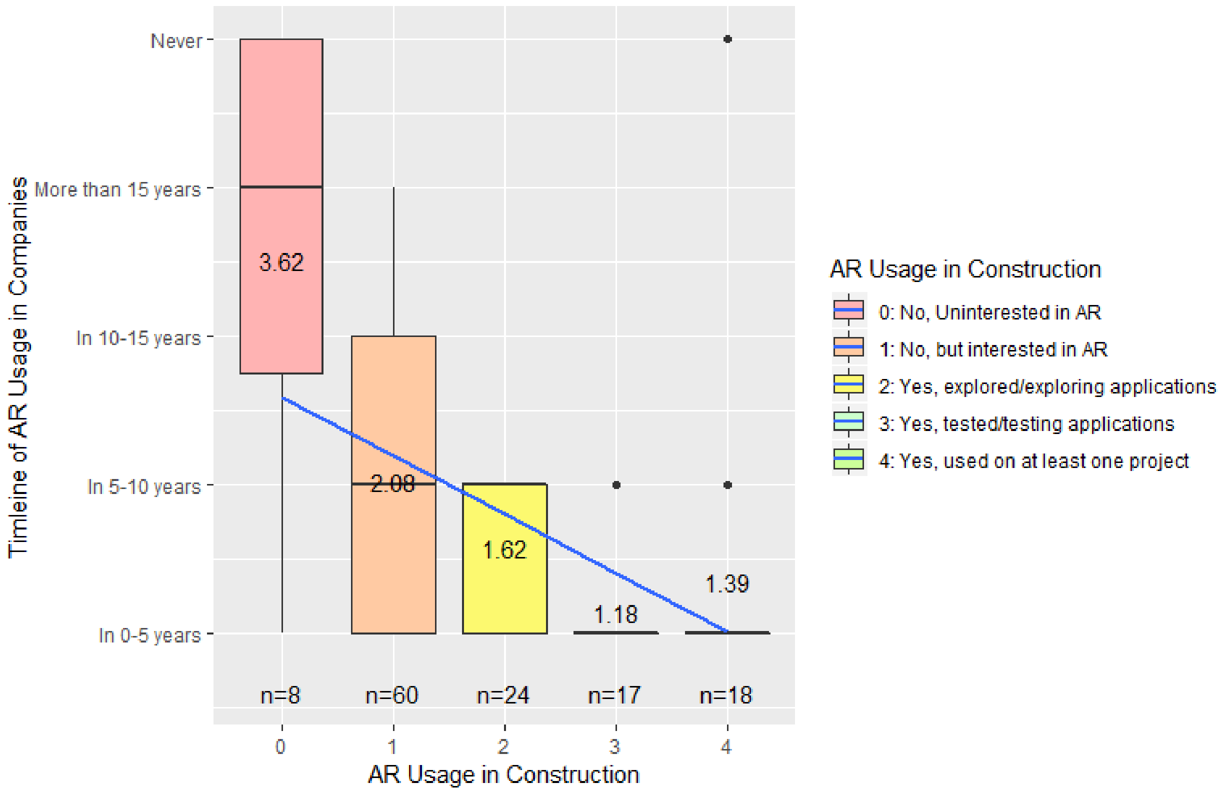


Figure 48 Timeline of using AR in Companies vs. Respondents' Level of Usage of AR

This relationship is statistically tested using Kendall's tau-b correlation coefficient which resulted in $\tau_b = -0.47$ and a p-value of 7.28×10^{-10}. This provides sufficient evidence to conclude that the timeline for using AR in companies is inversely proportional to the usage of AR in construction, i.e. respondents who have higher level of usage of AR in construction see that the technology will be adopted in their company sooner than those who have less or no experience.

Section III

Chapter 5: Objective B Methodology

The second objective (objective B) of this study is to investigate how AR can leverage the use of BIM and build upon the existing PSP lean practice. The methodology employed is inspired from (Davenport 1993) who chalked out a five step framework for process innovation: (1) identifying processes for innovation, (2) identifying change enablers, (3) developing a business vision and process objectives, (4) understanding and measuring existing processes, and (5) designing and building a prototype of the new process.

This research as a whole can be subdivided into three phases, each with its distinct stages and tasks. The overarching objective is, therefore, achieved through a series of intermediate objectives. The first phase is the 'understanding' phase. It consists of two stages (A and B) and four tasks (Tasks 1 – 4). The second phase is the 'envisioning' phase. It consists of Stage C and its three tasks (Task 5 –7). The third phase is the 'prototyping and validating' phase. It includes Stage D and its four tasks (Task 8 – 12). The methodology is outlined in Table 16

.

Table 16 Research Phases, Stages, and Tasks

Phases	Stages	Tasks
Understanding Phase	**Stage A** Detailed Review and Analysis of the Current State of the Production Strategy Process (PSP)	**Task 1** – Literature Review (Section 2.1.3.2.3)
		Task 2 – Structured interviews with Subject Matter Experts (Chapter 5)
	Stage B Current State of Production Strategy Process	**Task 3** – Documentation of the current state of PSP into a flowchart (Chapter 6)
		Task 4 – Review of the current state with subject matter experts (Chapter 6)
'Conceptualizing and Designing' Phase	**Stage C** Future State of Production Strategy Process	**Task 5** – Identification of challenges encountered in the existing process (Section 7.1)
		Task 6 – Identification of opportunities to integrate AR (Section 7.2)
		Task 7 – Specification of the requirements of the AR-enabled future state of PSP (Section 7.3)
		Task 8 – Envisioning the AR-enabled future state of PSP (Section 7.4)
'Developing, Implementing, and Validating' Phase	**Stage D** Development of the AR-Enabled PSP prototype	**Task 9** – Selection of AR hardware and software platform (Section 8.1.1)

		Task 10 – Specification of the requirements of the AR-enabled PSP prototype (Section 8.1.2)
		Task 11 – Design and Development of the structure of the prototype that illustrates the envisioned AR-enabled PSP (Sections 8.1.3 – 8.1.4)
	Stage E Implementation of the AR-Enabled PSP Prototype	**Task 12** – Implementation of the AR-enabled PSP prototype (Section 8.1.5)
	Stage F Validation of the AR-Enabled PSP Prototype	**Task 13** – Validation and testing of the prototype on an actual construction project (Section 8.2)
		Task 14 – Analysis of the validation data (Section 8.3)

5.1. ‘Understanding’ Phase

Stage A | Detailed Review and Analysis of the Current State of the Production Strategy Process

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Task 1: The initial phase of the research is to perform a comprehensive and extensive literature review on the current state of the practice of Production Strategy Process in the construction industry. The primary reference materials for this task will be the Lean Construction Institute (LCI) and the International Group Lean Construction (IGLC). The literature review offers an overview of the topic in-hand and describes the evolution and development of PSP in construction and apprise the researcher into its current status in the literature (this task has been covered in Chapter 2).

Task 2: The outcome of the Literature Review task informs questions, which are further pursued with follow-up meetings and interviews with industry practitioners and subject matter experts who have experience implementing PSP. The primary uniqueness of interviews is the high degree of interaction between the researcher and the participants. This allows the research to gain depths of information on the subject matter (Sheperis et al. 2010). The interview process forms an integral component of the research effort and will be ongoing as changes and new information comes to lights. Questions that are posed to interviewees include:

1. What are the key questions that you are trying to answer in this level?
    a. Specific examples
2. What are the key decisions you are trying to make in this level?
3. What are the deliverables/outcomes of this level?
4. What information is needed?
    a. What type of information is used?

   b. From what source do you obtain this information?
   c. Which parties are involved?
      i. Which parties participate in creating this level? (Cross functional teams)
      ii. Which parties receive this level? (Cross functional teams)
      iii. Who is the responsible party or leader?
   d. What tools/systems are used?
5. How is the process carried out?
   a. i.e. meet in a room, use white board, etc.
6. When is this level implemented?
   a. Before construction operations (timeline)
7. What is currently challenging or difficult in making your decisions?
   a. Identify pain points
   b. How can we improve the current level?
8. Are there any information/steps that you wish you could use/do but you are currently unable to?
   a. How can we transform this level?
9. How can AR be applied in this level?
   a. in developing, enriching, verifying, and using this level
10. What metrics/criteria could be used to measure the impact of AR?

Stage B | Current State of Production Strategy Process

Task 3: The first two tasks allow the understanding of the existing process, the culmination of which is a process documented in a flowchart which summarizes key findings of the current state of practice of PSP.

Task 4: The flowchart developed for the existing state of PSP is subsequently reviewed and discussed with subject matter experts.

5.2. ‘Conceptualizing and Designing’ Phase

Stage C | Future State of PSP aka AR-Enabled PSP

Task 5: The synthesize of key findings and the development of the current state of PSP allows for the identification of challenges, drawbacks, and weaknesses in the current process. These challenges provide the foundation for identifying areas of improvements and opportunities to integrated AR into the existing process.

Task 6: AR opportunities for improving the existing process and addressing the current challenges are explored and identified.

Task 7: Once the capabilities of AR have been identified, and in order to envision the future states, it is important to specify the requirements of this new state. The principle investigator (the author) met with PSP subject matter experts and identified a list of requirements and sub-requirements that need to be met in the AR-enabled future state of the PSP.

Task 8: The identification of AR opportunities and the specification of the requirements allow the envisioning of a future state of PSP, namely AR-enabled PSP. The future state embodies functionalities that improve the current process.

5.3. ‘Developing, Implementing and Validating’ Phase

Stage D | Development of the AR-Enabled PSP prototype

Task 9: The AR-enabled PSP prototype is developed for the HoloLens[5], one of the most widely anticipated display devices for the AR market. The AR-enabled PSP is developed using the Unity gaming engine.

Task 10: The prototype developed in this research is a proof-of-concept to showcase and validate the impact of AR on the PSP. Thus, the prototype does not incorporate all of the requirements identified in Task 7, and only a number of requirements were selected for the AR-enabled PSP prototype.

Task 11: Developing a prototype is a way to simulate and test the operations of the new process (Davenport 1993). Instead of describing the new process, prototyping allows the user to visualize and experience it. The prototype developed in this research is a small-scale, quasi-operational version of the AR-enabled PSP that is used to test the various aspects of the new process. Developing the prototype is carried out through an iterative process to ensure a proper fit to the requirements.

Stage E | Implementation of the AR-Enabled PSP prototype

Task 12: Based on the specific objectives, capabilities, and attributes of the AR-enabled future state identified in the previous tasks, a coded prototype was implemented in the gaming engine Unity.

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[5] HoloLens is mainly advertised for Mixed Reality (MR) which encompasses Augmented Reality.

Stage F | Validation of the AR-Enabled PSP prototype

Task 13: The AR-Enabled PSP prototype was tested and validated on-site at an ongoing construction project to study its potential benefits and impact on the PSP.

Task 14: Practitioners who participated in the validation phase were asked to complete a post-demo survey which explores the impact of the envisioned AR-enabled PSP prototype and investigates the potential of the technology. The responses collected from this survey were then analyzed using statistical methods.

Chapter 6: 'Understanding' Phase

Production Strategy Process Current State

Before embarking on any process re-engineering effort, it is important to gain a sound understanding of the current state of practice in order to allow those involved in the innovation initiative to develop a shared basis for further improvement (Sheperis et al. 2010). As such, this section describes the five principal steps of the PSP as it currently stands, using the example of an IPD project which requires (contractually) collaboration among project stakeholders. The current PSP is illustrated in Figure 49.

- Step 0 – Prerequisites

The nature of the PSP requires a high level of collaboration among the stakeholders and therefore, it is important to provide such an environment. The PSP stages describe in the following sections use the example of an Integrated Project Delivery (IPD) project as it contractually requires collaboration among project stakeholders. However, PSP can be implemented on projects using other types pf delivery systems such as Design-Build and Construction Management, however, the Terms and Conditions must include specific language stating the use of PSP and highlighting the need for collaboration and cooperation in the production planning. Implementing PSP on a design-bid-build project might be challenging as the contractors has little influence over the schedule under such type of contract. Additionally, it is crucial to develop a common understanding among all PSP participants regarding the terminology used and the steps to follow.

Prior to starting the PSP, the project team (including last planners) sets the expectations for the project and identified the major milestones for the project in the Master Scheduling phase. The project team then divides the project into phases (such as overhead, in-walls, exterior finishes).

Each phase should contain a series of activities performed by different trade partners. In the Production Strategy level, the project team works together to develop a production plan for each phase using the following four steps:

- Step 1 – Perform Sequence and Flow Analysis

The project team reviews the 2D construction drawings of each phase, identifies repeatable and non-repeatable work, determines flow and non-flow areas, agrees on the linear sequence of construction activities of the flow areas of the corresponding phase, and finally determines the direction of the flow (i.e., work to be performed from North to South, East to West, etc.). The sequence of the flow depends on the nature of each project and on the experience of the project team. For the overhead phase for the example, the project team can agree to adopt a top-down approach, meaning systems located at the highest elevation should be installed first. The output of this step is a set of 2D construction drawings highlighting the flow and non-flow areas and indicating the direction of the flow for each phase. The following steps are only applicable for flow areas. A separate plan is developed for non-flow areas which are later used as workable backlog and opportunities to preserve a continuous flow when a certain trade finished its work in a flow-area ahead of its schedule. Sequencing decisions can be also made by the last planners based on their intimate knowledge of working conditions and constructability issues. Sequencing directives are important to coordinate the work flow and production activities.

- Step 2 – Gather Information

The General Contractor (GC) conducts one-on-one interviews with the Trade Partners individually. For each activity within the corresponding phase, the GC provides the last planner of the corresponding trade partner with the 2D construction drawings. The last planner is then asked to use color markers to highlight the 2D drawings and show how much work they can complete in one day based on their ideal crew size. This is referred to as "daily production". The last planner uses the direction of the flow identified earlier for the corresponding phase as a reference to identify their daily production. The GC acts as a facilitator. A 2D color-up construction drawing is created for each activity within this step. Color-up drawings are not quantity takeoffs, as they require the last planner to think about how the work will be performed, by whom, where, and in what sequence (Frandson et al. 2013). The GC then asks the last planner from each trade partner to use the color-up drawings and divide their floor plan into production areas. The production area, also referred to as Takt area, is a collection of individual daily productions. For example, if the last planners are asked to develop one-week Takt areas, then each area should include five days' worth of work (assuming conventional schedule), or five daily productions. It should be noted that the precise mechanism of determining Takt-Time is beyond the scope of this research. One week is used as a threshold since it is consistent with the weekly work plan phase of the LPS. The output of this second phase is a set of 2D drawings with production areas for each activity assigned to the corresponding phase.

- Step 3 – Develop common areas

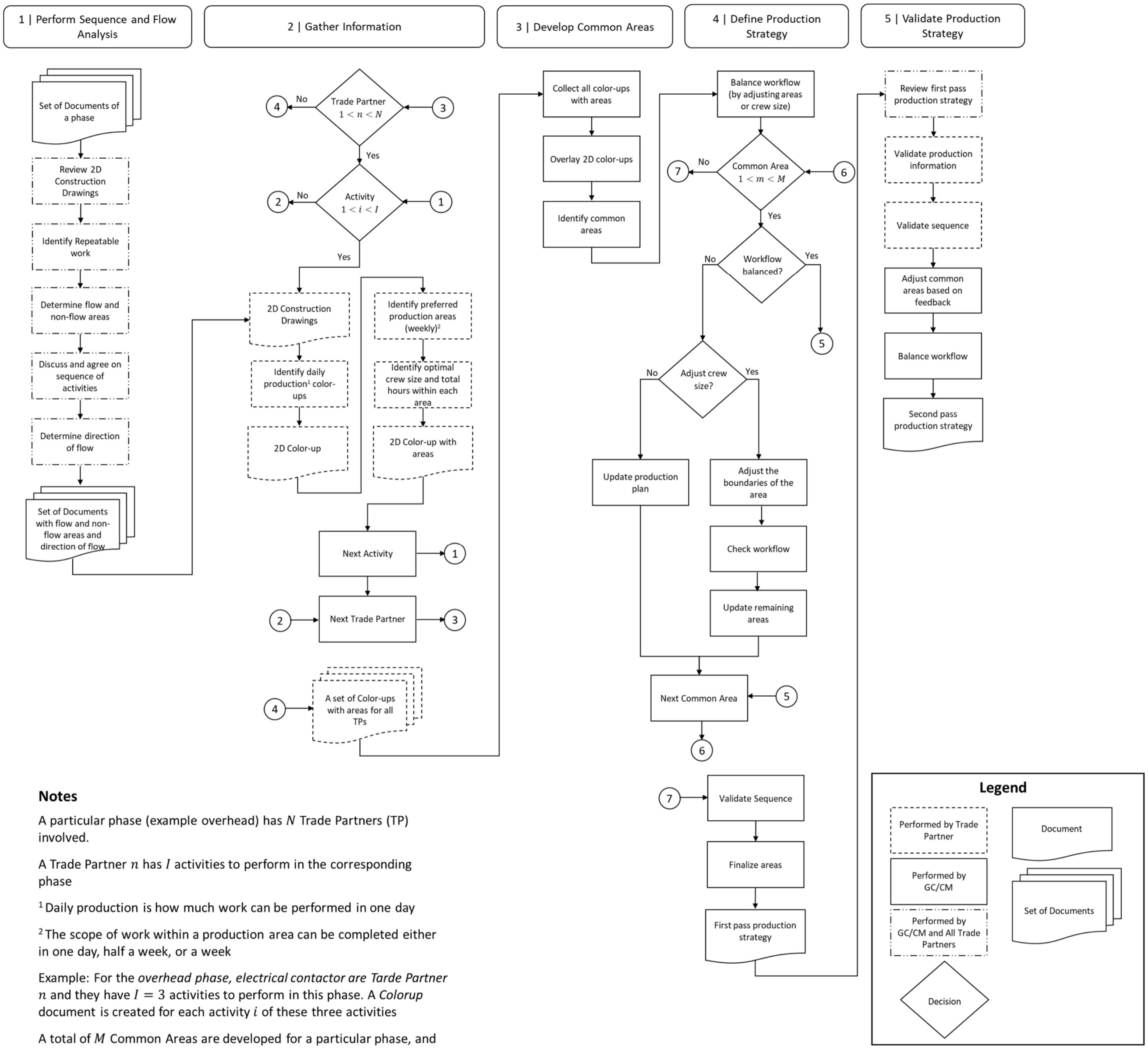
The GC collects the individual 2D production areas drawings, overlays them and attempts to identify common areas. The objective is to develop common areas wherein the scopes of work of all the different activities are balanced.

- Step 4 – Define Production Strategy

Once the common areas are determined by the GC, the GC determines the scope of work for each trade in that area and identifies which trade(s) are going to bottleneck. The objective is to balance the workflow such that all trades finish their work in an area within Takt-Time for that area. The workflows are balanced either by adjusting the crew size and hours or by adjusting the work area. This process should go through multiple iterations to produce a cohesive strategy.

- Step 5 – Validate the Production Strategy

The GC circulates the initial production plan to trade partners for feedback, which is collected and used to inform updates and revisions. Once a working plan is agreed upon, it should be documented via a convenient mechanism (e.g., an Excel spreadsheet).



Notes

A particular phase (example overhead) has N Trade Partners (TP) involved.

A Trade Partner n has I activities to perform in the corresponding phase

[1] Daily production is how much work can be performed in one day

[2] The scope of work within a production area can be completed either in one day, half a week, or a week

Example: For the *overhead phase, electrical contactor are Tarde Partner* n and they have $I = 3$ activities to perform in this phase. A *Colorup* document is created for each activity i of these three activities

A total of M Common Areas are developed for a particular phase, and the workflow within each Common Area m is balanced

Figure 49 Current State of the Production Strategy Process

Chapter 7: 'Conceptualizing' Phase

AR-Enabled Production Strategy Process

Prior to investigating how AR can be integrated into PSP, it is important to explore how and where the technology could be used. Therefore, challenges encountered in the existing state of PSP are identified, and opportunities to integrate AR are subsequently introduced and discussed. Finally, a flowchart is developed to map the future state of PSP (as known as the AR-enabled PSP).

7.1. Challenges

Challenges in the existing PSP were identified by reviewing the current state and by interviewing subject matter experts. PSP is information-dense, lengthy, and iterative. Project information is primarily exchanged via paper documents, and the visualization of the facility is marginally communicated using 2D drawings. The lynchpin of this process is the numerous sets of 2D construction drawings, which are the conventional and principal media of communication between different contracting parties (Ghaffarianhoseini et al. 2016). The identified challenges were grouped into 11 categories[6]: Collaboration, Communication, Decision-Making, Detection of errors, Documentation, Efficiency, Information Access, Input Accuracy, Interpretation of plans, Navigation, and Safety. The challenges of each category are further explained below.

- **Collaboration:** Parties such as the last planner (foremen, superintendents), project manager, project engineer, and production engineer from different trades are involved in the PSP. Thus, collaboration among parties from different levels involved in the PSP is at the core of production planning. However, collaboration cannot be supported due to

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[6] The categories are not listed in an ascending or descending order, but rather they are listed in alphabetical order.

the lack of effective visual renderings in the traditional paper media (Wang 2007). Furthermore, the existing PSP requires the project team to be available in the same space. Therefore, additional coordination efforts need to be considered in order to plan for the PSP, which usually results in a significant amount of time between meetings.

- **Communication:** Given the nature of the current PSP, participants face difficulties in sharing information among each other, which is a main cause of poor performance (Murray et al. 2007). 2D drawings, unlike 3D models, do not embed detailed information of building components, which can result in misunderstanding and miscommunication among different stakeholders, leading to inefficiencies in the PSP (Arayici et al. 2012). In addition, the tools used to represent and visualize the information are inadequate and lead to misunderstanding between stakeholders.
- **Decision-Making:** The output of the PSP is a production strategy that results from a series of decisions made throughout the process. Planners need to make decisions regarding analyzing the sequence and flow of the work, identifying daily productions, confirming commitment to the work, developing production areas for individual activities, designing balanced production areas, analyzing the workflow and ensuring a balanced workflow, reviewing production areas and approving production strategy. Project specific information and production information are communicated between planners through construction drawings in a 2D paper-based format. Specific information needs to be extracted from these drawings and processed in order to formulate the necessary knowledge for making decisions and taking actions (Waly and Thabet 2003). In addition, the nature of the existing PSP does not support rapid and right decision-making.

- **Detection of errors:** The 2D construction drawings that the last planners use during the current PSP do not allow the last planner to detect interferences during the development of their daily productions and production areas. 2D drawings do not allow for efficient design coordination, which can lead to inaccurate production input. With the current process, last planners adopt a view that focuses primarily on their own individual activities without any concern about interdependencies that exist with other activities
- **Documentation:** The documentation of the current PSP is decentralized where necessary data is often stored in various forms (hard copy, spreadsheets, email chains, etc.) across different devices or locations. The decentralization of the documentation process makes it difficult for planners to access the right information at the right time. In addition, the marked-up 2D construction drawings (i.e. daily production and production area) are not translated into the 3D model to keep track of their installation (control).
- **Efficiency:** The current PSP is a lengthy process that requires a great effort of coordination among the different participants. The one-on-one meetings with the last planners of each activity and the iterative process to develop common production areas and balance the workflow are time consuming. The production strategy of a certain construction phase (i.e. foundation, overhead) must be developed twelve weeks prior to the actual installation and performance of the work in the field.
- **Information Access:** While 2D drawings are useful to illustrate the spatial arrangement of a project, numerical information is often not represented and requires to be manually taken off construction drawings (Eastman et al. 1974). Therefore, when last planners highlight their daily production capacity, they are not provided with the actual quantity of their daily production (i.e. scope of work).

- **Information Flow:** Two-dimensional drawings and paper-based information storage that planners rely on often hinder information flow (Goedert and Meadati 2008). In the current PSP, information does not seamlessly flow from one stage to the other, especially when needed information is not properly captured.
- **Input Accuracy:** 2D construction drawings do not support the spatial sense of the last planners, and therefore the frequency of mistakes during the planning process increases. Based on the 2D drawings, a last planner must visualize the built product, which will exist in 3D space. This presents a difficulty, as some information will not correctly translate (e.g., flat pipe vs. inclined pipe). Moreover, some information depicted on the 2D drawings may not be current or consistent, which complicates the decision-making process of PSP participants (Eastman et al. 1974). In addition, each participant adopts a view that focuses primarily on their individual activities, without any concern about interdependencies with other activities. Furthermore, since there is a lack of centralized information storage, a challenge emerges in making sure last planners fully understand what work they are committing to.
- **Interpretation of plans:** 2D drawings present an individual view that is subject to individual interpretation (Cory 2001). Last planners are expected to visualize in abstract terms the perceived characteristics and spatial relationships among various components of the project, including site-related activities. Due to the interdependence between the different elements (i.e., design documents, means and methods, resources, site conditions, etc.) and the large amount of information that needs to be manually processed, this approach is difficult to undertake and imposes a heavy burden on the project team to carry out the planning process (Waly and Thabet 2003).

- **Safety Integration:** In addition to considering the seven flows (or pre-conditions) listed by (Koskela 1999), namely work, information, materials, equipment, team, space, and external conditions, researchers proposed that *safety* requirements should be also added to the list (Sacks et al. 2010b). Ganah and John (2015) stated that it is not easy for engineers to discuss and identify construction safety problems and considerations based on 2D drawings. Consequently, the current process does not effectively consider safety, which should be a perspective from which the plan is validated.

These challenges result in numerous iterations and mixed coordination of data, which ultimately increases the chances of miscommunications and associated non-valued added effort.

7.2. Augmented Reality Opportunities

Davenport (1993) stated that prior to integrating IT into a process, it is important to analyze the extension of IT support of this process. This section investigates how AR might be used to leverage the existing PSP by identifying opportunities to integrate the technology and address the challenges encountered in the existing PSP.

In order to identify the opportunities that AR has the potential to offer, it is important to study the impact AR can have. Using the nine impact categories identified by (Davenport 1993) in which IT can impact an existing process, the impact of AR in each of the nine categories was identified and is discussed below:

- Analytical: Data analytics and AR build off one another. AR can provide real-time in-situ information visualization of multi-dimensional data (ElSayed et al. 2015). AR brings a new dimension to present and visualize and interact with big data. The technology also offers a new medium that supports users in analyzing data (Luboschik et al. 2016). AR enhances the perception of the user which leads to a better cognition and an enhanced understanding of the environment. Better cognition results in more processed information, wider understanding and more effective learning leading to more successful and accurate decisions. AR supports the decision-making process by displaying the needed information and enhancing collaboration between those involved in the process (Székely 2015).

- Automation: AR systems allow the automation of processes. Information can be automatically generated in real-time and displayed onto the real environment (Verlinden et al. 2009).
- Disintermediating: With the transition to the digital era, technologies such as AR has the potential to disrupt industries and intermediate and disintermediate processes (Miller and Custis 2017). AR overcomes the big hurdles of data capture, storage, processing, and integration and therefore creates a new kind of disintermediation.
- Geographical: One of the greatest potentials of AR is the development of new types of collaborative interfaces. AR can be employed to enhance face-to-face and remote collaboration where remote participants can be added to the real world. AR enables a more natural co-located collaboration by blending the physical and virtual worlds to increase shared understanding. Researchers identified five key features of collaborative AR environments: 1) Virtuality – objects that don't exist in the real world can be viewed and examined; 2) Augmentation – real objects can be augmented by virtual annotations; 3) Cooperation – multiple users can see each other and cooperate in a natural way; 4) Interdependence – each user controls their own independent viewpoints; and 5)

Individuality – Displayed data can be different for each viewer (Billinghurst and Kato 2002).

- Informational: AR overlays digital content and contextual information onto real scenes which increases the perception the user has of reality. Furthermore, information can be captured from the user and saved for later analysis (Diaz et al. 2015)
- Integrative: AR is a new source of context-rich data that allows the user to connect the dots between cross-functional teams (Biron and Lang 2018)
- Intellectual: AR supports tacit knowledge exchange. A remote expert can transfer their tacit knowledge through AR via demonstration. Graphics, audio, and video could be used to effectively transfer tacit expert knowledge through AR (Aromaa et al. 2015).
- Sequential: AR systems support the performance of activities/tasks in parallel. This is also enabled with the remote collaboration feature that AR provide (Verlinden et al. 2009).
- Tracking: AR can visualize BIM data along with the real world of each construction activity and therefore, the status of the activity (complete, in progress, delayed) can be monitored and tracked, allowing the generation of an automatic report to check the progress of an activity (Wang and Love 2012).

Once the capabilities of AR have been identified, ways of integrating AR to overcome the challenges of the current PSP listed in the previous section are discussed. The nine impact areas laid the foundation for exploring opportunities to address the challenges encountered in the current process. A matrix was created to identify how each challenge will be addressed using the

AR impact areas (as shown in Table 17). Moreover, this section provides a detailed description of how AR can address each of the 11 challenges.

Table 17 Matrix of AR Impact Areas and PSP Challenges

	Analytical	Automation	Disintermediating	Geographical	Informational	Integrative	Intellectual	Sequential	Tracking
Collaboration	✓		✓	✓	✓	✓	✓		
Communication			✓	✓	✓	✓			
Decision-Making	✓				✓		✓		
Detection of Errors	✓				✓		✓		✓
Documentation		✓			✓	✓	✓		✓
Efficiency		✓	✓			✓		✓	
Information Access		✓			✓	✓			✓
Information Flow						✓			✓
Input Accuracy	✓	✓			✓		✓		
Interpretation of Plans	✓				✓		✓		
Safety Integration	✓				✓		✓		✓

- **Collaboration:** AR can be used to create a unique collaborative experience. Co-located users can see shared virtual objects (3D and 2D) that they can interact with. AR has the potential to augment the face-to-face (local) collaborative experience and to enable remotely stationed people to feel that they are virtually co-located (Lukosch et al. 2015). AR allows multiple users to be actively engaged in the PSP.
- **Communication:** Dong et al. (2013) reported that AR facilitates communication and discussion of engineering processes in real-time. AR supports the broadcasting of the user's view into a different screen allowing other users to freely exchange information.
- **Efficiency:** Wang and Dunston (2011) showed that AR can improve performance time and mental effort in collaborative design review. AR can be a proactive approach that enables efficient re-planning (Wang and Love 2012).
- **Decision-Making:** Wang et al. (2013) stated that using AR can result in better planning by reducing wastes of overproduction, waiting, unnecessary movement, and unnecessary inventory. AR can be used to make well informed decision on recourse allocation and dynamic adjustment. AR has the capability to process real-time graphics which allows the user to process data faster and more effectively (Waly and Thabet 2003).
- **Detection of errors:** Wang et al. (2013) mentioned that the integration of AR and BIM allows subcontractors to immediately recognize the interdependencies between activities. BIM provides the capabilities to identify activities and their interdependencies and AR serves a visualization tool that provides a context for the work that needs to be performed in the field. AR also displays singular and integrated views in real-scale, context, and

time and allows the planners to accurately recognize design errors which can therefore minimize repeated work.

- **Information Access:** While BIM aims to consolidate and archive all relevant information related to the project, the merge of AR with BIM improves the information search and access. User can also filter the 3D model by enabling and disabling different construction phases, levels, activities and components. Users can also select elements in the 3D model and extract information corresponding to that element. Furthermore, an AR system can be connected to other databases that contain other planning and relevant information that the user can search for and extract.
- **Information flow:** Replacing 2D drawings and paper-based information storage with data rich 3D models projected using AR facilitates seamless flow of information from one stage to the other, providing planners with the needed information at the right time. The last planners.
- **Input Accuracy:** AR allows the last planners to better recognize inter-relationships and links between activities. Furthermore, information can be associated with each element and the user can select a certain component and visualize and read its corresponding information (such as properties, material used, geometry, etc.). BIM can identify the interdependencies between the various activities and AR offers a powerful visualization tool to supply such information to the last planner who is directly involved in the execution phase. AR can make the interdependencies between activities more explicit (Wang and Love 2012).

- **Interpretation of Plans:** AR can display any chosen single view or integrated view into the real view of the user. The challenge to construct a mental model can be alleviated with AR because 3D models are visualized (Wang and Love 2012).

AR overcomes the challenges introduced with 2D documentation by presenting the documentation directly registered to the object in the 3D space surrounding the user (Mohr et al. 2015). The authors also indicated that using AR for technical documentation can reduce the cognitive load.

Using AR as the delivery mechanism for drawings and production information during the planning process has several advantages. First, it allows more advantageous use of BIM, as AR can operate in 3D space. Second, it creates a living single source of information, reducing miscommunication. This allows for an overall improvement in collaboration and communication, permits the last planner a better understanding of scope of work and as a result produces more reliable commitments, allows for safety analysis in more real space, improves spatial cognition, and allows an iterative tracking system. According to (Porter and Heppelmann n.d.) the use of AR eliminates the need to mentally translate two-dimensional information into the three-dimensional world, and improves the ability to absorb and interpret information which leads to better decision making, and faster and more efficient execution of tasks. A study by (Chu et al. 2018b) noted that AR eases information retrieval for those working in information-intensive environments, and increases the efficiency of the working processes through avoiding information overload. Finally, using AR facilitates standardization of the process to a single governing data point and citation.

7.3. AR-Enable PSP Requirements

Requirements analysis is the activity of determining and specifying the requirements of the customers. In this study, the customers are the parties involved in the PSP (Maciaszek 2007). Requirement determination provides a narrative definition of functional and non-functional requirements which the customers expect to have in the newly developed and implemented system. The requirements were defined through interviews with PSP subject matter experts. Eight different types of requirements were identified, namely visualization, processing, data storage and retrieval, data cataloging, interaction, collaboration, communication, and production control. Each of these eight categories contains multiple sub-requirements that provide details about the user requirements. Each of these categories and sub-requirements is further explained below. It is important to note that the AR-enabled PSP is being developed for AR glasses.

- Visualization

  PSP is based on location-based planning, namely Takt-Time Planning, and therefore, it is important for the users (i.e. the Last planner and/or project engineer) to visualize the space and understand their scope of work. The viewpoint of the user through the glasses of the AR headset is part of both the model and the real world. The users can visualize all the activities of a certain phase and identify repeatable work and thus break down the floor into flow and non-flow areas. The visualization of the flow areas then allows the parties involved in the PSP to agree on the direction of the flow. Individual

Last Planners can then choose to visualize a specific activity of a particular phase (for example visualize Duct Mains of the Overhead phase).

As the trades work interdependently and share the same space, it is important for each user to visualize the scope of work of other trades. This process increases coordination, validates the sequence, increases transparency between trades, and creates common understanding. Additionally, providing the user with the capabilities to visualize their scope of work in 3D, whether at full or adjustable scale, allows them to better understand their work and how it relates to the surroundings and to other trades. The visualization of the highlighted daily production along with its measurements (i.e. linear foot measurement) allows the user to better understand the work they are committing to and to keep track of the number of days they have created thus far. By walking through the model, users are able to detect any classes and errors in the model. They can also invoke pre-defined viewpoints and visualize the model from different angles. As 2D drawings are the most used medium of communication and users are familiar with reading them, the new system should allow the user to overlay imported 2D drawing on top of the 3D model. For example, if a user is looking at the 3D model of the first floor of a building, the user can have the option to overlay the needed 2D drawings of the first floor below or above the 3D model. Moreover, allowing the user to physically visualize production areas provides them with a deeper understanding of the scope of work within the selected boundaries. The visualization of the space also allows the user to spot any clashes, constraints, and safety issues.

The visualization of 4D animations of the sequence of activities of a phase will allow the user to validate their sequence. The visualization of flow will thus enhance the users' understanding of the flow of resources (such as materials, equipment, and workers).

- Processing

Data processing represents the *thinking* performed by the computer to analyze and represent the data. The AR system needs to provide the user with the measure of the created daily production by calculating the distance between the start and end point of selected daily production. This feature provides the user with additional information to develop a more accurate production plan. Additionally, when a production area is created, the total scope of work should be quantified. This will allow the user to input their production information accordingly. The square footage of the area can be also calculated to give the users an understanding of the space, which will allow them to accurately select the number of workers to perform work in the selected production area. Moreover, the users should be provided with the total number of days (i.e. daily productions) within the created production areas. This feature will enhance the decisions made by the user on whether the work flow is balanced or not within production areas. Furthermore, the quantification of the scope of work and number of days within each production area of a phase need to be graphically represented to the users.

- Data Storage/Retrieval

In order for the AR system to be valuable, user should be able to save any digital changes (created objects, annotations, information) made to the model and load them at any other time. Such feature allows the user to perform the PSP in multiple sessions without losing previous work. Furthermore, the outputs of the PSP need to be documented and made available for users for future use.

- Data Cataloguing

The 3D model is an information-rich repository that contains information related to each component in the system. The user can access this data through data cataloguing. This feature provides a query-able interface where information is stored, allowing user to access the required information when needed.

- Interaction

To perform the PSP, the user needs to identify and select repeatable work, create flow and non-flow areas, highlight their daily productions of an activity and create 3D production areas. The user needs to be able to adjust and delete the digital content that they created. Additionally, the 3D model and all associated contents need to be scalable to allow the user to configure their own preference settings. The user should be also able to rotate model and visualize it from different angles. The AR interface should also capture input from the user, such as allowing the user to enter production information for a production area. The AR system should not only display digital content to the user, but it should also allow the user to create in-situ information by annotating digital objects, highlighting constraints, and marking safety hazards. Furthermore, the user should be able to create new user-defined viewpoints and take screenshots of the displayed content. Furthermore, user needs to be able to specify the sequence of the work and create 4D simulations that simulate this sequence.

- Collaboration

The AR system should foster both local and remote collaboration. Face-to-face experience can be augmented with AR while having multiple users be virtually present in the model, improving collaboration. Co-located users can see shared 3D virtual objects and interact with or a remote user can annotate the live video view of a remote user, enabling multiple users to collaborate at a distance.

- Communication

  PSP participants should be able to visualize what the AR user is seeing. Streamlining and broadcasting of the live video of the user's view provide a new communication medium.

- Production Control

  The AR system should be also flexible to be used not only for planning, but also for production control. The user needs to be able to bring the 3D model and associated digital content to the site and overlay the onto the real environment at full scale. In addition, the user needs to be able to track the completion of their work.

In order to integrate AR into the PSP, the relationship between the aforementioned sub-requirements and the different AR opportunities should be outlined. Requirements Matrix (RM) illustrated in Figure 50 - Figure 53 displays the relationships between sub-requirements (rows) and AR impact areas (columns). This matrix helps visualizing how the AR opportunities are related to the requirements.

		Augmented Reality Opportunities								
Requirement Category	**Sub-Requirements**	Analytical	Automation	Disintermediating	Geographical	Informational	Integrative	Intellectual	Sequential	Tracking
Visualization	Visualize model at full and adjustable scale					x				
	Visualize individual and collective activities					x				
	Visualize Daily Productions					x				
	Display measurement of Daily Production					x			x	
	Display 'day' number associated with a Daily Production					x				
	Visualize Production Areas					x				
	Visualize activities within selected production areas		x			x				
	Visualize clashes between systems/activities					x				
	Display pre-defined viewpoints					x				
	Visualize imported 2D drawings overlaid over the corresponding 3D section					x	x			
	Walk through the model					x				
	Visualize saved snapshots					x				x
	visualize created 4D animations					x	x			
	Hide/Show Activities or Production Areas	x				x	x			
	Visualize idenitified flow					x				

Figure 50 Requirements Matrix of the AR-Enabled PSP Future State – Part I

		Augmented Reality Opportunities								
Requirement Category	**Sub-Requirements**	Analytical	Automation	Disintermediating	Geographical	Informational	Integrative	Intellectual	Sequential	Tracking
Processing	Measure Daily Production i.e. calculate the distance between the start and end points	x	x							
	Calculate total scope of work within a production area	x	x							
	Obtain square footage of a production area	x	x							
	Calculate total number of days within a production area	x	x							
	Generate bar charts for the number of days within individual production areas of a specific activity (i.e. plot number of days vs areas for an activity)	x	x							
	Generate bar charts for the total scope of work within individual production areas of a specific activity (i.e. plot total scope of work vs areas for an activity)	x	x							
	Generate bar charts for the number of days within a specific production areas for all activities (i.e. plot number of days vs activities for a selected common production area)	x	x							
	Make changes to the model (such as displaying a duct)	x	x			x				
	Send changes performed in the AR environment to the BIM sofwtare (suchas Revit)	x	x			x	x		x	x
Data Storage/Retrieval	Save data (i.e. any content displayed and added by the user such as created Daily Productions, Production Areas, comments, etc.)		x			x				x
	Load data		x			x				x
	Document the process		x			x		x		x
Data Cataloguing	Cataloguing data					x				

Figure 51 Requirements Matrix of the AR-Enabled PSP Future State – Part II

		Augmented Reality Opportunities								
Requirement Category	**Sub-Requirements**	Analytical	Automation	Disintermediating	Geographical	Informational	Integrative	Intellectual	Sequential	Tracking
Interaction	Represent Daily Productions in a virtual environment							x		
	Represent Production Areas in a virtual environment							x		
	Delete Daily Productions							x		
	Delete Production Areas							x		
	Scale the model up and down							x		
	Rotate the model							x		
	Input information form the user (such as crew size, number of hours, comments, etc.)	x						x		
	Annotate an element							x		
	Highlight constraints	x						x		
	Highlight safety issues	x						x		
	Create user-defined viewpoints							x		
	Create 4D animations	x	x				x	x		x
	Take snapshots		x							x
	Identify repeatable work	x			x	x		x		
	Identify/create flow and non-flow areas virtually	x			x	x		x		
	Specify the sequence of the flow	x			x	x		x		

Figure 52 Requirements Matrix of the AR-Enabled PSP Future State – Part III

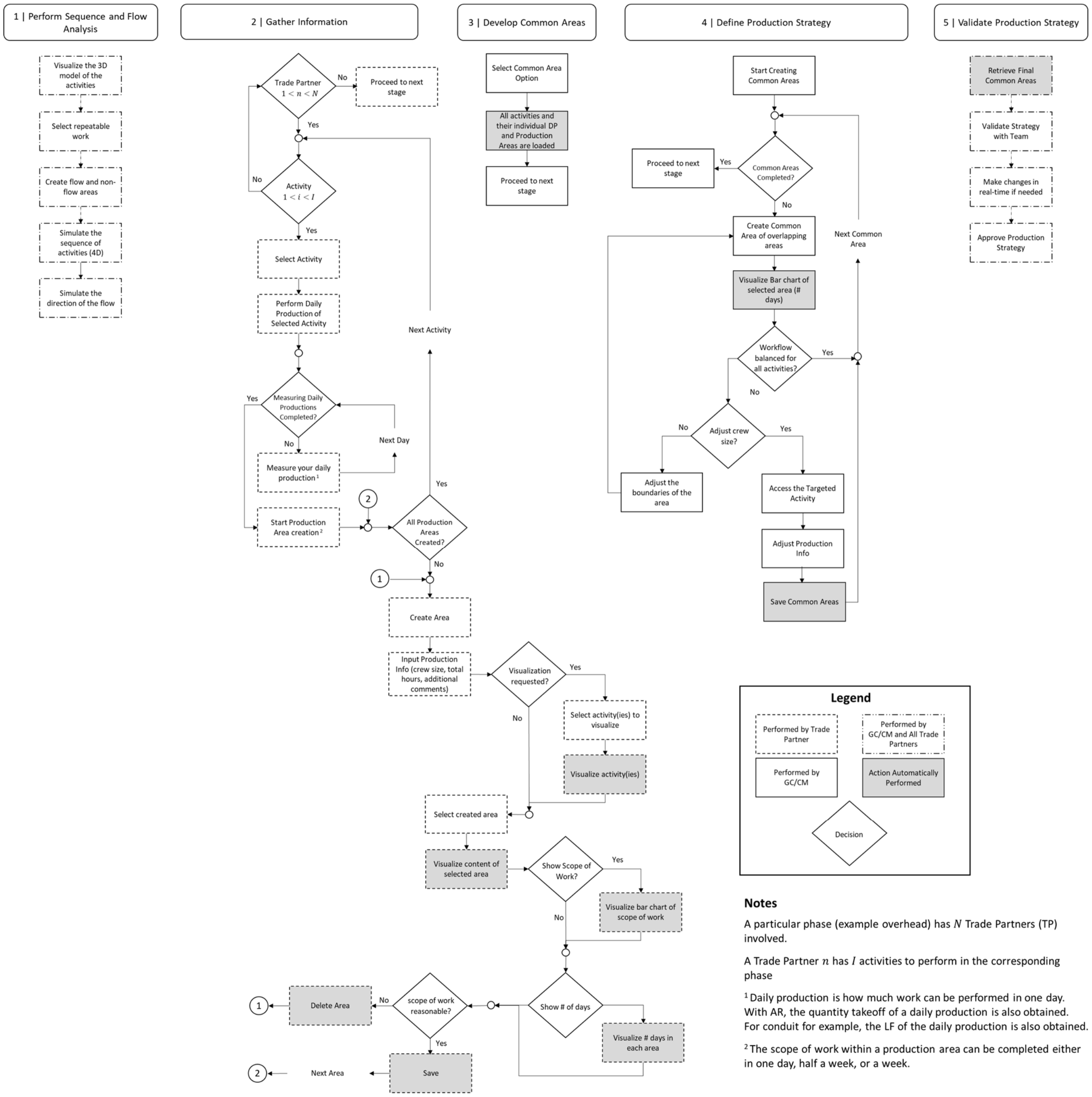
		Augmented Reality Opportunities								
Requirement Category	**Sub-Requirements**	Analytical	Automation	Disintermediating	Geographical	Informational	Integrative	Intellectual	Sequential	Tracking
Collaboration	Local collaboration			x	x					
	Remote collaboration				x					x
Communication	Broadcasting			x		x	x			
Production Control	Overlay production plan in the filed and track percent complete		x							x

Figure 53 Requirements Matrix of the AR-Enabled PSP Future State – Part IV

7.4. Future State

After identifying the challenges encountered in the current PSP and exploring opportunities for integrating AR, An AR-enabled PSP is envisioned in which the BIM model is used as the guide and chief reference for production strategy development. Thus, BIM is a precursor to implementing AR-enabled PSP. AR allows the last planners not only to see the BIM model from different perspectives, but also to become a participant in the process of the virtual production. Similar to the Traditional PSP, the production strategy is developed for an IPD project where collaboration among all stakeholders is required.

Figure 54 illustrates the flowchart of the AR-enabled PSP and the following five steps define the process by which AR-PSP can be implemented.



Notes

A particular phase (example overhead) has N Trade Partners (TP) involved.

A Trade Partner n has I activities to perform in the corresponding phase

[1] Daily production is how much work can be performed in one day. With AR, the quantity takeoff of a daily production is also obtained. For conduit for example, the LF of the daily production is also obtained.

[2] The scope of work within a production area can be completed either in one day, half a week, or a week.

Figure 54 Flowchart of the AR-Enabled Future State of the Production Strategy Process

- Step 0 – Prerequisite

In addition to the prerequisite of the Traditional PSP, the AR-Enabled PSP integrates AR with BIM and projects the 3D designed model (as well as other non-geometric data) into the user's view. As BIM is a prerequisite for the AR-Enabled PSP, it is important that the designed BIM model includes the information needed to perform the Production Strategy. When discussing the use and reliance of the BIM information, it is important to discuss the Level of Development (LOD) of the model.

LOD Specification is 'a reference that enables practitioners in the construction industry to specify and articulate with a high degree of clarity the content and reliability of Building Information Models at various stages in the design and construction process' (BIMForum 2018).In other terms, LOD is the degree to which the geometry of the element and attached information has been thought through, representing the degree to which project team members can rely on the information provided by the model. Level of Detail, on the other hand represents how much detail is included in the model element.

The Fundamental LOD definitions are as follows (BIMForum 2018):

- LOD 100: the model element may be graphically represented in the Model with a symbol or other generic representation, but does not satisfy the requirements for LOD 200.
- LOD 200: The Model Element is graphically represented within the Model as a *generic* system, object, or assembly with approximate quantities, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element.

- LOD 300: The Model Element is graphically represented within the Model as a *specific* system, object or assembly in terms of quantity, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element.
- LOD 350: The Model Element is graphically represented within the Model as a specific system, object, or assembly in terms of quantity, size, shape, location, orientation, *and interfaces* with other building systems. Non-graphic information may also be attached to the Model Element.
- LOD 400: The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of size, shape, location, quantity, *and orientation with detailing, fabrication, assembly, and installation information*. Non-graphic information may also be attached to the Model Element.
- LOD 500: The Model Element is a *field* verified representation in terms of size, shape, location, quantity, and orientation. Non-graphic information may also be attached to the Model Elements. This LOS represents the as-built model and is used by the owner and facility managers after the construction is completed.

The PSP requires an analysis of sequence and low, and therefore, an LOD 350 at least is needed. This level provides the necessary information and detail for cross-trade coordination and construction layout (Yoders 2017). Unlike the conventional practice where the model is based on no particular construction sequence, means, or methods, the model developed under in an IPD environment needs to be designed using the most efficient construction sequence (Luth et al. 2013). It is important to have the sequence of the different activities established prior to modeling the project. This practice is specifically possible and promoted on IPD projects where the construction team provides constructability feedback to the design team. As a result, the BIM model is designed for production optimization.

Leite et al. (2011) evaluated and analyzed the modeling effort and impact of different Level of Details in BIM and found that more details in a model does not necessarily mean more modeling work. The authors added that additional effort in modeling can lead to higher precision, and thus, supports decisions made during design and construction. This results of their study are reported to support the feasibility of using BIM LOD 350 during PSP.

- Step 1 – Perform Sequence and Flow Analysis

  The project team:

  1. collectively uses the 3D model as a guide and reference to visualize the corresponding construction phase(s) and the relevant activities
  2. interacts with the 3D model and selects repeatable work
  3. interacts with the 3D model and collectively develops the sequence of activities and identifies potential safety hazards, thus improving the decision-making process in a collaborative environment
  4. interacts with the 3D model and collectively discuss flow and non-flow areas
  5. interacts with the 3D model and collectively assess the project and determine the direction of flow.

AR helps project participants from diverse trades better understand each other’s scope and flow of work, facilitating better collaborative decision making. The output of this step is saved within the 3D model and accessible at any later point by the project team. This central information repository is more efficient than traditional methods and provides additional transparency – all participants are provided with the same information.

- Step 2 – Gather Information

Last planners will be among the project team participants with access to the information generated in Step 1. Integration of BIM and AR allows 3D visualization of the scope of work and improves visual understanding by providing an interactive solid model of the whole project. Within the augmented environment, the last planner:

1. selects to only visualize their scope of work
2. performs their daily production for the entire phase in a virtual environment, which in addition to generating 3D color-up drawings, will also create quantity takeoffs. The last planner can also investigate the space for any safety problems and adjust their daily production accordingly
3. creates production areas virtually. This allows the last planner to automatically visualize the scope of work within each area, obtain the total quantity of work to be installed, and input production information (such as labor hours, crew size, working days, constraints, etc.). This information can be easily retrieved by the last planner.

Each last planner can create their production areas and save them to the same source, allowing project managers to coordinate and check for trade clashes

- Step 3 – Develop Common Areas

The GC/CM retrieves the results of the last planner's work from step 2. Their production areas are overlaid, allowing visual creation of common areas.

- Step 4 – Define Production Strategy

The GC, once common areas are developed, retrieves the production information that was input pertinent to each scope of work. This information facilitates the performance of workflow balancing in an environment that updates in real-time, which improves its efficiency. AR thus acts as a decision support tool for the GC as they create the production strategy plan draft.

- Step 5 – Validate Production Strategy

Once the first-pass production strategy is complete, the team meets in the augmented environment to review it. This greatly enhances collaboration, as it facilitates meetings that do not require co-location of participants, as well as changes that are visible in real-time to all parties. The production plan created in AR can be used during project execution to visualize the work to be installed and to track performed work. Project Percent Complete could be then calculated more accurately and effectively.

In summary, AR has the potential to transform the current state of the PSP. It provides a common source of truth which enables a higher level of collaboration among the participants of the PSP when working in the same space or from remote locations. The AR-enabled PSP is a centralized reference that encompasses the different types of information used during the PSP. AR enables the users to interact with the built product in real-time, thereby enhancing visualization, space perception, and decision-making. The technology also allows last planners to identify potential safety hazards during planning and integrate safety more effectively into the production strategy.

Chapter 8: ‘Developing, Implementing and Validating’ Phase

AR-Enabled PSP Prototype

This chapter presents the development, testing and validation aspects of the AR-PSP prototype. The first section introduces the steps undertaken to develop the software and illustrates the process in a class diagram. The second section focuses on the validation methodology. Finally, the results of the validation are reported.

8.1. Development and Implementation

In Chapter 7, the challenges associated with the existing PSP were discussed, opportunities to integrate AR were explored, and a future state was envisioned. Once the concept of AR-PSP was identified, a prototype was built to illustrate it. Bill Verplank suggested that ‘prototyping is externalizing and making concrete a design idea for the purpose of evaluation’ (Muñoz and Miller-Jacobs 1992). Prototyping is a useful tool for solving problems and answering questions. Throughout the development of the prototype, feedback from the construction industry, specifically from PSP subject matter experts was incorporated into the design to continuously furnish usability insights and to ensure the effectiveness of the software. There are various prototyping methods that can be used to meet the needs of the prototype. The two kinds that are employed in this research are: paper prototype (created in the prototype development stage) and coded prototype (developed in the prototype implementation stage).

8.1.1. Hardware and Software Selection

AR HMD have been used and developed in the past; however, they are often expensive and custom-made for research (Evans et al. 2017). The HoloLens (see Figure 55) has a see-through holographic display and is the only AR HMD commercial system that is available with potential for applications for the construction industry (Agarwal 2016). Microsoft first released the Development Edition of the HoloLens in 2016 and then launched the consumer version. While other companies have worked on their AR HMD (Such as Google Glass and DAQRI), the HoloLens remains the first in the AR market with little to no competitors for consumer grade wireless AR HMDs (Evans et al. 2017).

Figure 55 Microsoft HoloLens Headset
(Microsoft 2018)

The first consumer version of the HoloLens weighs about 1.2 pounds and has a battery life of 2-3 hours that allow standalone operation of the device. The HoloLens enables hand-free operations while projecting the digital content. Unlike other AR HMDs, the HoloLens is a completely self-contained HMD that does not require to be tethered to a separate computing device. In addition to the capabilities of the HoloLens, the decision to use the Microsoft HoloLens in this study was supported with insights from the construction industry. Respondents who participated in the AR survey indicated that the HoloLens is HMD device that is most commonly used in construction (see Figure 30).

Users wearing the HoloLens can interact with holograms or displayed content via *gaze*, gestures, and voice command. The two forms of input that were mainly used in this research are gaze and gesture. Gaze refers to tracking what the user is looking at. This concept is used in HoloLens applications to select and interact with the displayed content. Gaze is accompanied with a cursor which provides a visual representation of the user's gaze. The cursor, depicted as a hollow circle symbol, allows the user (as well as other observers) to know what the user is looking at (Newnham 2017).

While gazing provides the mechanism for targeting objects, gestures provide the mean to interact with them. Gestures could be either discrete or continuous. Each discrete gesture execute a specific action – for example, the air-tap gesture is equivalent to a double-click on the mouse or tap on a touch screen. Continuous gestures, on the other hand, are entered and exited. and while they are active, they provide continuous updates to their state. For instance, *tap and hold* is an example of continuous gesture and is equivalent to dragging items on a desktop or a home screen (Newnham 2017).

When the user chooses to select or interact with the digital content, the representation of the cursor changes to become a point indicating that an action (i.e. selection or click) is being performed.

The cross-platform Unity 3D game engine was used to build a proof-of-concept of the AR-enabled PSP. Developing for the Microsoft HoloLens requires the use of the Universal Windows Platforms (UWP) to create 3D (holographic) applications. Such applications use Windows Holographic Application Program Interface (API). Therefore, Microsoft recommends the use of Unity to create 3D applications for the HoloLens.

Unity is a powerful program for building 2D and 3D games and applications and is very popular among developers (Ong 2017). Unity supports application developments for the

HoloLens and is considered the preferred software platform for developing Windows AR experiences and applications (Ong 2017).

8.1.2. AR-Enabled PSP Prototype Requirements

The requirements categories and their sub-requirements specified in Section 7.3 were identified to envision and design the future AR-Enabled state of PSP. Prototyping is a visualization of the requirements. The principal investigator discussed the requirements with subject matter experts and end users and based on the programming knowledge and the current maturity of the technology, 25 sub-requirements out of the 58 were selected to be included in the AR-Enabled PSP prototype. These 25 sub-requirements and their relationship to the AR opportunities are illustrated in Figure 56.

		Augmented Reality Opportunities								
Requirement Category	**Sub-Requirements**	Analytical	Automation	Disintermediating	Geographical	Informational	Integrative	Intellectual	Sequential	Tracking
Visualization	Visualize model at full and adjustable scale					x				
	Visualize individual and collective activities					x				
	Visualize Daily Productions					x				
	Display measurement of Daily Production					x			x	
	Display 'day' number associated with a Daily Production					x				
	Visualize Production Areas					x				
	Visualize activities within selected production areas		x			x				
	Visualize clashes between systems/activities					x				
	Walk through the model					x				
	Hide/Show Activities or Production Areas	x				x	x			
Processing	Measure Daily Production i.e. calculate the distance between the start and end points	x	x							
	Calculate total scope of work within a production area	x	x							
	Calculate total number of days within a production area	x	x							
	Generate bar charts for the number of days within individual production areas of a specific activity (i.e. plot number of days vs areas for an activity)	x	x							
	Generate bar charts for the total scope of work within individual production areas of a specific activity (i.e. plot total scope of work vs areas for an activity)	x	x							
	Generate bar charts for the number of days within a specific production areas for all activities (i.e. plot number of days vs activities for a selected common production area)	x	x							
Data Storage/Retrieval	Save data (i.e. any content displayed and added by the user such as created Daily Productions, Production Areas, comments, etc.)		x			x				x
	Load data		x			x				x
Interaction	Represent Daily Productions in a virtual environment							x		
	Represent Production Areas in a virtual environment							x		
	Delete Daily Productions							x		
	Delete Production Areas							x		
	Scale the model up and down							x		
	Input information form the user (such as crew size, number of hours, comments, etc.)	x						x		
Communication	Broadcasting			x		x	x			

Figure 56 Requirements Matrix of the AR-Enabled PSP Prototype

8.1.3. Model Acquisition

The Navisworks model was acquired from The Boldt Construction company (TBC), a nationally ranked general contractor with more than 2,000 employees and 14 locations. TBC provided the BIM model (LOD 350) of the Aurora Health Center Pleasant Prairie (AHCPP) project. AHCPP is a 190,000 square foot two-story surgical and imaging center with a rooftop mechanical penthouse and a three-story medical office building (MOB) in Pleasant Prairie, Wisconsin (USA). The building includes an imaging floor, a surgical floor, a urology and sports health floor, an orthopedic floor, and a pediatric floor. It is expected to be complete in spring of 2020.

From the moments the 3D model was acquired to the time when the validation phase would take place, it was anticipated that the construction team would be developing the production strategy of the overhead to the 3rd floor of the MOB. Therefore, a series of selection sets were created in Navisworks to only show the overhead work of the 3rd floor of MOB.

Including all of the overhead activities and systems resulted in a very large file size that couldn't be exported into FBX (Filmbox) format In an attempt to reduce the size of the model, it was decided to only include 4 overhead activities: Duct Mains, Duct Low Pressure, Hot Mechanical Water, and Domestic Water and Medical Gas. In addition, walls (including studs and the top and bottom track) were also kept visible in order to allow the user to position themselves in the building. The four activities and the walls of the 3rd floor of MOB were exported from Navisworks into FBX format (size 98 MB) and imported into the Unity gaming engine, where it was optimized to run smoothly on the HoloLens.

8.1.4. Prototype Development

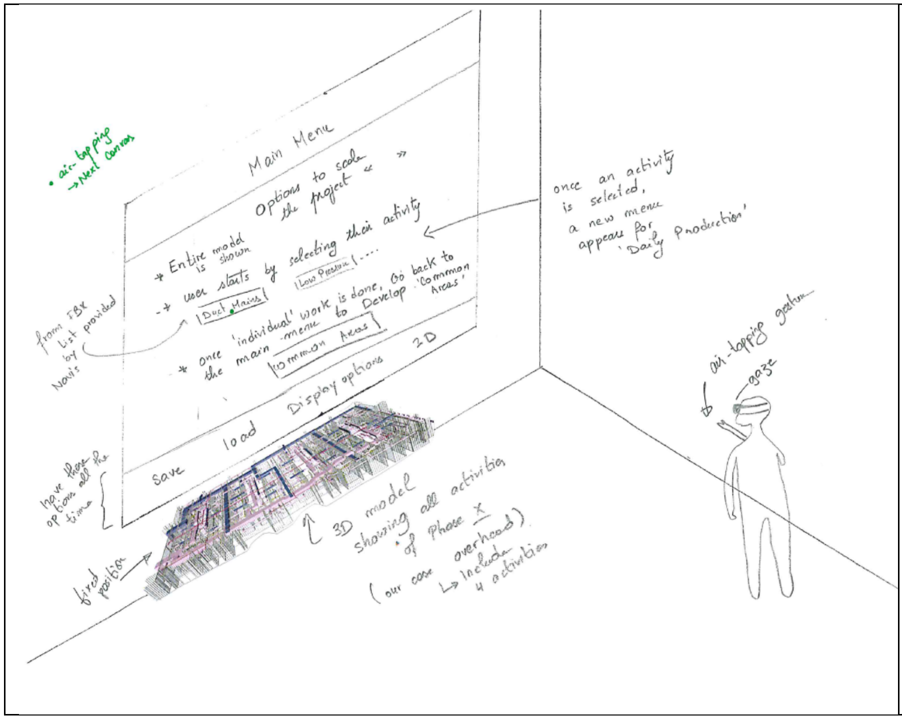
This section sketches the steps needed to develop the prototype.

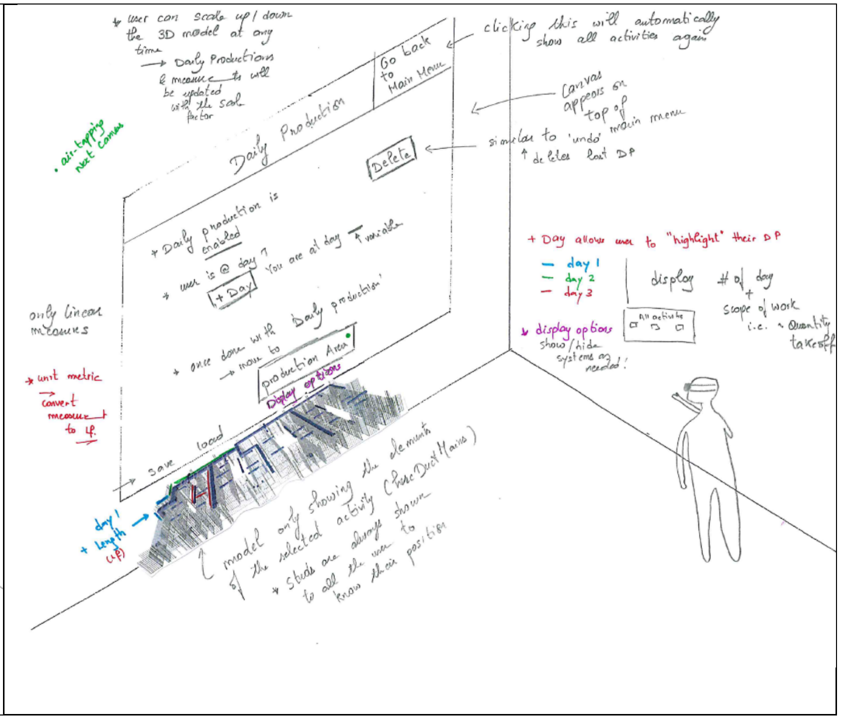
8.1.4.1. Paper Prototype

Paper prototyping is an interactive technique that consists of a paper mockup of the desired user interface (Arnowitz et al. 2010). It is a well-established and widely used technique in traditional user interface design that supports the design team in early development phases to brainstorm, design, create, test, communicate and discuss ideas and concept variations (Snyder 2003). Paper prototyping also allows the design team to receive early feedback from the users and adjust and refine the design accordingly (Lauber et al. 2014). Snyder (2003) stated that anything that has a human-computer interface is a potential candidate for paper prototyping. When designing 2D applications, paper prototypes are typically the starting point, however, there is no equivalent techniques for the development of AR applications. Lauber et al. (2014) developed *PapAR*, a prototyping technique that is similar to the traditional paper prototyping, but also takes into consideration two specifics of AR systems: content stabilization and coexistence of virtual and real content.

The AR-enabled PSP prototype developed in this research does not require the overlay of virtual content with the real world, and therefore, the traditional paper prototyping technique was employed to turn abstract ideas more concrete, brainstorm, design, and create the user interface and communicate the design to industry practitioners and received their feedback. Once the paper prototype was created, usability tests were conducted with PSP subject matter experts to iterate, improve, and refine the design based on input from real users.

The following pictures (Figure 57) illustrate the paper prototype that was developed for the AR-enabled PSP.


• air-tapping
→ Next Canvas
Main Menu
Options to scale the project « »
* Entire model is shown
-* user starts by selecting their activity
Duct Mains
Low Pressure
....
* once 'individual' work is done, Go back to the main menu to Develop 'Common Areas'
Common Areas
2D
Display options
Save
load
from FBX list provided by Navis
have these options all the time
fixed position
once an activity is selected, a new menu appears for 'Daily Production'
3D model showing all activities of phase X
(our case overhead) ↳ Includes 4 activities
air-tapping gesture
gaze


* user can scale up / down the 3D model at any time
→ Daily Productions & measurements will be updated with the scale factor
Go back to Main Menu
clicking this will automatically show all activities again
Daily Production
Canvas appears on top of main menu
Delete
similar to 'undo' ↑ deletes last DP
• air-tapping next canvas
* Daily production is enabled
* user is @ day 7 You are at day _ ↑ variable
+ Day
* once done with Daily production' → move to
production Area
Display options
only linear measures
* unit metric → convert measurement to LF. →
Save
load
day 1 + Length (LF)
model only showing the elements of the selected activity (here Duct Mains)
* studs are always shown to all the user to know their position
+ Day allows user to "highlight" their DP
— day 1
— day 2
— day 3
display
# of day + scope of work i.e. ~ Quantity takeoff
* display options show / hide systems as needed!
All activities
☐ ☐ ☐

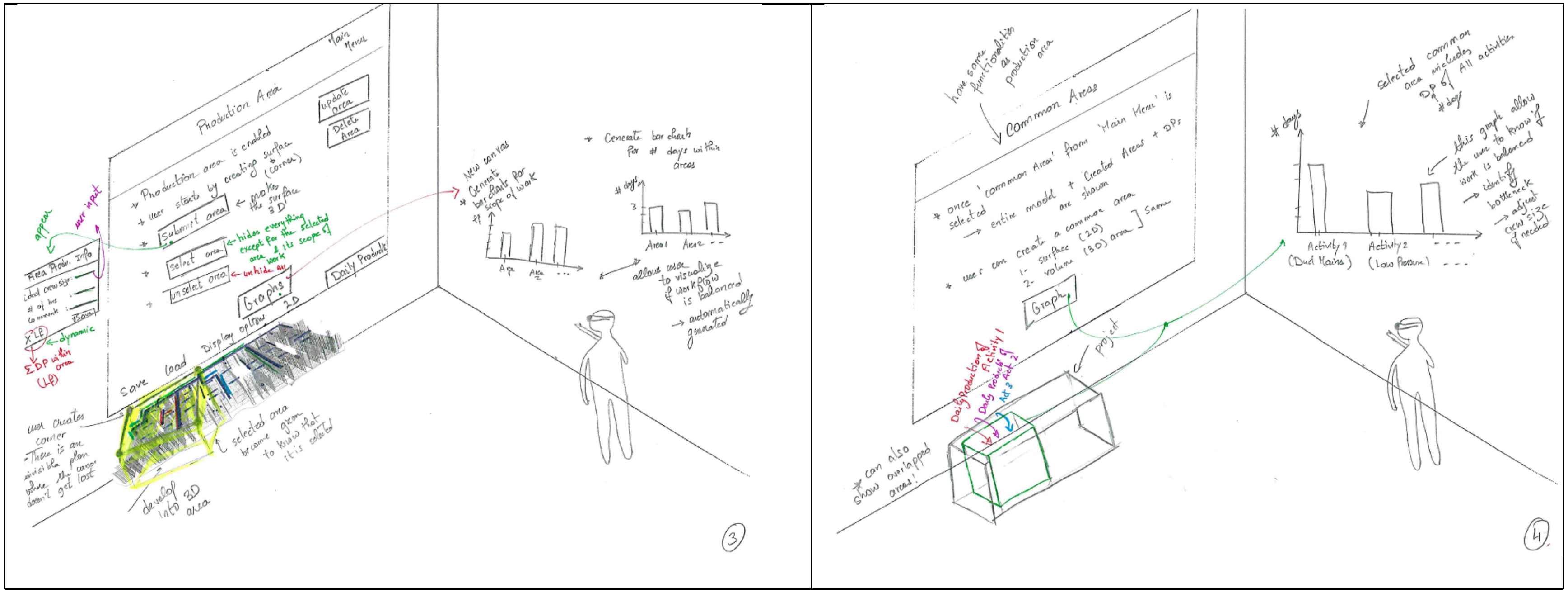


Figure 57 Paper Prototype Illustration

8.1.4.2. Class Diagram

Once the paper prototype is, and prior to coding the prototype, it is important to visualize the design of the software and model the static structure of the system. Class diagrams are one of the most commonly used Unified Modeling Language (UML) diagram that encapsulate details about the entities that make up the system (software) and the static relationships between them (Pilone and Pitman 2005). A class diagram is developed to model the system of the application and translate the model (paper prototype) into programing code. UML class diagrams are an important step that lays out the foundation for the implementation of the prototype (Glover 2018). The class diagram can be seen in Figure 58.

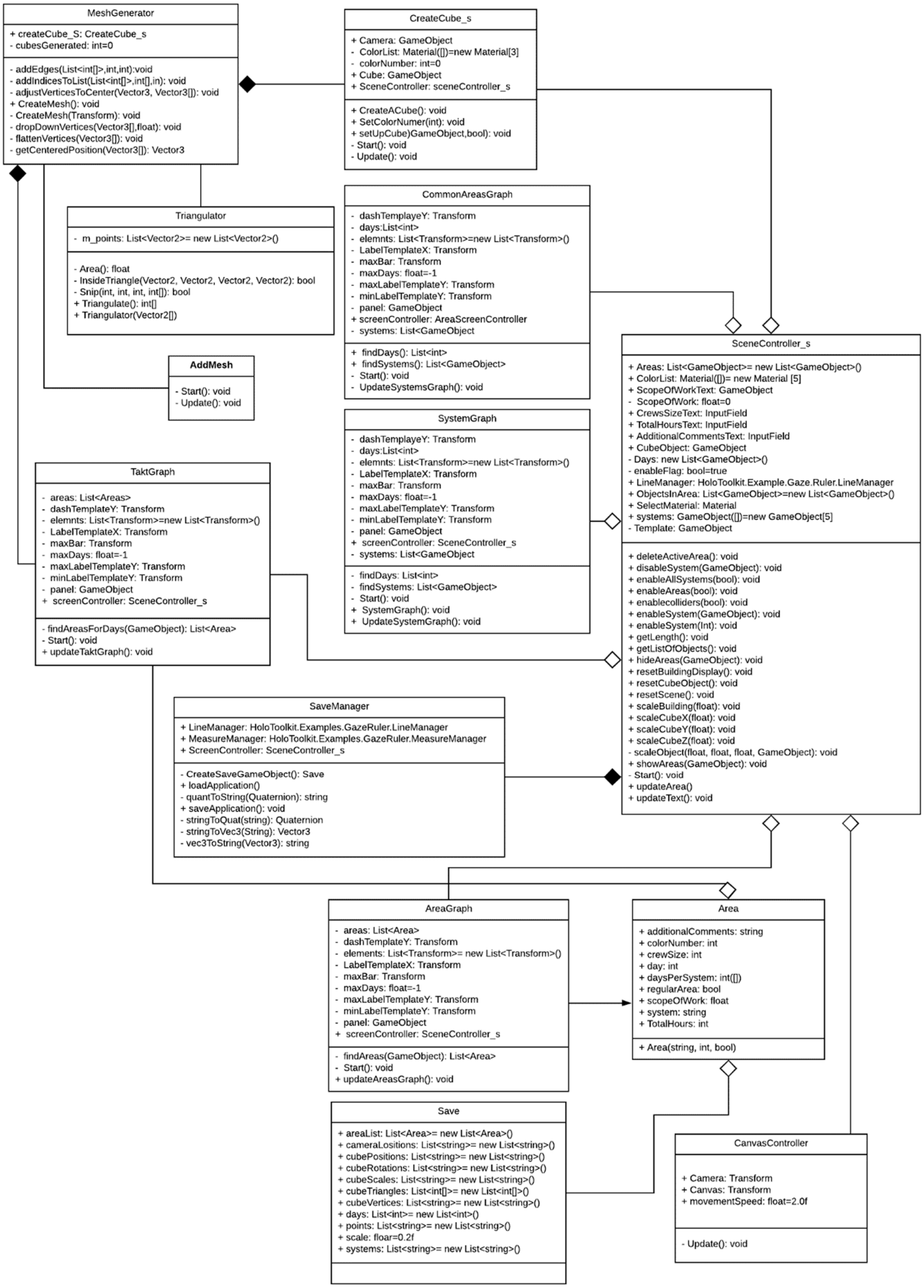


Figure 58 Class Diagram of AAR-Enabled PSP Prototype

8.1.5. Prototype Implementation

8.1.5.1. Coded Prototype

The coded prototype has been developed in the Unity gaming engine (using the C# programming language) at the University of Wisconsin – Madison. Once the coded prototype was developed in Unity, Holographic Remoting was used to stream the application to the HoloLens. This technique allows to run the application on the device while skipping the time-consuming build and deployment processes.

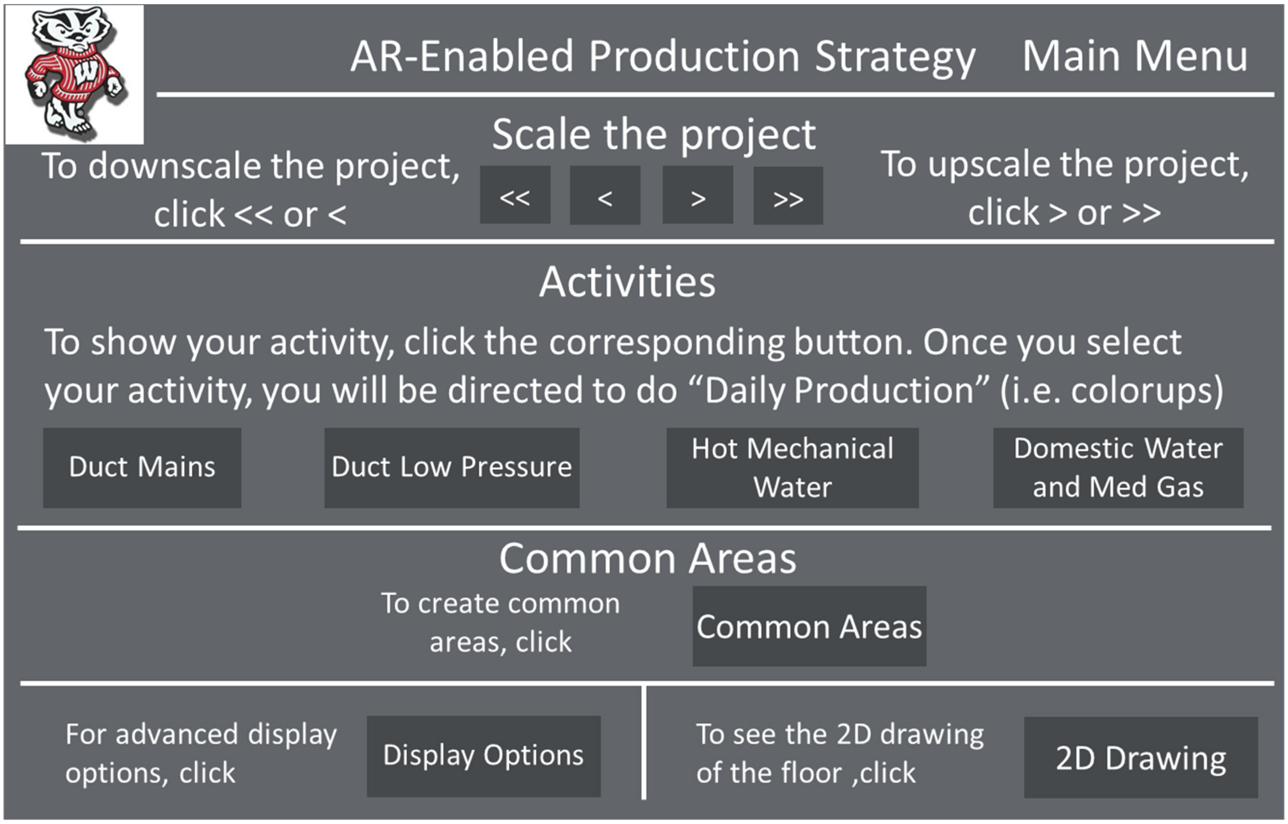
8.1.5.2. User Manual

To use the remoting feature, the *Holographic Remoting Player* application must be installed on the HoloLens (can be downloaded and installed for free from the Microsoft Store). Once installed, the application should be launched and a new window with the device IP address will be displayed. While the HoloLens is running the *Holographic Remoting Player*, the Unity project needs to be open, under *Windows*, click on *XR* and select *Holographic Remoting* from the dropdown menu. A new window will open, and the user will be directed to input 1) the Emulation Mode (Remote to Device), and 2) Remote Machine (the IP address shown in the HoloLens). It is important to have both the HoloLens and the computer on which Unity is running connected to the same network.

Once those steps are followed, click on Connect and if successful, the *Connection Status* will turn green. With the device connected, click on *Play* in the Unity Editor and the application will be streamed to the HoloLens. The user wearing the HoloLens will be able to test and validate the prototype.

8.1.5.3. User Interfaces

The different user interfaces of the AR-enabled PSP are illustrated below:


AR-Enabled Production Strategy Main Menu

Scale the project

To downscale the project, click << or <

To upscale the project, click > or >>

Activities

To show your activity, click the corresponding button. Once you select your activity, you will be directed to do “Daily Production” (i.e. colorups)

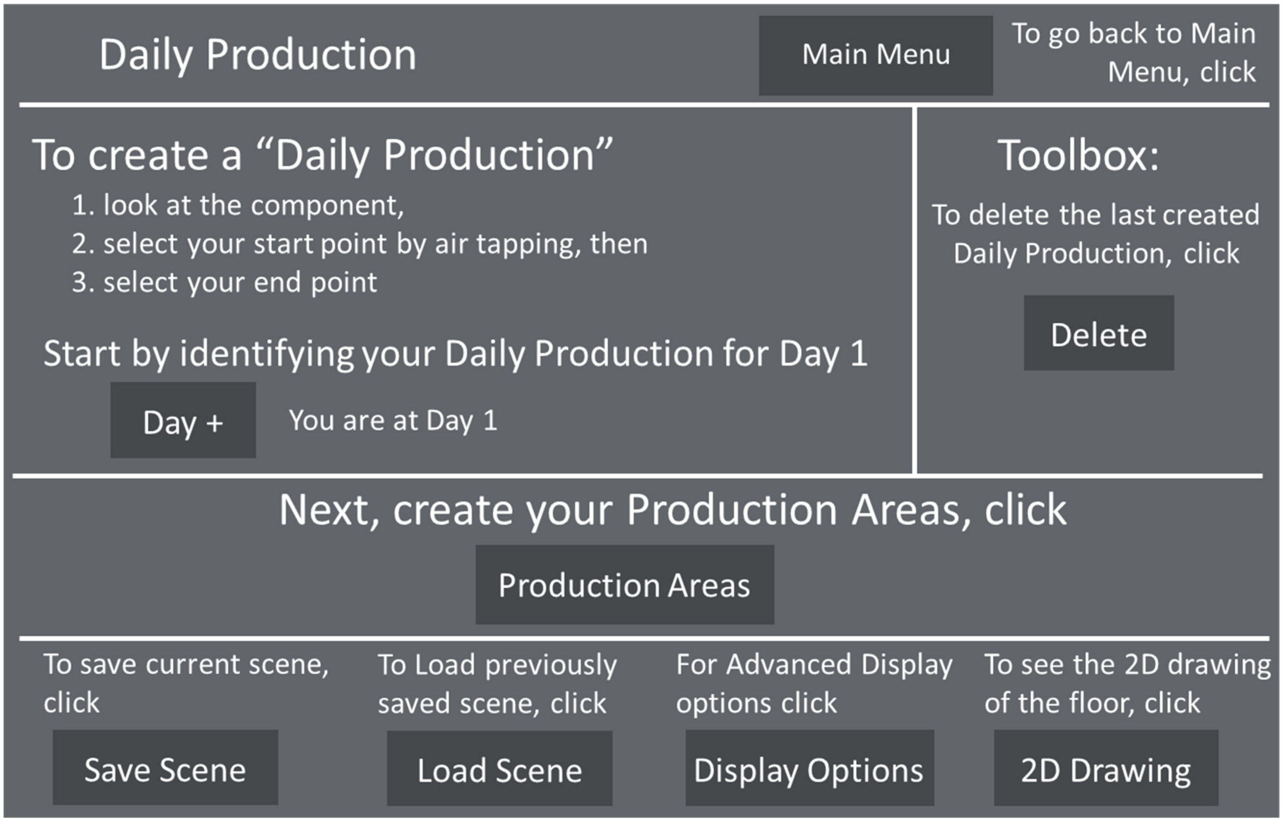
Common Areas

To create common areas, click

For advanced display options, click

To see the 2D drawing of the floor ,click

Figure 59 Main Menu



To go back to Main Menu, click

To create a “Daily Production”

1. look at the component,
2. select your start point by air tapping, then
3. select your end point

Start by identifying your Daily Production for Day 1

You are at Day 1

To delete the last created Daily Production, click

Next, create your Production Areas, click

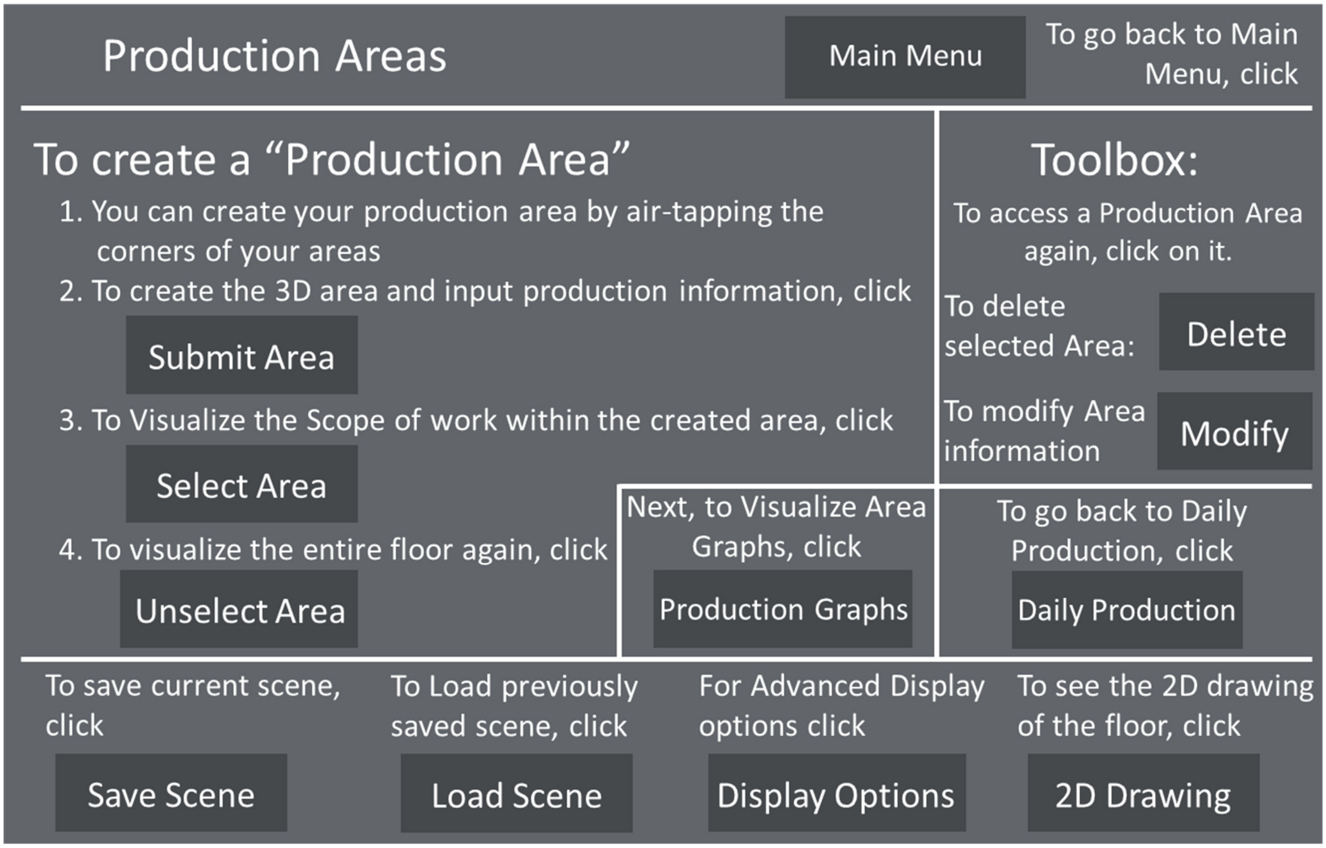
To save current scene, click

To Load previously saved scene, click

For Advanced Display options click

To see the 2D drawing of the floor, click

Figure 60 Daily Production Menu



Production Areas

Main Menu

To go back to Main Menu, click

To create a “Production Area”

1. You can create your production area by air-tapping the corners of your areas
2. To create the 3D area and input production information, click

Submit Area

3. To Visualize the Scope of work within the created area, click

Select Area

4. To visualize the entire floor again, click

Unselect Area

Toolbox:

To access a Production Area again, click on it.

To delete selected Area:

Delete

To modify Area information

Modify

Next, to Visualize Area Graphs, click

Production Graphs

To go back to Daily Production, click

Daily Production

To save current scene, click

Save Scene

To Load previously saved scene, click

Load Scene

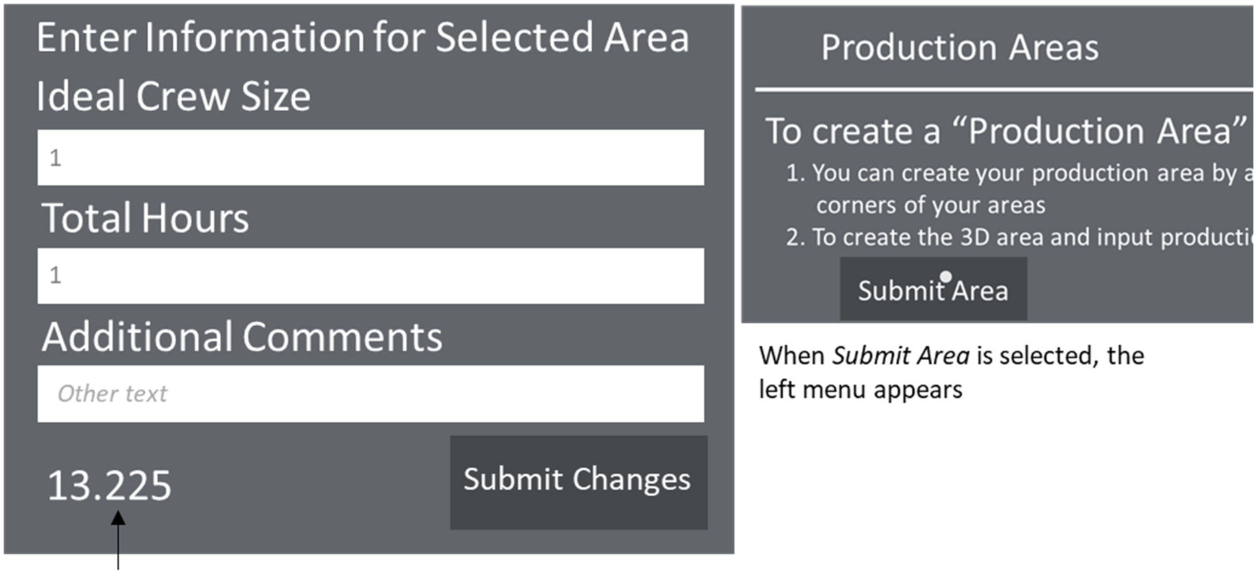
For Advanced Display options click

Display Options

To see the 2D drawing of the floor, click

2D Drawing

Figure 61 Production Areas Menu



Enter Information for Selected Area

Ideal Crew Size

1

Total Hours

1

Additional Comments

Other text

13.225

Production Areas

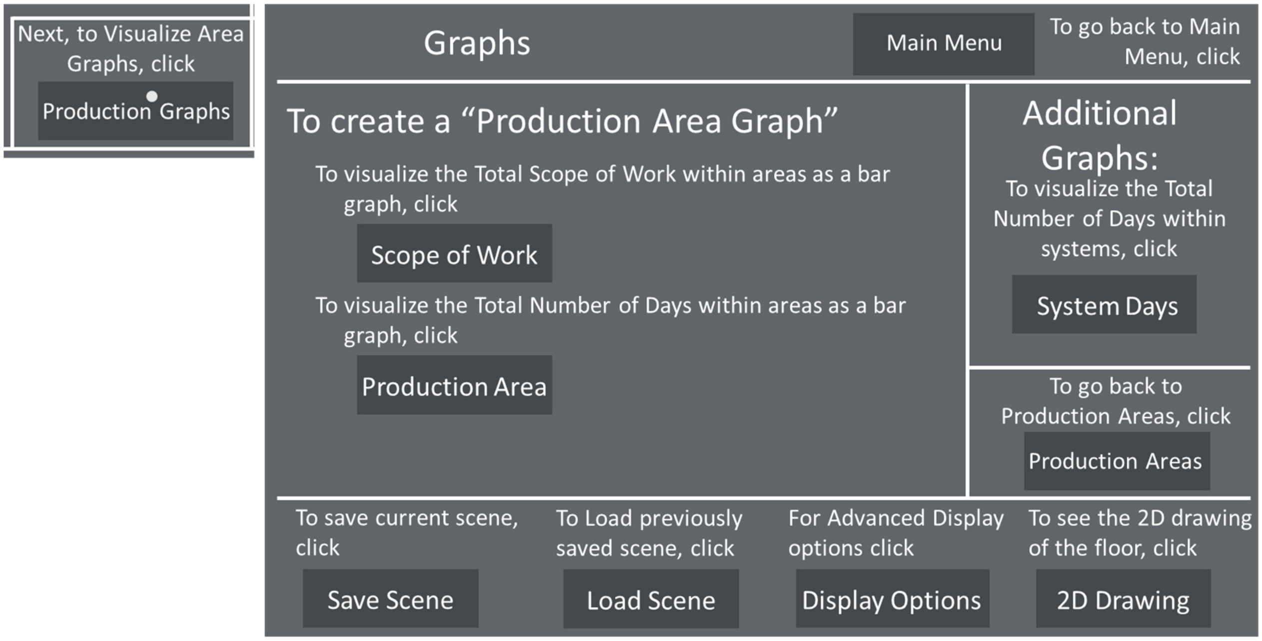
To create a "Production Area"

1. You can create your production area by a
corners of your areas
2. To create the 3D area and input producti

When *Submit Area* is selected, the left menu appears

Scope of work within the area (LF)

Figure 62 Production Area Information Menu



Next, to Visualize Area Graphs, click

Graphs

To go back to Main Menu, click

To create a "Production Area Graph"

To visualize the Total Scope of Work within areas as a bar graph, click

To visualize the Total Number of Days within areas as a bar graph, click

Additional Graphs:

To visualize the Total Number of Days within systems, click

To go back to Production Areas, click

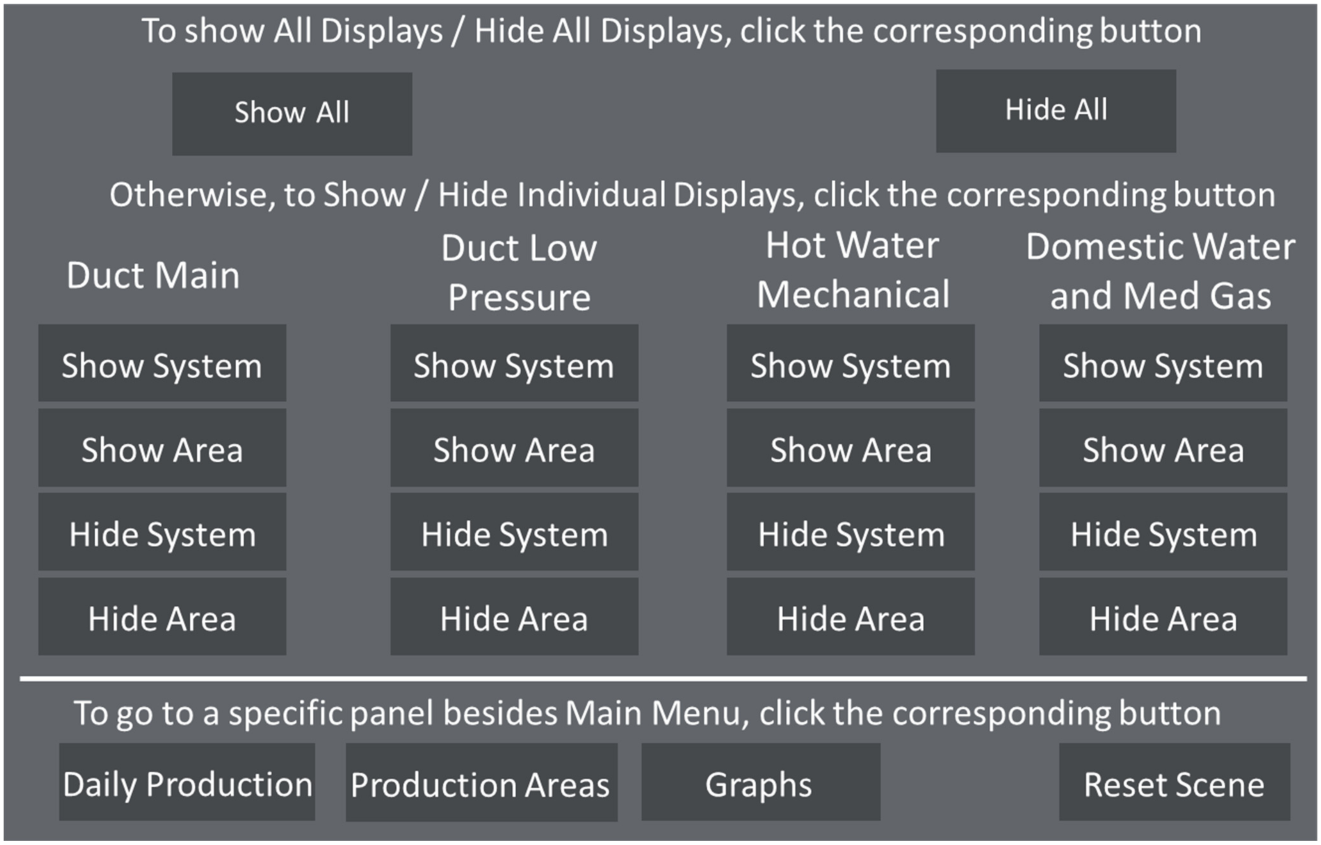
To save current scene, click

To Load previously saved scene, click

For Advanced Display options click

To see the 2D drawing of the floor, click

Figure 63 Graphs Menu



To show All Displays / Hide All Displays, click the corresponding button

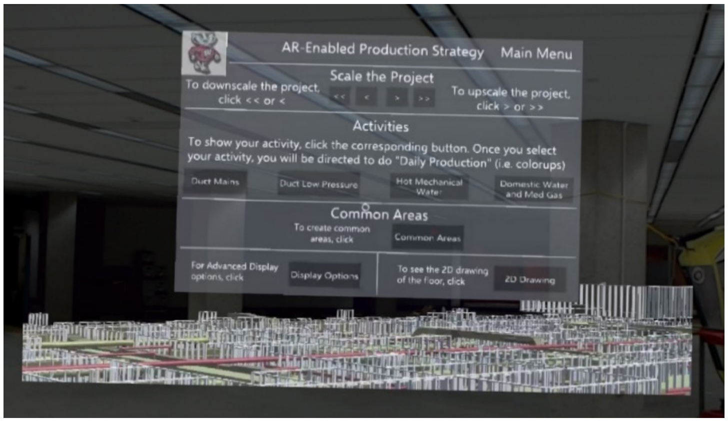
Otherwise, to Show / Hide Individual Displays, click the corresponding button

To go to a specific panel besides Main Menu, click the corresponding button

Figure 64 Display Options Menu

8.1.5.4. Prototype Demonstration

The following series of pictures are screenshots of the prototype. An Explanation is provided below each picture.



To downscale the project, click << or <

To upscale the project, click > or >>

To show your activity, click the corresponding button. Once you select your activity, you will be directed to do "Daily Production" (i.e. colorups)

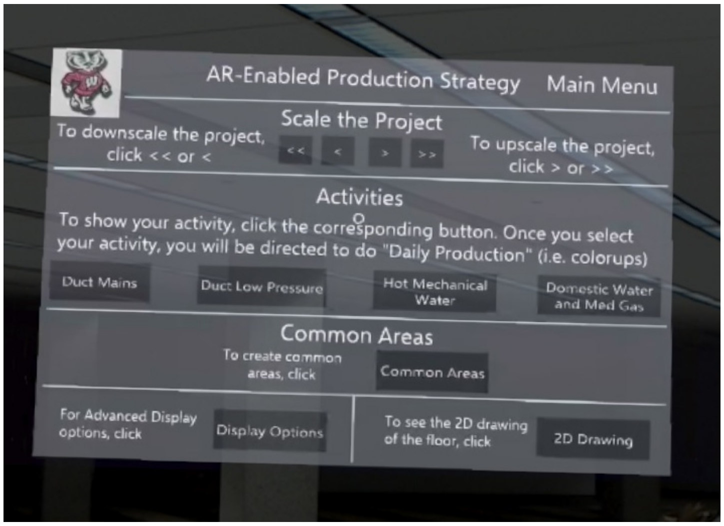
To create common areas, click

For Advanced Display options, click

To see the 2D drawing of the floor, click

Figure 65 User's First View

Figure 65: The first scene that the user sees is the 3D model and the Main Menu. The user can walk through the model and move closer to the different systems and elements.



AR-Enabled Production Strategy Main Menu

Scale the Project

To downscale the project, click << or <

To upscale the project, click > or >>

Activities

To show your activity, click the corresponding button. Once you select your activity, you will be directed to do "Daily Production" (i.e. colorups)

Common Areas

To create common areas, click

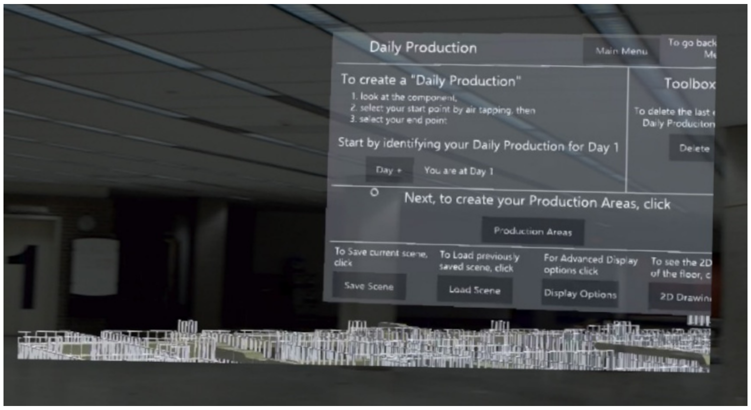
For Advanced Display options, click

To see the 2D drawing of the floor, click

Figure 66 Main Menu

Figure 66: The Main Menu includes different functions that the user can select. The user can first start by scaling down or scaling up the building depending on the setup and their preference. The user can scale the project by *gazing* at the arrow and *air-tapping* the dark areas. Once the user is satisfied with the scale of the building, they can then select the activity for which they would like to obtain the ‘colorup’ drawings.

Once the user performs daily production and creates production areas for individual activities (steps discussed below), the user can then select *Common Areas* from the Main Menu to develop common areas. Other features included in the Main Menu are *Display Options* and *2D Drawing.*



Daily Production

To go back Me

To create a "Daily Production"

1. look at the component,
2. select your start point by air tapping, then
3. select your end point

Start by identifying your Daily Production for Day 1

You are at Day 1

Toolbox

To delete the last Daily Produciton

Next, to create your Production Areas, click

To Save current scene, click

To Load previously saved scene, click

For Advanced Display options click

To see the 2D of the floor, c

Figure 67 Daily Production Menu

Figure 67: For this demonstration, *Duct Mains* was selected from the *Main Menu*. Once *Duct Mains* (or any other activity) is selected, a new menu titled *Daily Production* appears. The menu provides the user with introductions on how to perform daily production of the selected activity. The user needs to look at the component which they would like to select as their daily production, *air-tap* to select the start point and the look at the end of the element and *air-tap* again to select the end point. The menu also includes a *Delete* button that allows the user to remove the last daily production performed. The S*ave Scene* button saves the view and work of the user for later. The *Load Scene* button loads the latest scene saved by the user.

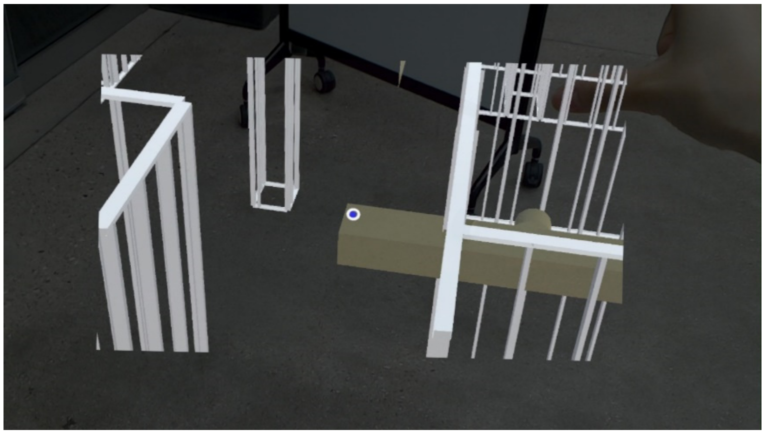


Figure 68 Daily Production – Start Point

Figure 68: The user first needs to look at the component and then *air-tap* to select their start point.

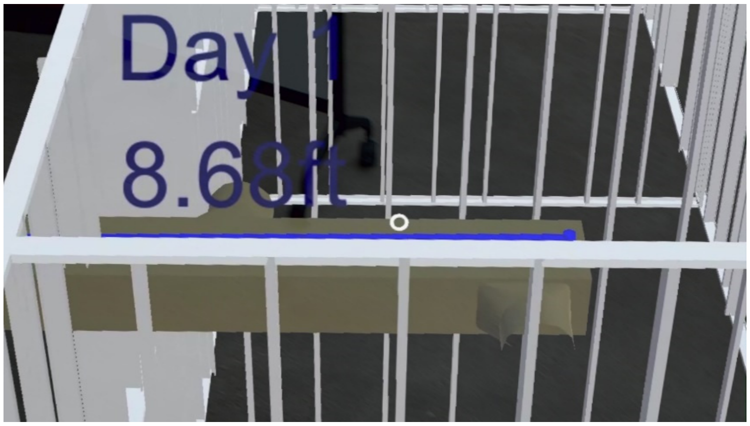


Figure 69 Daily Production – Day 1

Figure 69: Once the start point is selected, the user needs to look at the end of the component and *air-tap* to select the end point. A line will be formed between the start and end points and the quantity (in linear foot) will be displayed informing the user of the quantity (or scope of work) of their chosen daily production. The prototype only allows linear measurements. Therefore, if an element has an angle, the user will need to select the start and end points of the first segment, and subsequently select the start and end points of the second. The precision of the measurement depends on the *gaze* of the user.

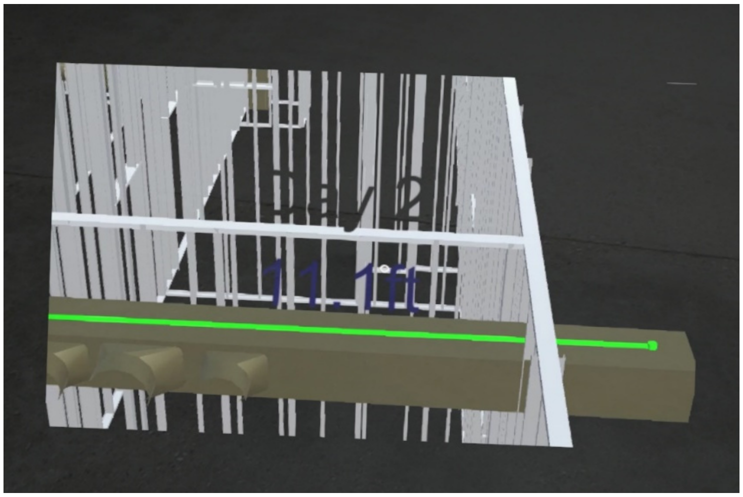
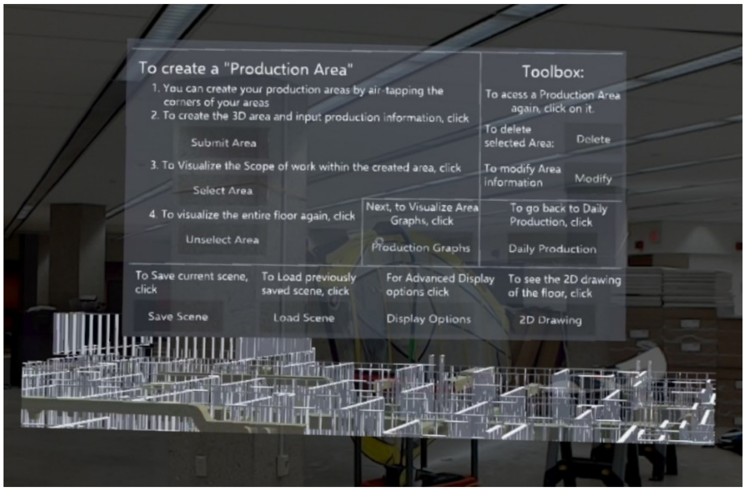


Figure 70 Daily Production – Day 2

Figure 70: Once the user has specified their daily production for the first day, they need to go to the *Daily Production* menu again and click on *Day* +. A message reading "You are at Day 2" will be displayed for the user to let them know that they are ready to perform the daily production for the following day. Three colors were used for the days: Blue, Green, and Red.



To create a "Production Area"

1. You can create your production areas by air-tapping the corners of your areas
2. To create the 3D area and input production information, click
3. To Visualize the Scope of work within the created area, click
4. To visualize the entire floor again, click

Next, to Visualize Area Graphs, click

Toolbox:

To acess a Production Area again, click on it.

To delete selected Area:

To modify Area information

To go back to Daily Production, click

To Save current scene, click

To Load previously saved scene, click

For Advanced Display options click

To see the 2D drawing of the floor, click

Figure 71 Production Area Menu

Figure 71: Once the user has 'highlighted' their daily production for the entire floor of the corresponding activity, they then need to create production areas. The number of days to include in each area is a called Takt-Time and is a parameter that is set by the general contractor (the specifics of how to determine Takt-Time are outside the scope of this research). The user is provided with instructions to create production areas.

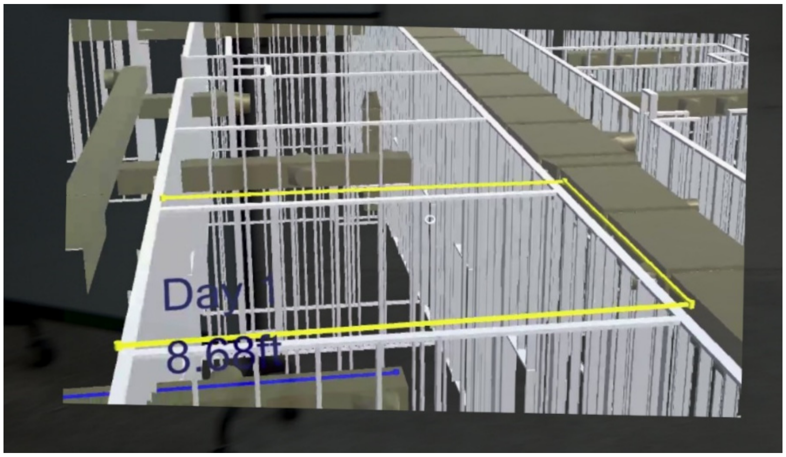


Figure 72 Surface of Production Area

Figure 72: The user starts by air-tapping to select the corners of their production area and the edges of the production area surface will be formed.

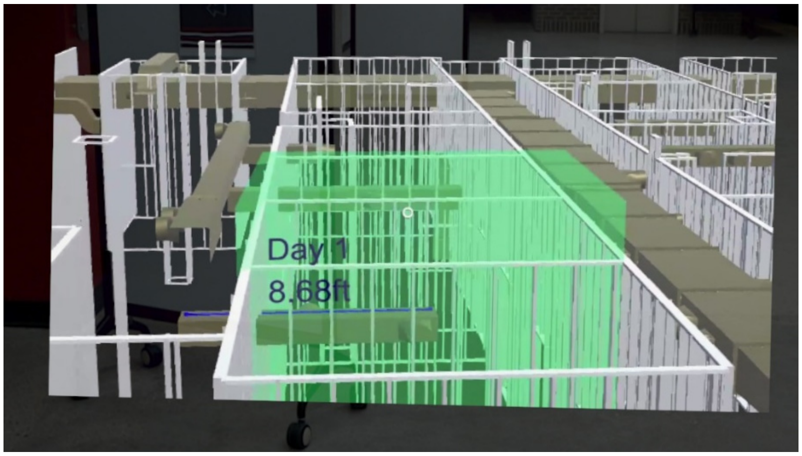
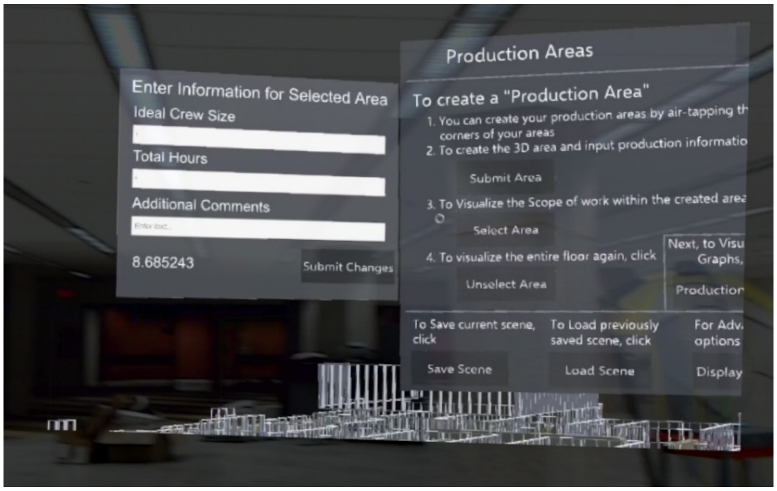


Figure 73 Production Area (3D)

Figure 73: Once the 2D surface is created, the user needs to select *Submit Area* from the Production Area Menu and the 3D area will be formed. The formed area will be highlighted in green indicating that the area is selected.


Enter Information for Selected Area

Ideal Crew Size

Total Hours

Additional Comments

8.685243

Production Areas

To create a "Production Area"

1. You can create your production areas by air-tapping th
corners of your areas
2. To create the 3D area and input production informatio
3. To Visualize the Scope of work within the created area
4. To visualize the entire floor again, click

Next, to Visu
Graphs,

To Save current scene, click

To Load previously saved scene, click

For Adv. options

Figure 74 Input Production Information Related to the Created Production Area

Figure 74: Once the user *air-taps* on *Submit Area* a new input menu will appear to allow the user to input production information related to the formed production area. By *tapping* on the white space, a virtual keyboard will appear in front of the user. It is important to note that the number shown on the bottom left corner of the *Input Menu* represents the total scope of work within that area which is obtained by summing all the individual daily productions included in the formed area. Once the user is done entering the production information, they can click on *Submit Changes* and the information is stored in the background.

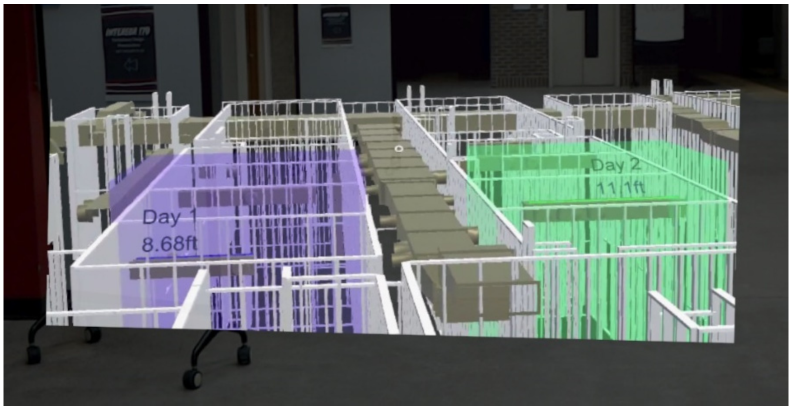


Figure 75 Create Another Production Area

Figure 75: Once done with the first area, the user can create another area by following the steps explained earlier. Areas are color-coded. It can be noticed that one area is green, and the other area is purple. The green color means that the corresponding area is selected, while the purple area means that this area belongs to the *Duct Mains* activity. Other activities have different colors for their areas. The color-coding is useful especially when areas of individual activities are overlapped to determine common areas.

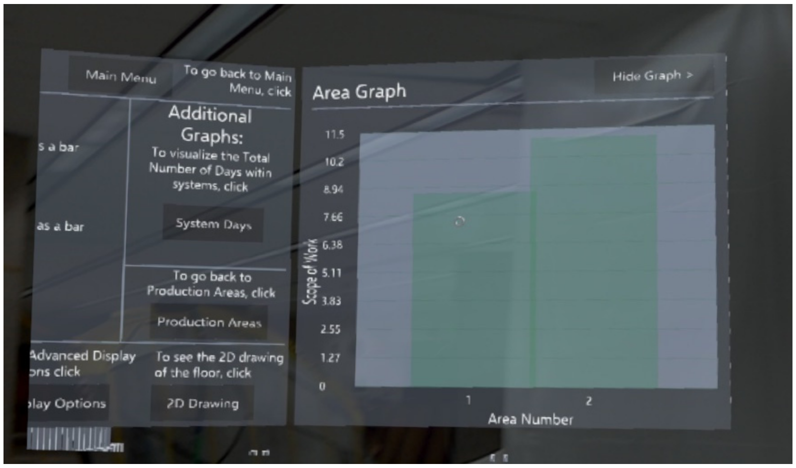


Figure 76 Automated Bar Chart of Scope of Work within the Different Production Areas of the Selected Activity

Figure 76: Once the areas are developed for an activity, the user has the option to look at bar charts to visualize the scope of work within areas and analyze and determine if the workflow is balanced. For individual activities, the user can visualize two types of graphs. The first graph illustrates the Scope of Work (linear foot in this case) in each area of the selected activity.

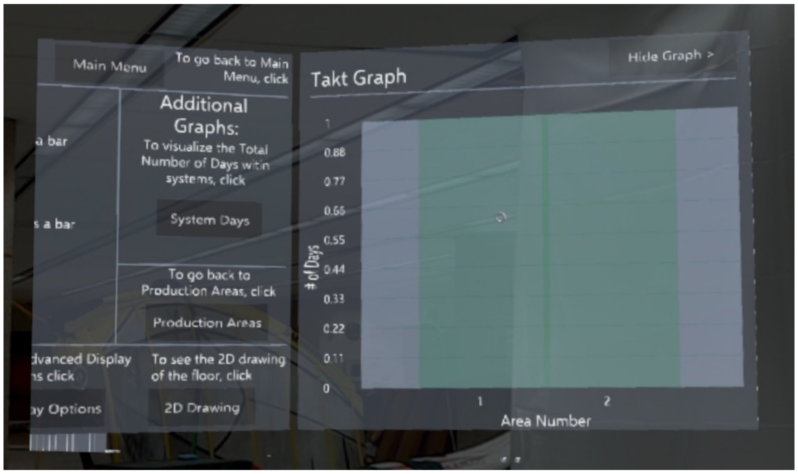


Figure 77 Automated Bar Chart of Number of Days within the Different Production Areas of the Selected Activity

Figure 77: The second type of graph shows the number of days (daily production) within each area.

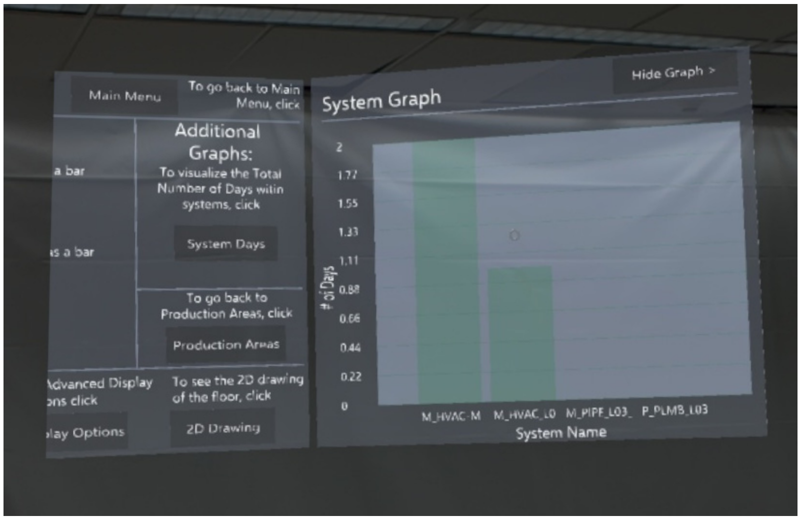


Figure 78 Bar Chat of Workflow Balance Across the Different Activities of a Selected Common Area

Figure 78: Users responsible for different activities (in our case – duct mains, low pressure, hot mechanical water, and domestic water) need to go through the aforementioned steps and perform daily production and develop areas for their corresponding activities. Once the areas of individual activities have been created, the user can go back to the main menu and *tap* on *Common Areas*.

The user then has the option to create a new area (common area) that includes the daily productions of all activities. The user can then select *System Days* which allows to visualize the number of days for each activity within the created common area.

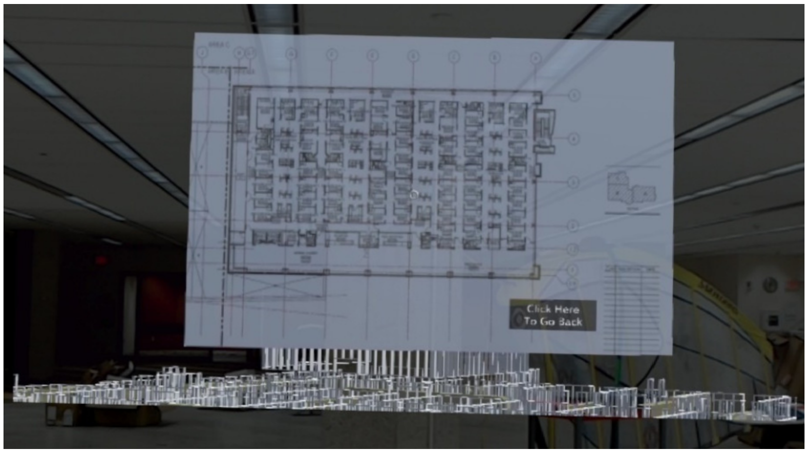
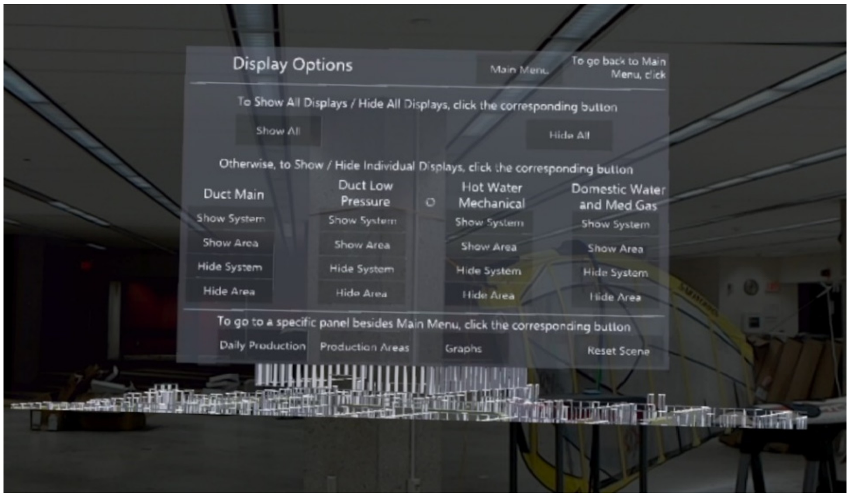


Figure 79 Display of 2D Drawing

Figure 79: The user can also *tap* on *2D Drawings* to visualize the 2D floor plan of the building. This feature was added to show that 2D information can also be visualized in AR.


Display Options

To go back to Main Menu, click

To Show All Displays / Hide All Displays, click the corresponding button

Otherwise, to Show / Hide Individual Displays, click the corresponding button

To go to a specific panel besides Main Menu, click the corresponding button

Figure 80 Additional Display Options

Figure 80: At any step throughout this process, the user can access the *Display Options* feature that allows the user to show or hide activities and areas as they wish.

A video demonstration of how the prototype functions can be accessed by scanning the following QR codes:

- Video 1 – Overview

  Scan the following QR code or click this link to access the video.

- Video 2 – Perform Daily Production

  Scan the following QR code or click this link to access the video.

- Video 3 – Develop Area

Scan the following QR code or click this link to access the video.

- Video 4 – Additional Options

Scan the following QR code or click this link to access the video.

8.2. Prototype Validation

Throughout the development of the prototype, feedback from the construction industry, specifically from PSP subject matter experts was incorporated into the design to continuously furnish usability insights to ensure the effectiveness of the software.

Once the prototype was fully developed, it needed to be reviewed and validated by external stakeholders – PSP subject matter expert in this case. Multiple evaluation methods can be used to assess and validate the coded prototype. The two methods that are used to validate the AR-PSP are: (1) usability testing and (2) survey. (Arnowitz et al. 2010) indicated that these two evaluation methods are very appropriate to validate coded prototypes. Usability testing is conducted using a one-on-one protocol to validate the usability of the design with selected participants via direct review and interaction with a simulation of the design. Surveys, on the other hand, allow for a more formal evaluation of the software (Arnowitz et al. 2010).

8.2.1. Usability Testing

(Arnowitz et al. 2010) sketched 14 sequential steps that are needed to validate a prototype using usability testing:

1. Develop a test plan
2. Prepare a screener questionnaire to pre-qualify participants
3. Develop a contact list of potential test participants, including pilot test participants
4. Identify an internal test participant recruiter or hire one externally
5. Reserve room or lab space for the duration of the validation sessions
6. Ensure necessary equipment for conducting each session

7. Prepare a schedule of validation sessions
8. Develop a participant guide to provide users with the usage context and any objectives
9. Provide test stimulus – the prototype or software to be validated
10. Conduct a pilot session with a conveniently available participant
11. Conduct validation in an appropriate predetermined number of scheduled sessions
12. Using notes and video recordings, review and analyze the validation data
13. Prepare validation results document
14. Prepare a presentation of the validation results and design successes and improvements

Using the 14 steps outlined above, the usability testing was conducted. The validation effort was coordinated with TBC who took the initiative to identify potential participants and set up dates to conduct the validation. The HoloLens (or the HoloLens hard hat more specifically) was also provided by the company (steps 1-7).

The prototype was validated on an ongoing construction project. A short presentation was delivered to participates to introduce them to the research topic, review the steps of the PSP, explain the technology (AR), outline the research hypotheses, and provide an overview of the demonstration software. Participants were also provided with short tutorial videos that demonstrated the functionalities of the prototypes and familiarize themselves with the software and its capabilities. In addition, the means of interacting with the prototype (*gaze* and *air-tap* and *tap and hold* gestures) were explained and demonstrated to the participants (step 8).

The primary investigator (the author) demonstrated the use of the application through a live demonstration of the prototype (steps 9-10). The prototype was validated through two group sessions with a total of 20 participants (step 11). All of the previously discussed steps were performed in a group setting. The validation itself, however, was performed in a one-by-one setting. Each participant was provided with the HoloLens and was assisted in wearing and adjusting the device for comfort. Each participant was again given a short introduction to the device and its how-tos. For practice, each participant was asked to select the *Holographic Remoting Player* application on the HoloLens and provide the IP address. Then, the application was run in Unity and the participant was able to visualize the prototype. The primary investigator (the author) guided participants through the validation phases and directed them by explaining the menu and the different functionalities when needed.

The following pictures depict the usability testing of the AR-Enabled PSP Prototype.

Figure 81 Primary Investigator Providing Participants with a Live Demo of the Prototype

Figure 82 Field Engineer Testing the Prototype

Figure 83 Ability of Other participants to visualize what the user is Seeing through the Microsoft HoloLens Application

Figure 84 Project Manager Testing the Prototype

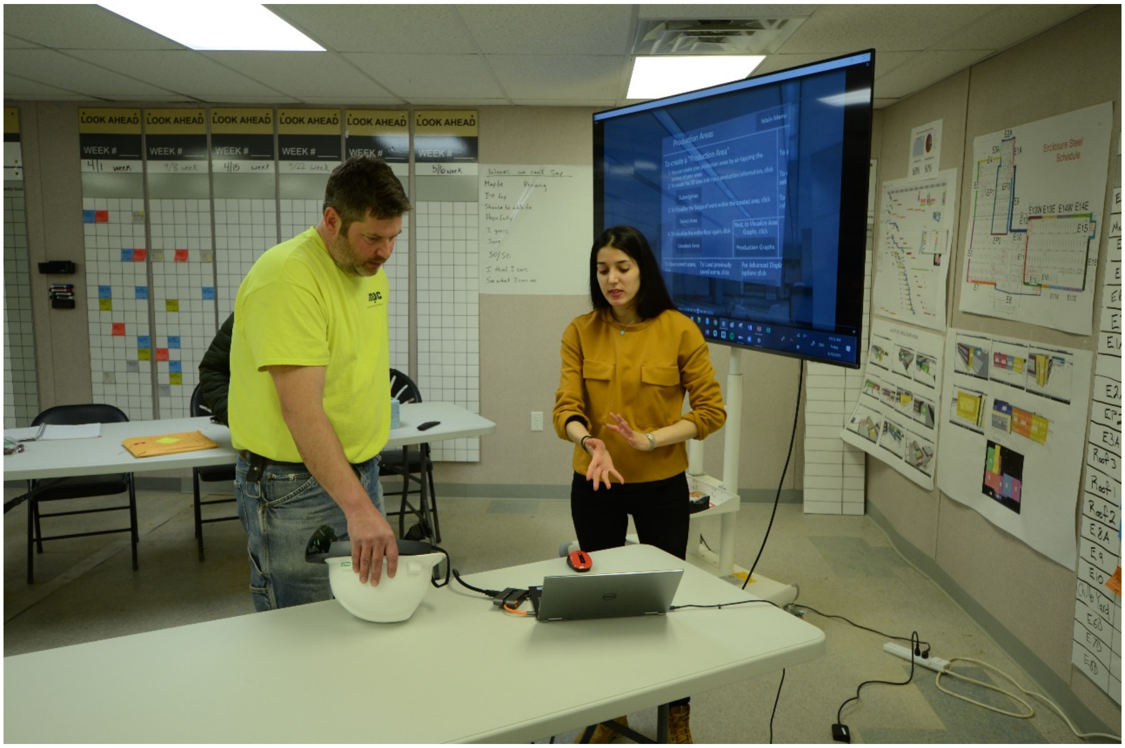


Figure 85 Primary Investigator Providing an Overview of the Prototype to a Foreman

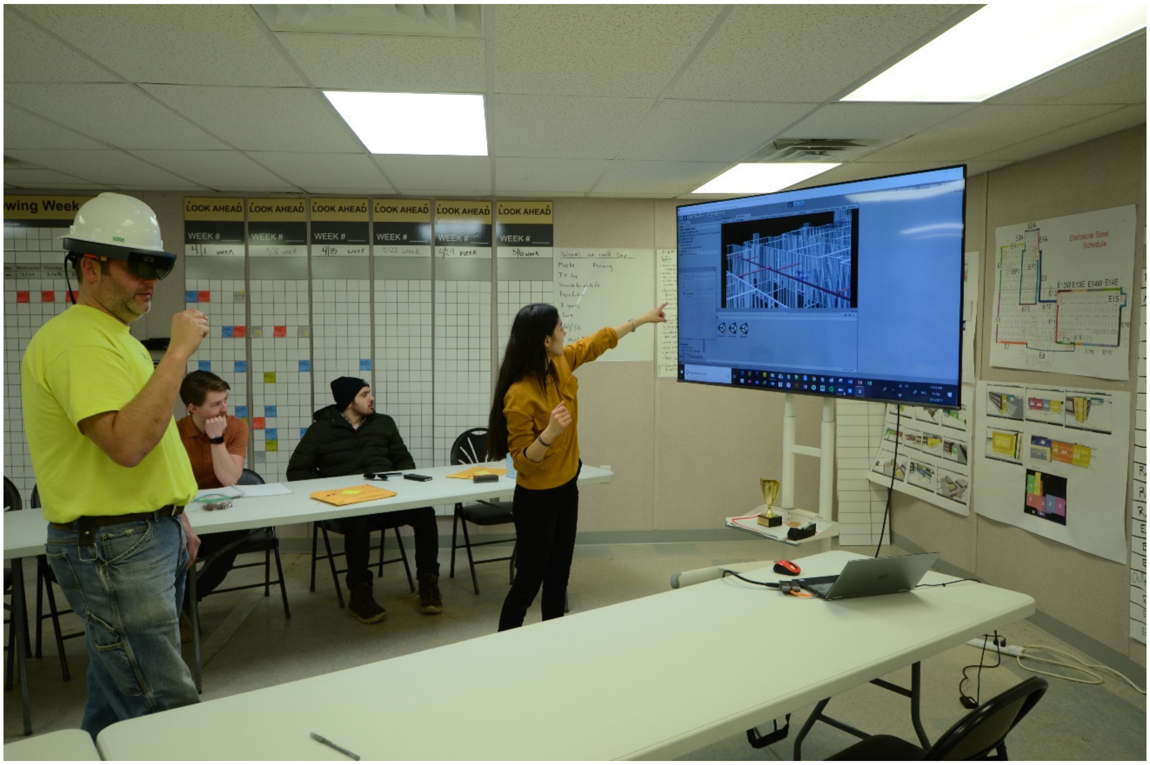


Figure 86 Foreman Testing the Prototype

The results of the usability test are reported in the Validation section (Section 8.3) along with the survey results (steps 12-14).

The challenges encountered during usability testing were technological, mainly related to running the software. When the user the user spent testing the prototype (creating all daily productions and multiple production areas), the software would disconnect on its own. However, using the 'save' feature in the prototype allowed the user to reload their work and continue their validation.

8.2.2. Surveys

A pre-demonstration survey was designed to collect qualitative data from participants to assess and evaluate the AR-PSP prototype. The survey was divided into six sections.

The first section concerned general information about the participants. The second section was concerned with comparing the Traditional PSP (Current State) and the AR-PSP Prototype (Future State) through 11 hypotheses (discussed in section 8.3). The third focused on the software itself and its evaluation criteria. The fourth section included questions to evaluate the hardware (the Microsoft HoloLens). The fifth section concerned AR evaluation criteria. The sixth section included open-ended questions to collect additional feedback from the participants.

To ensure the effectiveness of the survey, the questions were reviewed by industry experts and UW-Madison faculty members. The survey was further refined and was then ready for distribution.

Participants were first asked to test the prototype and were then asked to complete a survey to capture their feedback. Physical and digital copies of the survey were distributed and a total of 20 surveys were obtained. The results of the collected data are discussed in the next section of this chapter.

8.3. Validation Results

This section discusses the analysis of the data collected from the validation phase from 20 participants.

8.3.1. Participant Information

Participants were asked to select their age category. 45% of participants were between 18 and 34 years, 35% between 35 and 44 years, 15% between 45 and 54, and the remaining 5% between 55 and 64. Participants were also asked to specify their current job title. 5 out of the 20 participants are Project Managers and 3 participants are Field Engineer. Single responses were collected from participants with the following titles: Project Engineer, Project Technology, VDC

Specialist, Project Manager/BIM Manager, Steamfitter Foreman, Foreman, MEP Coordinator, Senior Project Manager, Director of Production Planning and Innovation, Production Engineer, BIM Coordinator, Member of the Performance and Innovation Resources Team.

The respondents' expertise in construction ranged from 2 years to 27 years, with an average expertise of over 13 years. Collectively, the respondents totaled 248 years of experience in construction. During their years of experience in the construction industry, the number of projects that the participants worked on ranged from 2 to over 100 projects. Out of these projects, participants were asked to identify the number of projects on which they have been involved in PSP. The respondents' experience with PSP ranged from 1 project to over 20 projects.

Participants were finally asked to identify their experience with AR in the construction industry. 20% of participants indicated that they were not aware of the existence of AR; 50% indicated that they are aware of the technology, but have not had any experience with it; 15% of respondents reported that they have explored or are currently exploring AR application for construction projects; finally, the remaining 15% indicated that they have tested or are currently testing AR applications for future use. Unlike the data collected from the AR survey in the Chapter 3 of this dissertation, the original scores collected from the prototype survey were not adjusted according to the participants' prior experience with AR in construction. The reasoning behind this assumption is that the hands-on experience testing the prototype allows participants to answer questions with less subjectivity as they have been directly exposed to the technology and its capabilities.

8.3.2. Traditional PSP vs AR-PSP

The second section of the survey consisted of 11 questions that compared between the traditional and AR-enabled processes in 11 areas: collaboration, communication, interpretation of plans, detection of errors, decision-making, efficiency, safety integration, input accuracy, information access, navigation, and documentations. These questions were extracted from the challenges identified in Chapter 7 (Section 7.1). From these questions, 11 hypotheses were formulated which are discussed in the following sections. Since there are two groups under comparison (Traditional PSP and AR-PSP Prototype) and due to the qualitative nature of the collected data, the non-parametric MWW test was used to test the hypotheses and determine any statistical significance between the two processes.

8.3.2.1. Null Hypothesis 1: Collaboration is the same in the Traditional and AR-Enabled PSP

Participants were asked to rate how successfully collaboration was promoted in each of the Traditional PSP and AR-enabled PSP. Collaboration was measured on a five-point Likert scale of marginally (1), somewhat (2), moderately (3), significantly (4), and extremely (5). Figure 87 presents comparative boxplots of the level of collaboration in each of the traditional and AR-enabled processes. As can be seen, the AR-enabled PSP promoted collaboration more than the traditional process.

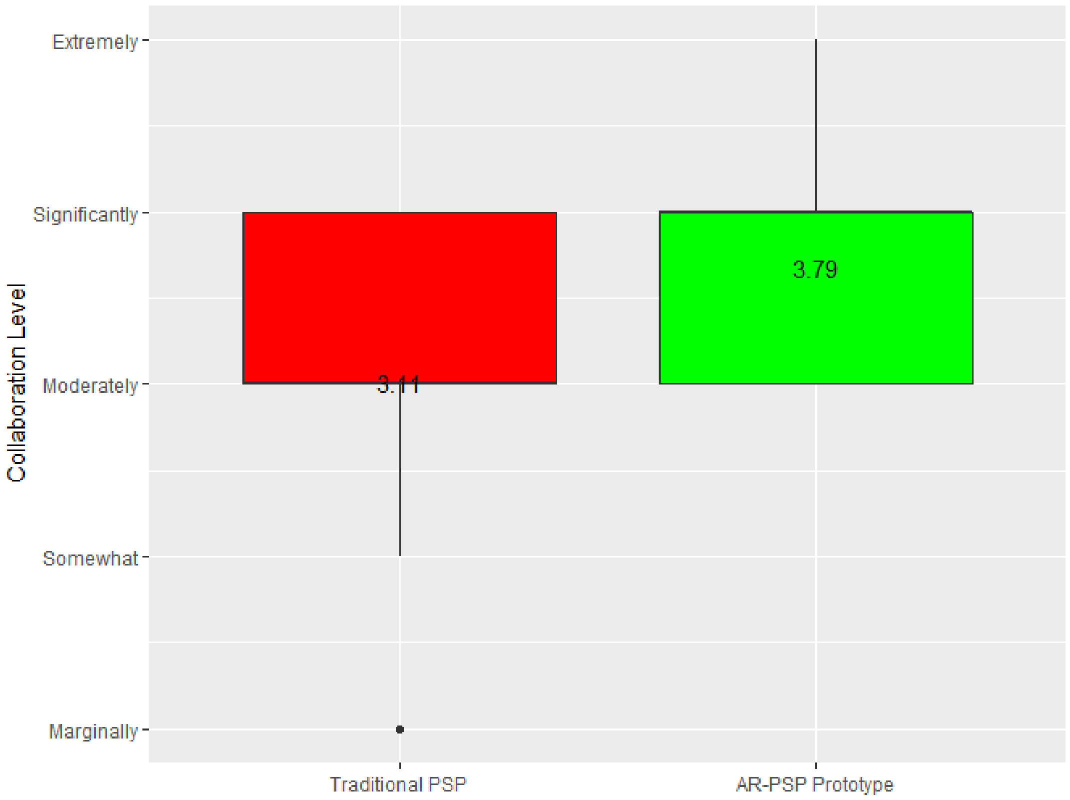


Figure 87 Collaboration – Traditional PSP vs AR-PSP

In order to test whether this difference is significant, the non-parametric MWW test was conducted to statistically compare the level of collaboration in the two processes. The low p-value resulting from the MWW test (0.016) provides a statistical evidence at the 95% confidence level indicating that, on average, the AR-enabled PSP promotes collaboration more than the Traditional process.

8.3.2.2. Null Hypothesis 2: Miscommunication is the same in the Traditional and AR-Enabled PSP

Participants were asked to rate how successfully miscommunication was minimized in each of the Traditional PSP and AR-enabled PSP. The reduction of miscommunication was measured on a five-point Likert scale of marginally (1), somewhat (2), moderately (3), significantly (4), and extremely (5). Figure 88 presents comparative boxplots of the level of miscommunication reduction in each of the Traditional and AR-enabled processes. As can be seen, miscommunication is reduced more in the AR-enabled PSP.

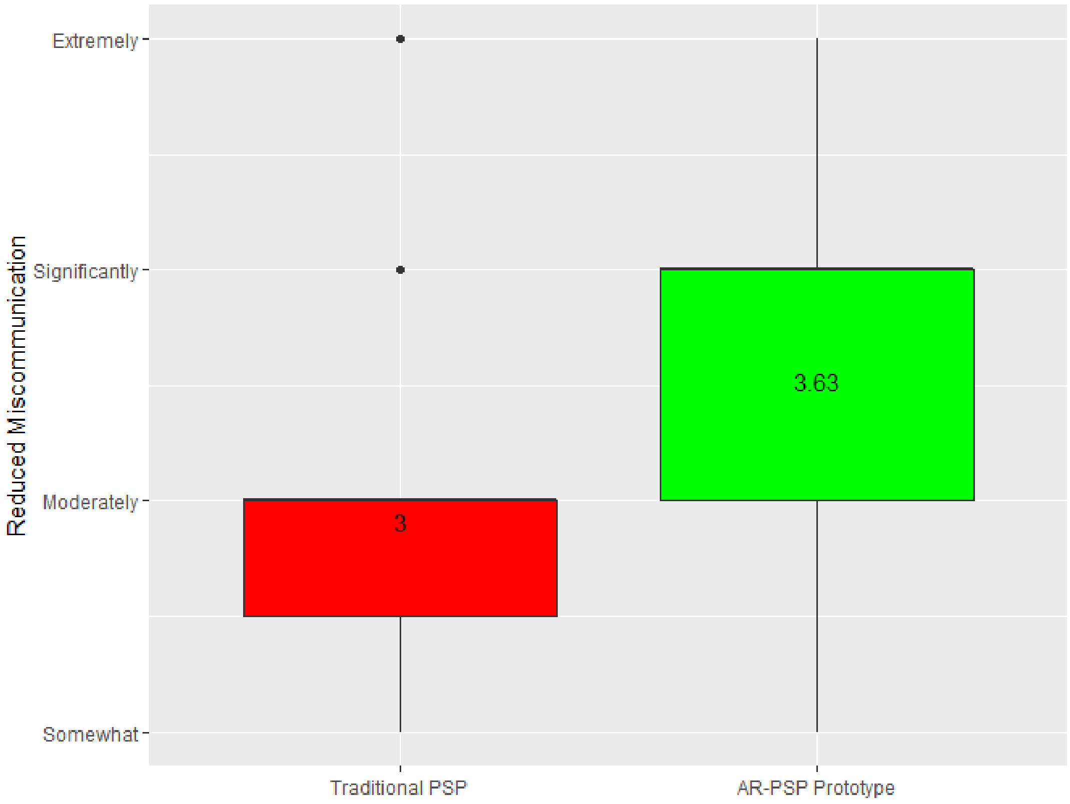


Figure 88 Miscommunication – Traditional PSP vs AR-PSP

In order to test whether this difference is significant, the non-parametric MWW test was conducted to statistically compare the level of miscommunication reduction in the two processes. The low p-value resulting from the MWW test (0.0108) provides a statistical evidence at the 95% confidence level indicating that, on average, the AR-enabled PSP reduces miscommunication more than the Traditional process.

8.3.2.3. Null Hypothesis 3: Spatial Cognition is the same in the Traditional and AR-Enabled PSP

Respondents were asked to rate how easy it was to interpret the drawings/plans used in each of the traditional PSP and AR-enabled PSP using the following five-point Likert scale: very hard (1), hard (2), moderate (3), easy (4), very easy (5). Figure 89 illustrates comparative boxplots of the ease level of interpreting drawings and plans in each of the Traditional and AR-enabled processes. Both processes seem to have similar level of ease on average, with plans and drawings being interpreted slightly easier with the AR-PSP.

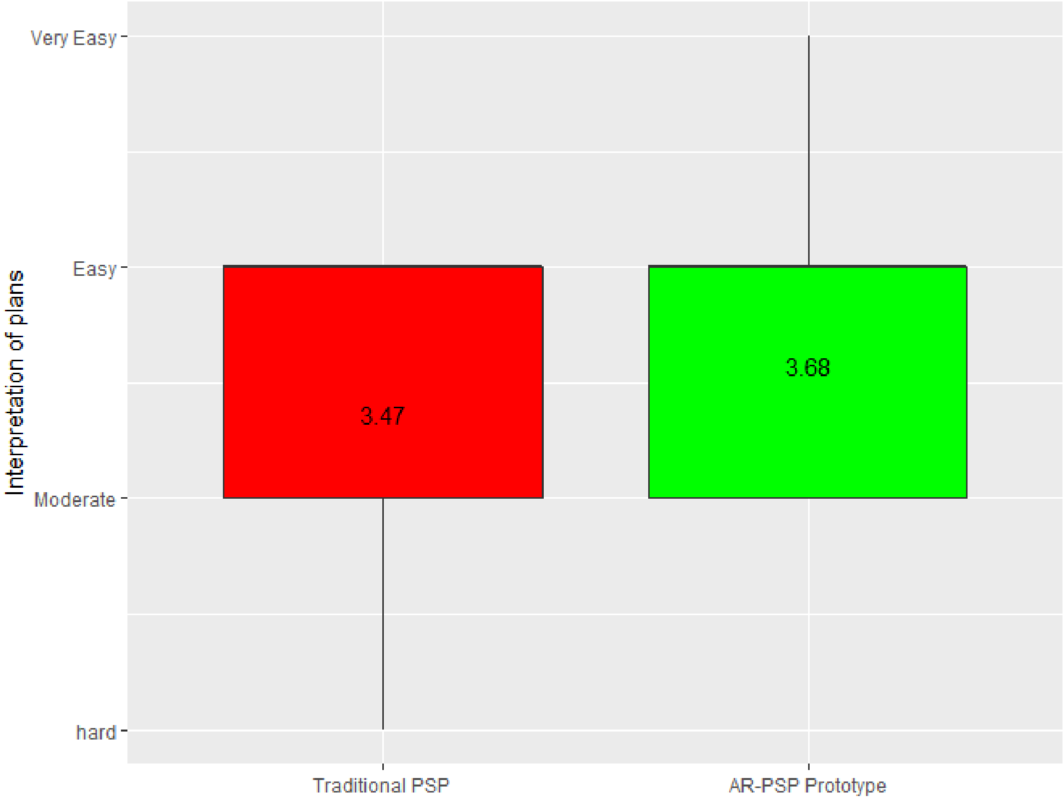


Figure 89 Interpretation of Plans – Traditional PSP vs AR-PSP

In order to test whether this difference is significant, the non-parametric MWW test was conducted to statistically compare the level of ease of interpreting drawings and plans in the two processes. The high p-value resulting from the MWW test (0.369) does not provide enough evidence to prove a statistical difference between the two processes, indicating that at the 95% confidence level, and on average, the interpretation of plans has similar level of ease in Traditional PSP and in the AR-enabled PSP. The results of this hypothesis can be supported with the fact that participants have on average 13 years of experience is construction and reading 2D drawings, and therefore, the mental workload between the two mediums (2D drawings and 3D projected model) is similar. The small sample size did not allow for a comparison of participants' responses based on their age category.

8.3.2.4. Null Hypothesis 4: Quality and Error Detection are the same in the Traditional and AR-Enabled PSP

Respondents were asked to rate how easy it was to interpret the drawings/plans used in each of the Traditional PSP and AR-enabled PSP using the following five-point Likert scale: very hard (1), hard (2), moderate (3), easy (4), very easy (5). Figure 90 illustrates comparative boxplots of the level of difficulty of detecting errors in each of the Traditional and AR-enabled processes. Both processes seem to have similar level of ease on average, with plans and drawings being interpreted slightly easier with the AR-PSP.

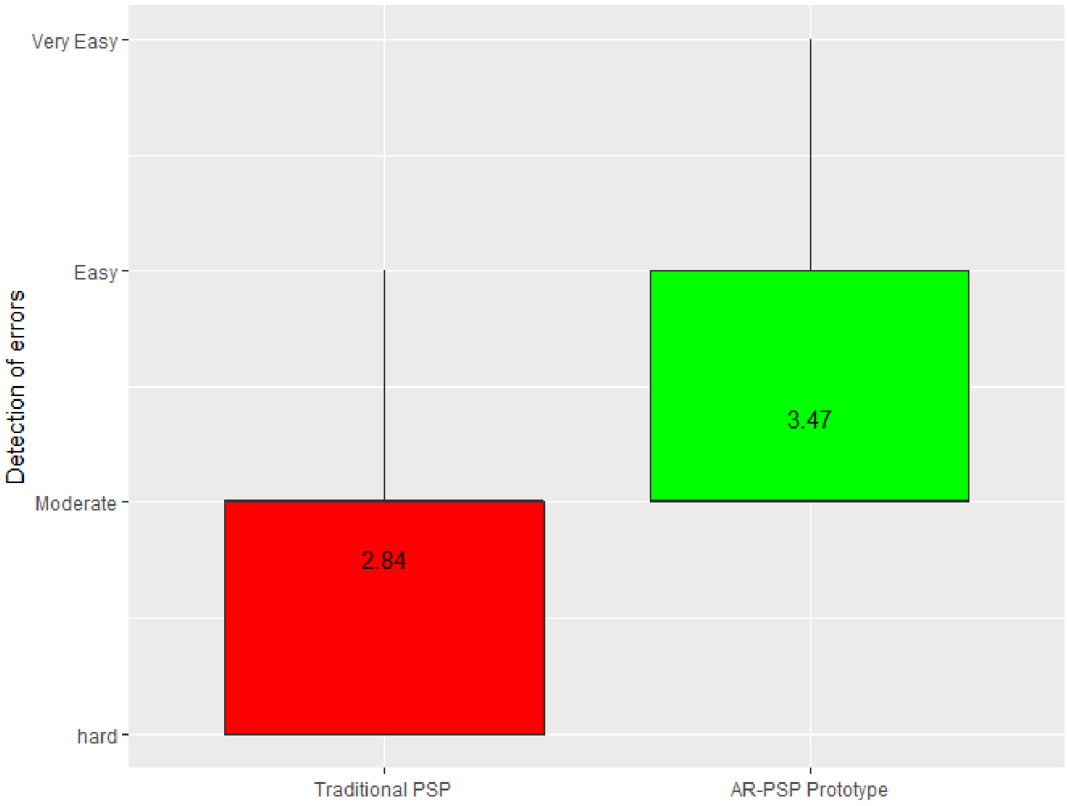


Figure 90 Detection of Errors – Traditional PSP vs AR-PSP

In order to test whether this difference is significant, the non-parametric MWW test was conducted to statistically compare the level of difficulty of detecting errors in both processes. The low p-value resulting from the MWW test (0.0121) provides a statistical evidence at the 95% confidence level indicating that, on average, it is easier to detect errors in the AR-PSP than it is in the Traditional PSP.

8.3.2.5. Null Hypothesis 5: Decision-Making is the same in the Traditional and AR-Enabled PSP

Participants were asked the identify degree to which decision-making was facilitated in each of the Traditional PSP and AR-enabled PSP using a five-point Likert scale of marginally (1), somewhat (2), moderately (3), significantly (4), and extremely (5). Figure 91 presents comparative boxplots of the degree to which decision-making in facilitated in each of the

Traditional and AR-enabled processes. As can be seen, the AR-enabled PSP facilitates decision-making more than the traditional process.

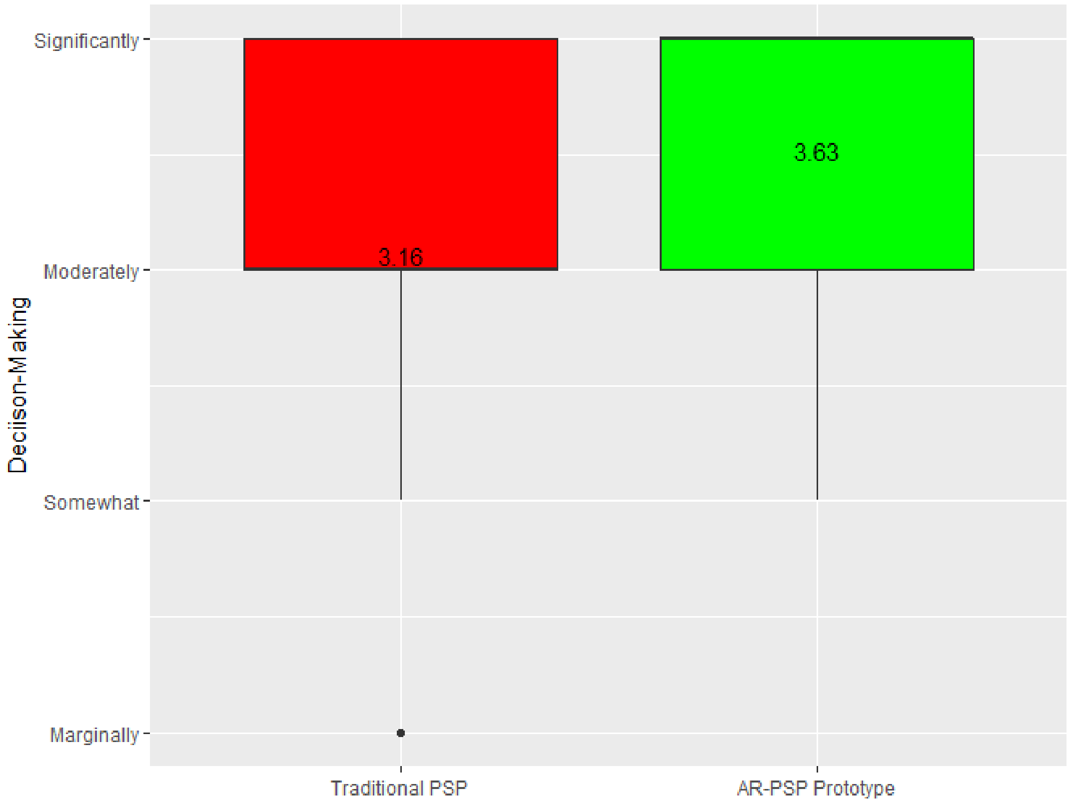


Figure 91 Decision-Making – Traditional PSP vs AR-PSP

In order to test whether this difference is significant, the non-parametric MWW test was conducted to statistically compare the degree to decision-making in the two processes. The low p-value resulting from the MWW test (0.0313) provides a statistical evidence at the 95% confidence level indicating that, on average, the AR-enabled PSP facilitates decision-making more than the Traditional process.

8.3.2.6. Null Hypothesis 6: Process Efficiency is the same in the Traditional and AR-Enabled PSP

Respondents were asked to rate how time efficient each of the Traditional PSP and AR-enabled PSP was. Efficiency was measured on a five-point Likert scale of marginally (1), somewhat (2), moderately (3), significantly (4), and extremely (5). Figure 92 illustrates comparative boxplots of the level of time efficiency for each of the Traditional and AR-enabled processes. Both processes seem to have similar level of efficiency on average, with the AR-PSP being slightly more time efficient.

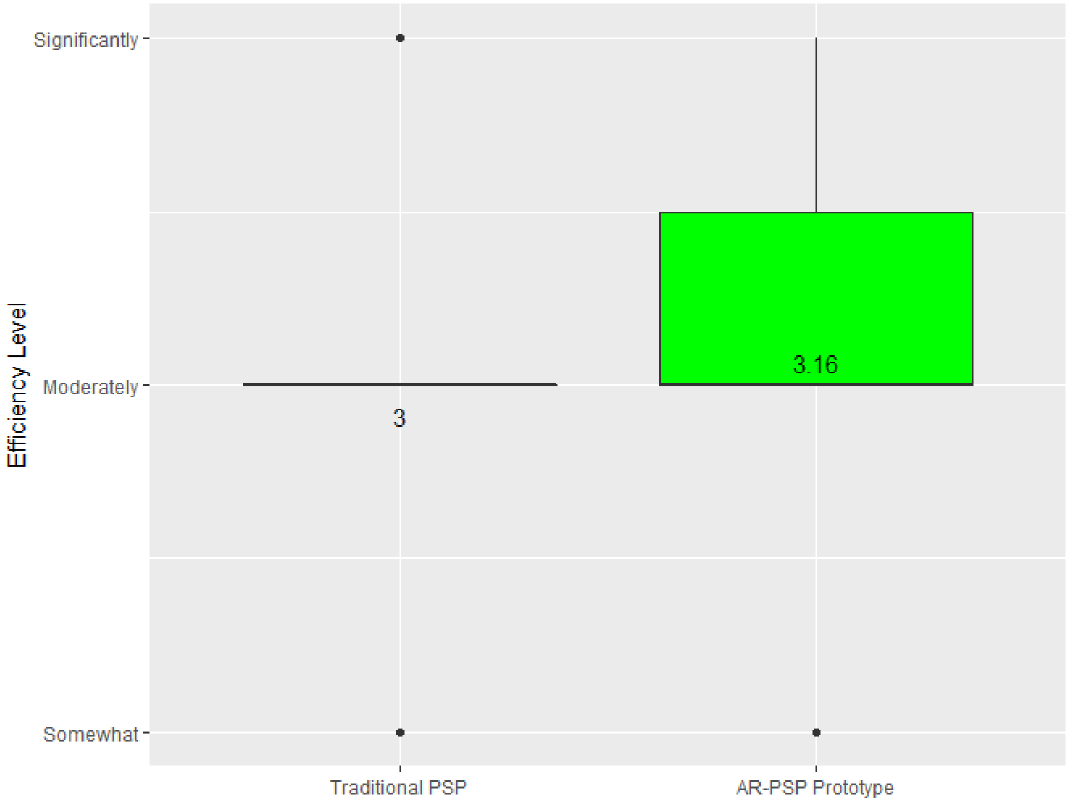


Figure 92 Time Efficiency – Traditional PSP vs AR-PSP

In order to test whether this difference is significant, the non-parametric MWW test was conducted to statistically compare the level of time efficiency of both processes. The high p-value resulting from the MWW test (0.413) does not provide enough evidence to prove a statistical difference between the two processes, indicating that at the 95% confidence level, and on average, the traditional PSP and the AR-enabled PSP have similar level of efficiency. In the sixth section of the survey, respondents indicated that it takes time and practice to get used to the AR environment which makes the AR-Enabled PSP seem slower.

8.3.2.7. Null Hypothesis 7: Integration of safety management is the same in the Traditional and AR-Enabled PSP

Respondents were asked to rate how easy and efficient it was to consider and integrate safety mitigation techniques and identify safety hazards is each of the Traditional PSP and AR-Enabled PSP, using the following five-point Likert scale: very hard (1), hard (2), moderate (3), easy (4), very easy (5). Figure 93 illustrates comparative boxplots of the level of integrating safety practices into each of the Traditional and AR-enabled processes. As can be seen, the AR-enabled PSP allows for the integration of safety more than the Traditional process.

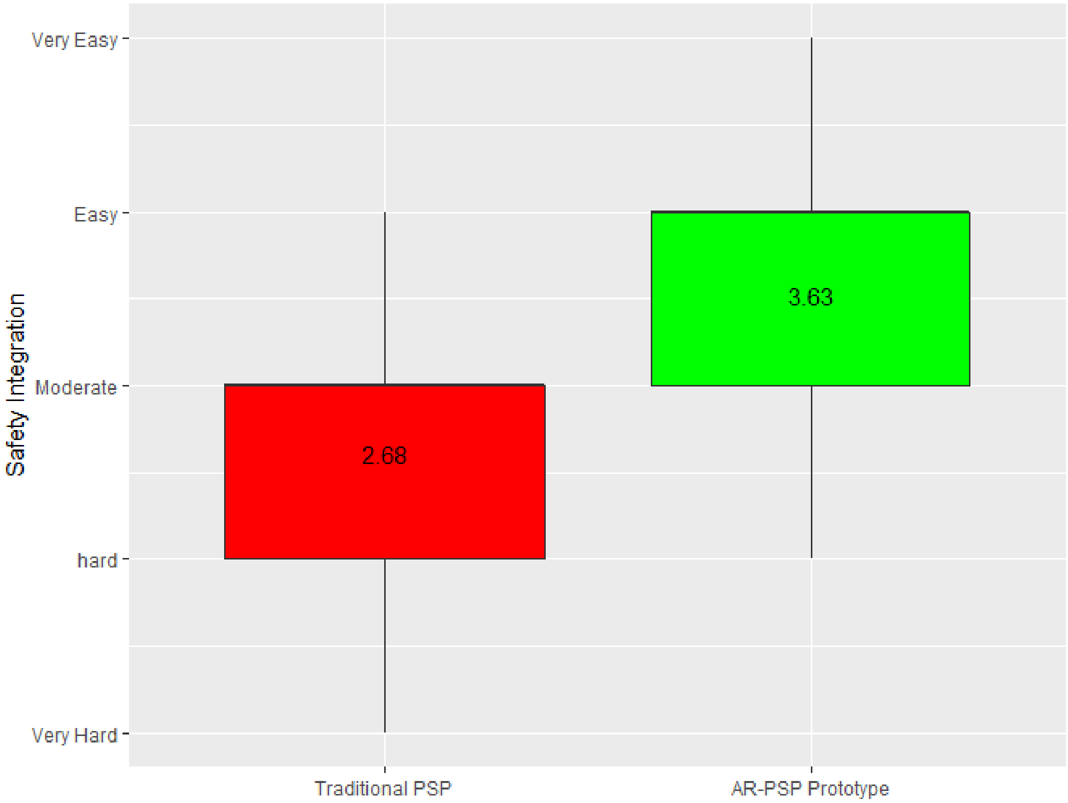


Figure 93 Safety Integration – Traditional PSP vs AR-PSP

In order to test whether this difference is significant, the non-parametric MWW test was conducted to statistically compare the level of safety integration into the two processes. The low p-value resulting from the MWW test (0.0002) provides a statistical evidence at the 95% confidence level indicating that, on average, the AR-enabled PSP allows and facilitates the integration of safety management more than the Traditional process.

8.3.2.8. Null Hypothesis 8: Reliable commitments are the same in the Traditional and AR-Enabled PSP

Respondents were asked to rate how accurately the production input of the user (i.e. daily production, productivity information) was represented is each of the Traditional and AR-enabled processes. The daily production input reflects the commitments of the user to performing the work. The input accuracy was measured on a five-point Likert scale of marginally (1), somewhat (2), moderately (3), significantly (4), and extremely (5). Figure 94 presents comparative boxplots of the level of input accuracy in each of the Traditional and AR-enabled processes. As can be seen, the AR-enabled PSP allows for the representation of more accurate input, and therefore, produces more reliable commitments.

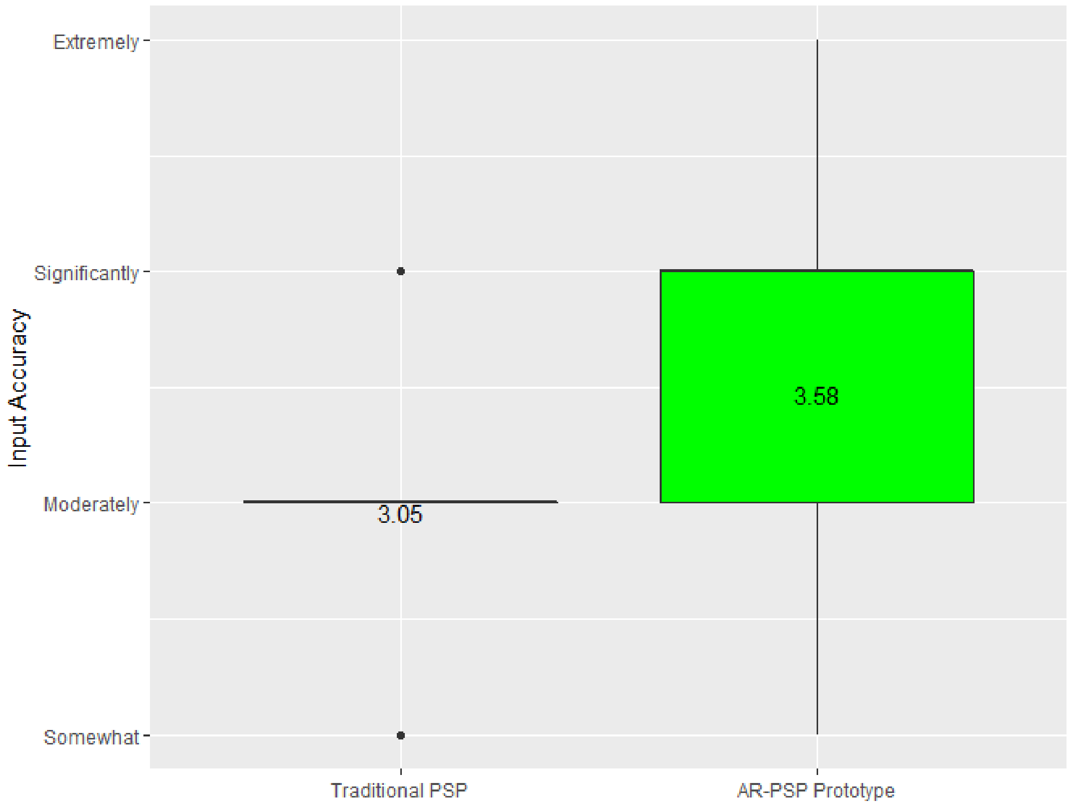


Figure 94 Input accuracy – Traditional PSP vs AR-PSP

In order to test whether this difference is significant, the non-parametric MWW test was conducted to statistically compare the input accuracy of the two processes. The low p-value resulting from the MWW test (0.0115) provides a statistical evidence at the 95% confidence level indicating that, on average, the AR-enabled PSP produces more reliable commitments than the Traditional process.

8.3.2.9. Null Hypothesis 9: Information retrieval is the same in the Traditional and AR-Enabled PSP

Respondents were asked to rate how easy and intuitive it was to access, gather, and retrieve information from multiple systems within each of the Traditional and AR-Enables PSP. The level of information access and retrieval was measured on a five-point Likert scale of very hard (1), hard (2), moderate (3), easy (4), and very easy (5). Figure 95 illustrates comparative boxplots of information access within each of the Traditional and AR-enabled processes. As can be seen, information is easily accessed and retrieved the AR-enabled PSP than it is in the Traditional process.

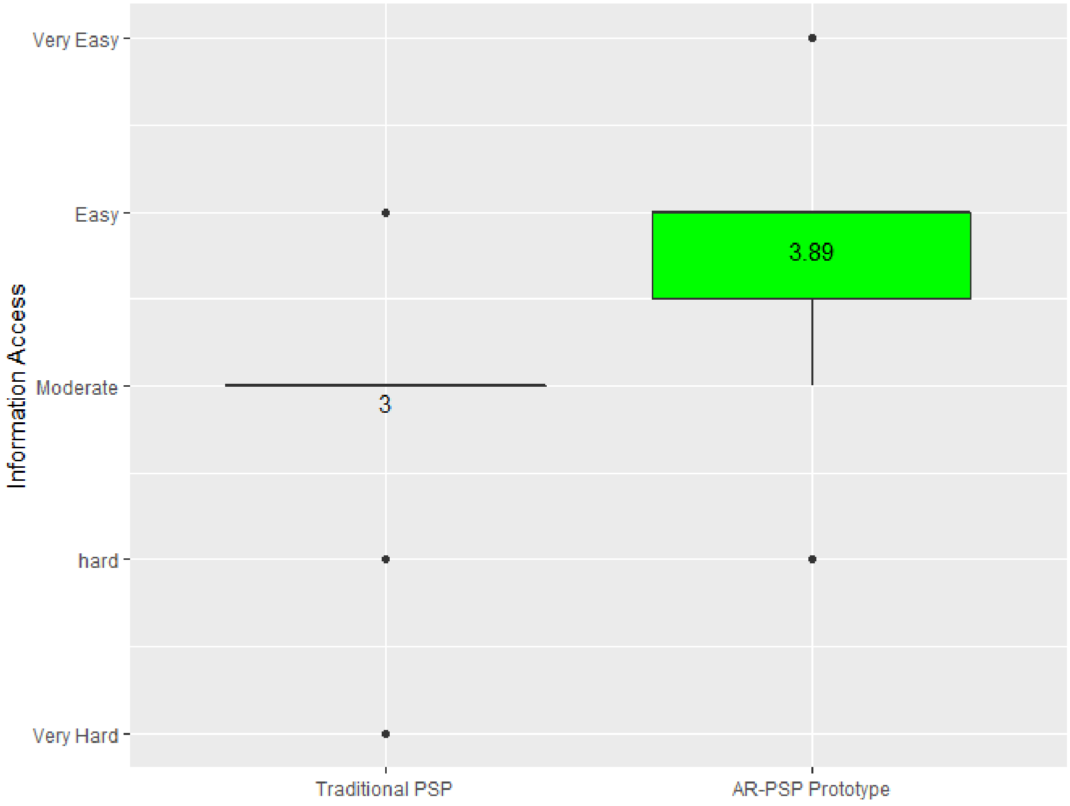


Figure 95 Information Access – Traditional PSP vs AR-PSP

In order to test whether this difference is significant, the non-parametric MWW test was conducted to statistically compare information access and retrieval in the two processes. The low p-value resulting from the MWW test (0.0013) provides a statistical evidence at the 95% confidence level indicating that, on average, the AR-enabled PSP eases information access and retrieval than the Traditional process.

8.3.2.10. Null Hypothesis 10: Information flow is the same in the Traditional and AR-Enabled PSP

Respondents were asked to rate how easy it was to navigate and browse project information each of the Traditional and AR-enabled processes using a five-point Likert scale of very hard (1), hard (2), moderate (3), easy (4), and very easy (5). Figure 96 presents comparative boxplots of information flow within each of the Traditional and AR-enabled processes. Respondents reported that the level of information flow is similar within the two processes.

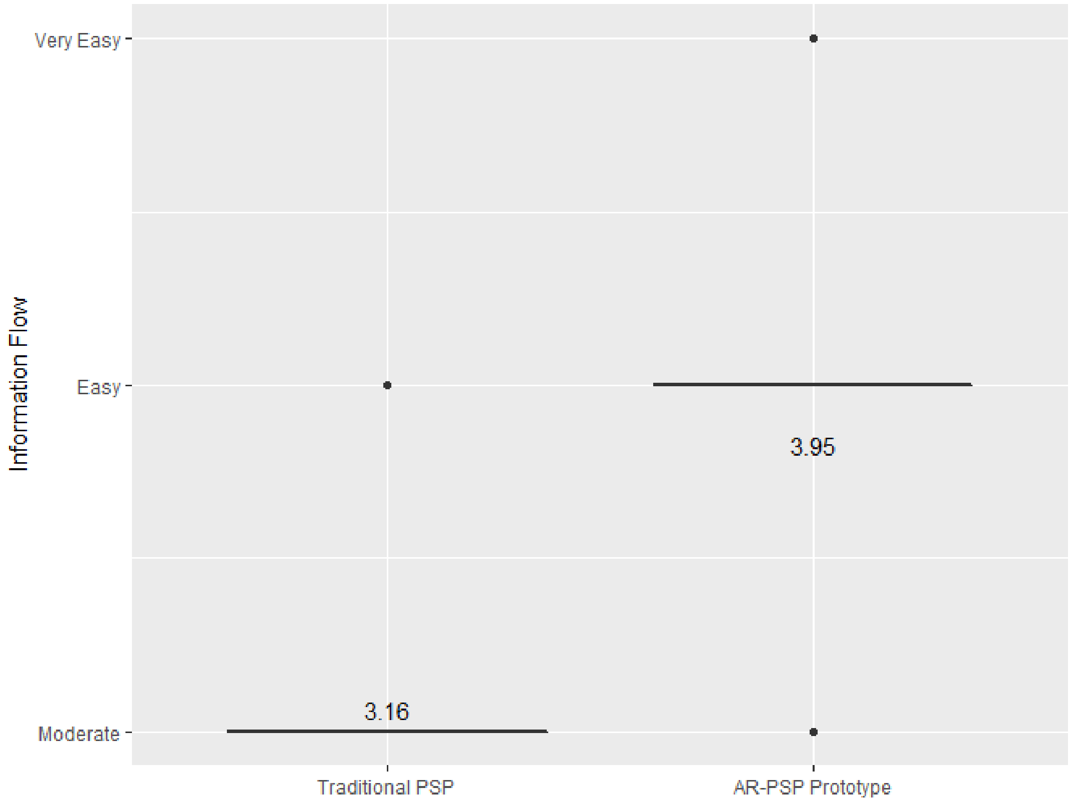


Figure 96 Information Flow – Traditional PSP vs AR-PSP

In order to test whether this difference is significant, the non-parametric MWW test was conducted to statistically compare the level of information flow of both processes. The low p-value resulting from the MWW test (3.33×10^{-5}) provides a statistical evidence at the 95% confidence level, indicating that on average, the AR-enabled PSP supports information flow more than the traditional PSP.

8.3.2.11. Null Hypothesis 11: Process documentation/archive is the same in the Traditional and AR-Enabled PSP

Respondents were asked to rate the level of efficiency of documenting and archiving each of the Traditional PSP and AR-enabled PSP. The level of efficiency of documentation was measured on a five-point Likert scale of very low (1), low (2), moderate (3), high (4), and very high (5). Figure 97 presents comparative boxplots of the efficiency of documentation of each of the traditional and AR-enabled processes. As can be seen, the AR-enabled PSP allows for a more efficient documentation than the Traditional process.

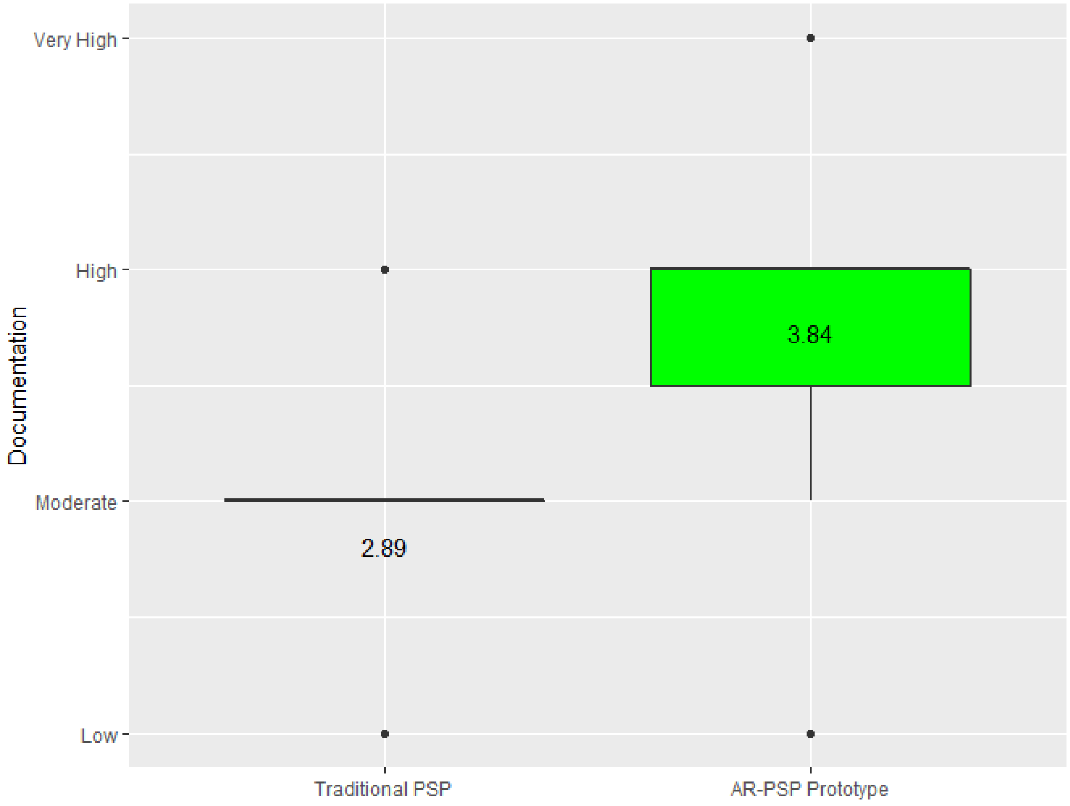


Figure 97 Documenting and archiving – Traditional PSP vs AR-PSP

In order to test whether this difference is significant, the non-parametric MWW test was conducted to statistically compare information access and retrieval in the two processes. The low p-value resulting from the MWW test (0.00022) provides a statistical evidence at the 95% confidence level indicating that, on average, the AR-enabled PSP improves the efficiency of the documenting and archiving of the process.

8.3.3. Prototype (Software) Evaluation Criteria

The third section of the survey concerned the participants opinion and experience with the AR-enabled PSP prototype. The questions included in this section were mainly focused on evaluating the software itself. Respondents were asked to rate the following software evaluation criteria: (1) level of satisfaction with the prototype, (2) quality of the prototype, and (3) level of precision of the prototype. Each criterion was measured on a five-point Likert scale of very low (1), to low (2), moderate (3), high (4), very high (5). Figure 98 shows that, on average, respondents were moderately to highly satisfied with the prototype (3.63) and were moderately satisfied with the quality and level of precision of the prototype (3.26 and 3.16, respectively).

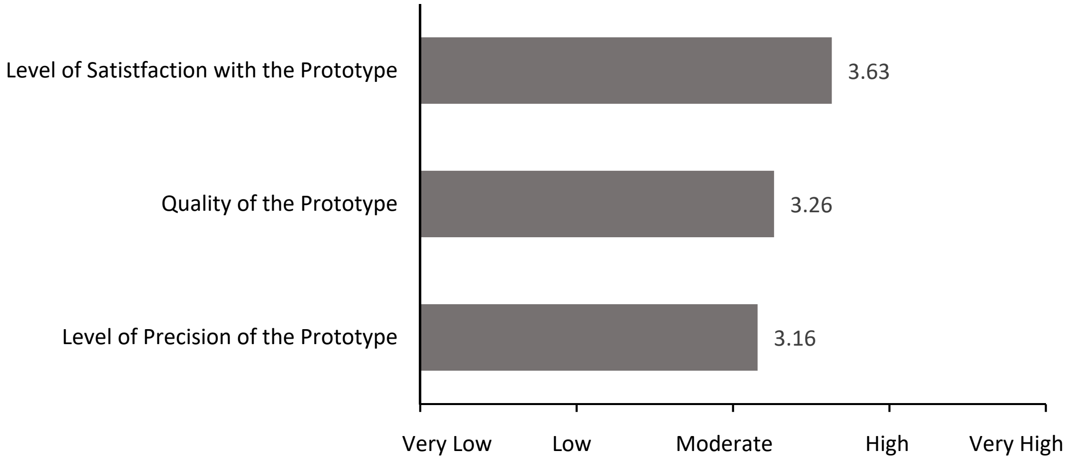


Figure 98 Prototype (Software) Evaluation Criteria

In addition to investigating their level of satisfaction with the prototype, participants were asked about their potential future use of the AR-enabled PSP. Participants were asked about 1) their likelihood to use the AR-enabled PSP over the Traditional PSP, and 2) their likelihood to recommend the AR-enabled PSP to others. This likelihood was measured on a five-point Likert scale of not at all (1), slightly (2), moderately (3), very likely (4), and extremely (5). On average, participants were moderately likely to use the AR-enabled PSP over the Traditional PSP (3.05) and to recommend the use of the AR-enabled PSP to others (3.16).

8.3.4. Device (Hardware) Evaluation Criteria

In addition to evaluating the software, it was important to evaluate the hardware as well. This fourth section of the survey concerned the participant experience and opinion with the HoloLens HMD. Participants were asked to rate four hardware evaluation criteria using the following five-point Likert scale: very low (1), to low (2), moderate (3), high (4), very high (5). The results reported in Figure 99 show that participants were on average moderately to highly comfortable wearing the device (3.63), moderately satisfied with the rate of adaptation to using the device (3.37) and with the device itself (3.16), and moderately comfortable while operating the device (3.11).

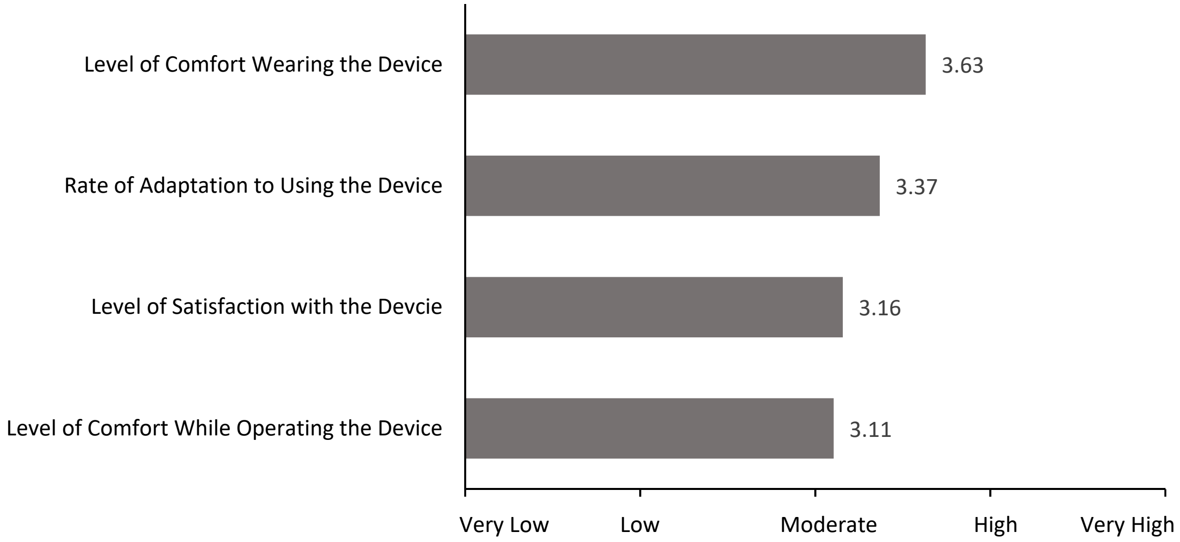


Figure 99 Device (Hardware) Evaluation Criteria

8.3.5. Technology (AR) Evaluation Criteria

The fifth section of the survey included two sets of questions to solicit participants' opinions and feedback regarding the capabilities of AR as a promising technology in PSP. The first set of questions asked participants about their level of agreement with four AR capabilities using a five-point scale of strongly disagree (1), disagree (2), undecided (3), agree (4), and strongly agree (5). The results displayed in Figure 100 show that on average, respondents agree that AR enhances their cognitive understanding of the process, facilitates the decision-making process (these results also support those of Null Hypothesis 5), provides the user with the needed and desired type of information, and allows for a natural way to interact with the displayed information.

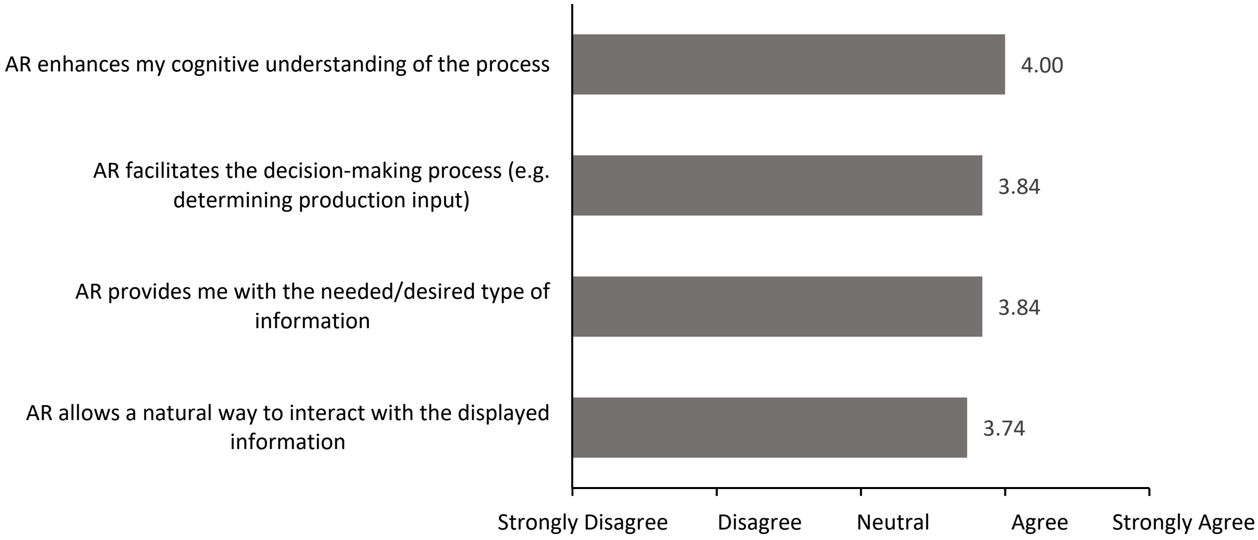


Figure 100 Technology (AR) Evaluation Criteria

The second set of questions asked participants to rate the impact of AR on PSP in nine different areas or categories using a five-point Likert scale of very low (1), low (2), moderate (3), high (4) and very high (5). The results are reported in Table 18.

Table 18 Clustered Table of the Impact Areas of AR on PSP

Impact Area	**Explanation**	**Average Impact**	**Clusters**
Analytical	Improving analysis of information and decision making	3.95	Cluster 1
Tracking	Closely monitoring process status and objects	3.79	
Informational	Capturing process innovation for purposes of understanding	3.74	
Geographical	Coordinating process across distances	3.63	Cluster 2
Integrative	Coordinating between tasks and processes	3.58	

Sequential	Changing process sequence or enabling parallelization	3.47	
Automation	Reducing human labor from a process	3.16	Cluster 3
Disintermediating	Eliminating intermediaries from a process	3.16	
Intellectual	Capturing and distributing intellectual assets	3.05	

The nine impact areas were divided into clusters to gain a better understanding about the areas in which AR has the highest impact on PSP. The cluster analysis grouped the nine areas into three clusters based on the participants' average impact with each cluster encompassing three areas.

The three areas of Cluster 1 are the areas where AR has the highest impact on PSP and are as follows: Analytical (3.95), Tracking (3.79), and Informational (3.74).

8.3.6. Sixth Section – Semi-Structured Interview Questions

The final section of the survey included semi-structured interview questions to allows participants to elaborate on their experience testing the AR-Enabled PSP prototype.

The following list includes the advantages that participants reported regarding the use of the AR-Enabled PSP prototype:

- AR has the capabilities to standardize the PSP and guide users through the correct steps to ensure an effective implementation of the process.
- The AR-Enabled PSP allows for real-time implementation of the process, eliminating the need for paper pushing and manual documentation.
- AR provides a true integration between the 3D model and production planning.

- The generation of quantities improves the accuracy of production.
- The generation of bar chart graphs is great to visualize all trades/systems and improve decision-making.
- The 3D production areas feature is an easy way to create areas and allow the user to better understand the cope of work within the corresponding area.
- The use of the AR-Enabled PSP can help identifying and reducing constraints.
- Users can obtain more information from the 3D model than they currently do from the 3D drawings
- The AR-Enabled PSP can enable a better pull of more data than the Traditional PSP.
- The AR-Enabled PSP has the potential to increase data recording and accuracy.
- Communication will be increased with the AR-Enabled PSP.
- It was easy to understand how the prototype functions.
- The AR-Enabled PSP allows the user to be immersed in the space. Planning by using *hands and feet* to move around and select and build the plan was better than sitting at a computer or marking a 2D drawing.
- The AR-Enabled PSP allows the user to better understand and visualize the layering of systems and how they inform the production plan.
- AR can result is a major cost savings in design.
- The AR-Enabled PSP allows for the actual visualization of the process and locations.

- Users can better understand the scope of work in a given area.
- With the AR-Enabled PSP, multiple people can see the process and locations at once and walk through the model.

Survey participants were also asked to list any disadvantages they noted in the AR-Enabled PSP. The participants feedback can be grouped into three categories: software, hardware, and technology. The results are summarized below:

- The process can be made easier by enabling voice command.
- Air-tapping was challenging.
- The field of view of the headset was disturbing.
- Introducing the AR-Enabled PSP to workers who don't have exposure to technology or don't want to learn the technology can be challenging. There could be some push back from the field personnel.
- It makes the process seem slower and more time intensive, but this can change with improvements to the hardware (primarily the field of view) and software.
- It would have been great to see 'plan view' and flip back and forth between the 2D drawings and 3D model.
- It would have been better if the user was able to know what 'button' was selected.
- Some items were hard to select at times.

Another question in this section asked respondent to describe their experience using the AR-Enabled PSP. Figure 101shows that participants saw this experience as engaging, interesting, innovative, fun, and easy.

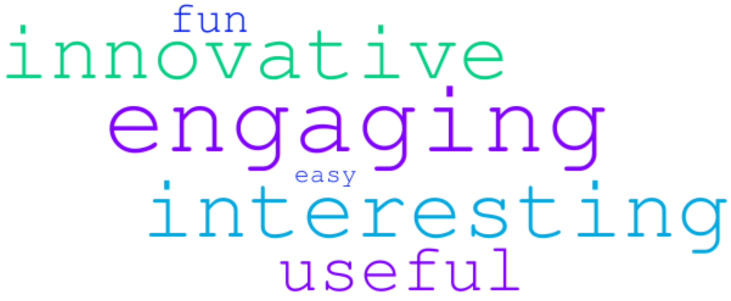


Figure 101 User Experience
(generated with WordItOut)

Section IV

Chapter 9: Conclusions and Future Recommendations

Augmented reality (AR) is an emerging technology within construction, and there is still little existing data about its uses, challenges, and successes. This study first provide a comprehensive investigation of the potential of AR in the construction industry. The study then investigated how AR can be integrated into the Production Strategy Process (PSP) by designing, developing, and validating a new AR-enabled Production Strategy Process.

This chapter summarizes the findings of this dissertation and suggests avenues for future research to further develop and expand on its results.

9.1. Summary of Results and Contributions

9.1.1. Objective A

A total of 128 responses were collected from industry practitioners, with the bulk of responses obtained from the United States. One question of the survey looked at the role of their firm: 36% of respondents reported that they work for General Contractors/Construtcion Managers (GC/CM), 27% work in the Mechanical/Electrical/Plumbing Trades (MEP Trades), 16% work for Owners, 12% work for Architect/Engineer firms (A/E), and the remaining 9% work for Owner's Representatives (OR).

Respondents were asked about their level of familiairty and usage of AR in construction. Respondents who have had some experience exploring, testing, and using AR in the construction industry reported that they have predominantly used the HoloLens head-mounted display as their AR platform. The majority of those respondents have indicated that they have employed AR in the Construction, Design, Pre-Construction Planning, Operation and Maintenance, and Commissioning phases. Respodnents also elaborated on their experience with the tehcnology, showing that GC/CM had the most experience employing AR in most of the phases of a construtcion project lifecycle. The majority of respondents reported that they see AR being used on Healthcare and Industrial projects.

The following 20 AR-cases were identified to have the highest *Usage Potential*:

- 2 Conceptual Planning use-cases, namely *Real-time visualization of conceptual project* and *Understanding of how the desired project connect with its surroundings*
- 4 Design user-cases, namely *Virtual tours for clients while on site or in the office*, *Design visualization at full scale on site*, *Overlay of 3D models over 2D plans*, and *Real-time design change*
- 6 Pre-Construction use-cases, namely *Clash Detection*, *Constructability reviews during design*, *Virtual planning and sequencing*, *Early identification of early design clarification*, *Space validation and engineering constraints check*, and *Full-scale site logistics*
- 6 Construction use-cases, namely *Visualization of the construction systems*, *Augmented mock-ups*, *Visualization of underground utilities*, *Visualization of augmented drawings in the field*, *Construction progress visualization and monitoring*, and *Visualization of layout and integration of prefab components in the shop*
- 2 Operation and Maintenance use-cases, namely *Locate building systems that need maintenance without disruptive demolition or further survey work* and *Training for maintenance and repair*.

As for AR potential benefits, *Improving real-time visualization of project*, *Enhancing decision-making*, *Improving collaboration and communication*, and *Enhancing spatial cognition* are identified as the benefits with the highest *Benefit Potential*.

The following 10 obstacles to the implementation of AR in construction were reported to have the highest *Obstacle Potential*:

- 3 Financial obstacles, namely *Cost of* implementation, *Time and cost required to train existing staff*, and *Actual in-field applications*
- 4 Human obstacles, namely *Lack of skilled personnel*, *The need for specialists' assistance*, *Lack of IT resources* (3.47 – #6), and *Resistance to change*
- 2 Technological obstacles, namely *Maturity of the technology* and *Integration with existing technology*

Architects/Engineers and *Project Engineers* were found to have the highest potential to use AR in construction and Design, Pre-Construction Planning, Construction, and Conceptual Planning were identified as the phases where AR is most useful.

Moreover, the analysis of the AR statements highlighted the transformative impact AR can have on construction. Specifically, respondents agreed that AR has the potential to build upon existing Lean practices and that the Head-Mounted Display devices will become commonly used in the industry. These findings support Objective B of this dissertation.

The findings of the AR survey serve a shared-knowledge platform to exchange AR practices and experiences among construction stakeholders. It also provides the construction industry with a roadmap to guide the implementation of AR.

9.1.2. Objective B

While most of the reviewed literature focused on the avenues to integrate AR into site operations (visualizing blueprints, safety, etc), this research effort focuses on integrating AR into the Production Strategy Process (PSP). A process map was presented to illustrate the current state of the practice of PSP based on previous research and industry expertise. Challenges encountered in the existing PSP were identified, and opportunities to address them via AR were explored. A conceptual future state of the PSP was described. A prototype of the AR-Enabled PSP was then developed and implemented. Using a BIM model from real-world construction project, the prototype was then validated on an ongoing construction project. The results of the validation phase (usability testing and surveys) showed that the AR-Enabled PSP has the following benefits over the Traditional PSP: improved collaboration, reduced miscommunication, increased quality and detection of errors, enhanced decision-making, increased integration of safety considerations, increased input accuracy, better information access, improved information flow, and better documentation. These benefits were tested through a series of hypotheses comparing both processes. On the other hand, no significant difference was found between the Traditional and AR-Enabled PSP in terms of spatial cognition and time efficiency of the process.

The validation results revealed that, on average, respondents were moderately to highly satisfied with the prototype and were moderately satisfied with the quality and level of precision of the prototype. Participants also reported that they were moderately likely to use the AR-enabled PSP over the Traditional PSP and to recommend the use of the AR-enabled PSP to others. Additionally, participants were, on average, moderately satisfied with the HoloLens headset.

Regarding the technology itself, participants agreed on average that AR enhances their cognitive understanding of the process, facilitates the decision-making process, provides them with the needed and desired type of information, and allows for a natural way to interact with the displayed information. According to participants, the average impact of AR on the nine areas varies between high and moderate with Analytical, Tracking, and Informational being the areas with the highest impact (cluster 1). Overall, participants saw this experience as engaging, interesting, innovative, fun, and easy and recognized the value AR can add to the PSP.

9.2. Future Recommendations

The findings of this study contribute further knowledge to understanding the potential of AR in the construction industry. Further research could gather a broader dataset that includes other types of companies, such as Facility Managers, and perform a more detailed analysis for each company type.

While the AR-Enabled PSP explored in this research covers only the production planning part of Production Planning and Control, the applicatin of the AR-enabled process can be extended to control, reinforcing the view of AR-Enabled PSP as a single point-of-truth that centralized information. Further studies can build upon this work to study the integration of AR throughout the entire production planning and control system. The implemenation of AR could be also extended to design.

Additionally, future research could focus on optimizing Takt-Time in the production strategy. The specifcs of how Takt-Time is selected were outside the scope of this research, however, an algorithm could be developed to optimize the selection of Takt-Time. Consequently, algorithms could be developed to automatically generate production areas. AR can be then used to as a decision support tool that provides the user with a real-time visual representation of the generated production areas.

As indicated by Moore’s law, improvements and accessibility of AR technology will increase in the future. This has also become evident with the reveal of the new Microsoft HoloLens (HoloLens 2), which is reported to have addressed the shortcomings of the first version. Trimble, a software developer, have also announced the next generation of Mixed-Reality (including AR) device – Trimble XR10 with HoloLens 2.

Finally, this research does not perceive AR as the sole solution to improve construction. AR on its own cannot demolish the wall of inefficiencies and waste in construction, but it can punch holes in its wall of convervatism.

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Appendix B: Clustered Table of AR Use-Case by Company Type

AR Use-Case	Phase	GC	Trades	AE	OOR
Real-time visualization of conceptual projects	Conceptual Planning	3.75	3.91	3.83	4.03
Overlaying 4D content into real world (or physical objects) such as traffic flow, wind flow, etc.	Conceptual Planning	3.43	3.19	3.83	3.74
An understanding of how the desired project connects with its surroundings	Conceptual Planning	3.79	3.71	3.91	4.00
Overlay of 3D models over 2D plans [Design (or project) visualization in the office over 2D plans]	Design	3.59	3.75	3.73	3.92
Design (Project) visualization at full scale onsite	Design	3.90	4.00	3.64	3.95
Virtual tours for clients while on site or in the office (AR walk-through)	Design	4.05	4.24	4.15	4.08
Real-time design change (material selection, design functionalities)	Design	3.57	3.62	3.83	3.87
Clash detection	Pre-Construction	3.72	4.34	3.75	4.04
Early identification of design clarification	Pre-Construction	3.62	3.91	3.55	3.63
Constructability Reviews during design	Pre-Construction	3.75	4.11	3.40	3.71
Full-scale site logistics (virtually locate equipment, trailers, laydown areas, storage, etc.)	Pre-Construction	3.51	3.57	3.39	3.66
Space Validation and Engineering Constraints Checks (collaboratively locate and operate virtual construction equipment, such as cranes)	Pre-Construction	3.33	3.89	3.65	3.68
Virtual planning and sequencing	Pre-Construction	3.73	3.83	3.60	3.48
Safety orientation (do safety orientation in an AR environment)	Pre-Construction	3.51	2.58	3.63	3.13
AR-simulation based safety training programs for workers	Pre-Construction	3.43	2.82	3.37	3.20
Visualizing layout and integration of prefab components in the shop	Construction	3.65	3.85	3.22	3.29
Site layout without physical drawings	Construction	3.49	3.21	4.09	3.07
4D Simulations on site (augmented simulated construction operations)	Construction	3.53	3.16	3.41	3.25
Monitoring progression of workflow and sequence	Construction	3.43	3.08	3.59	3.06
Visualization of augmented drawings in the field	Construction	3.67	4.03	3.83	3.27
On-site inspection	Construction	3.36	2.72	3.49	3.22

Remote site inspection	Construction	🟦 3.08	🟦 2.75	🟦 3.14	🟩 3.23
Visualization of underground utilities	Construction	🟥 3.87	🟥 3.95	🟥 3.82	🟩 3.42
Visualization of the proposed excavation area	Construction	🟩 3.45	🟩 3.24	🟥 3.70	🟩 3.35
Visualization of the construction systems/work (i.e. MEP, structural, etc.)	Construction	🟥 4.19	🟥 4.16	🟥 3.99	🟥 3.70
Planning the positioning and movement of heavy/irregular objects/equipment	Construction	🟩 3.46	🟩 3.36	🟩 3.60	🟩 3.48
Real-time support of field personnel	Construction	🟥 3.65	🟩 3.30	🟦 2.88	🟦 2.94
On-site safety precautions (site navigation and in-situ safety warning)	Construction	🟩 3.34	🟦 2.68	🟦 2.99	🟦 3.10
Augmented Mock-ups	Construction	🟥 3.96	🟥 3.92	🟦 3.19	🟥 3.62
Construction progress visualization and monitoring	Construction	🟥 3.71	🟩 3.65	🟩 3.54	🟩 3.31
On-site material tracking	Construction	🟦 3.00	🟦 2.38	🟦 3.33	🟦 2.52
Create design alternatives on-site	Construction	🟦 3.07	🟩 3.44	🟦 2.88	🟩 3.36
Visualization of augmented work instructions/manuals/procedures in the field	Construction	🟩 3.49	🟦 2.92	🟩 3.40	🟦 2.94
Real-time visualization, review and analysis of data associated with a particular worker, equipment, construction system, etc.	Construction	🟩 3.46	🟦 3.04	🟦 3.05	🟦 3.08
On-site inspection/Punchlists	Commissioning	🟦 3.10	🟦 2.92	🟦 3.18	🟦 3.03
Remote site inspection	Commissioning	🟦 2.79	🟦 2.52	🟦 3.07	🟦 2.86
Availability of Maintenance information	Operation & Maintenance	🟩 3.57	🟩 3.34	🟩 3.31	🟩 3.33
Locate building systems that need maintenance without destructive demolition or further survey work	Operation & Maintenance	🟥 3.81	🟩 3.59	🟩 3.57	🟥 3.63
Refurbishment visualization	Operation & Maintenance	🟦 3.19	🟦 2.92	🟦 3.05	🟩 3.29
Real-time support of engineers and technicians	Operation & Maintenance	🟥 3.70	🟩 3.36	🟦 2.81	🟩 3.39
Training for maintenance and repair	Operation & Maintenance	🟥 3.70	🟩 3.25	🟦 3.22	🟩 3.45
Remodeling visualization	Decommissioning	🟩 3.33	🟩 3.60	🟦 3.26	🟩 3.38
Evaluation of the new facility/installations over the existing one	Decommissioning	🟦 3.21	🟩 3.57	🟦 3.01	🟩 3.32

Key:

🟥 cluster 1	🟩 cluster 2	🟦 cluster 3

Appendix C: Clustered Table of AR Potential Benefits by Company Type

Potential Benefit	BP GC	BP Trades	BP AE	BP OOR
Improving owner's engagement	🟩 3.84	🟦 3.42	🟥 3.93	🟩 3.79
Improving real-time visualization of project	🟥 4.27	🟥 4.19	🟥 4.01	🟥 4.13
detecting design errors	🟩 3.74	🟥 4.10	🟩 3.60	🟥 3.92
Improving collaboration and communication	🟥 3.99	🟩 3.96	🟥 3.92	🟥 4.02
Reducing wastes, defects, and construction rework	🟩 3.72	🟩 3.81	🟩 3.54	🟩 3.81
Improving the quality of planning and scheduling	🟦 3.50	🟦 3.41	🟥 3.92	🟩 3.66
Improving productivity	🟦 3.55	🟩 3.81	🟩 3.73	🟩 3.66
Improving safety	🟦 3.41	🟦 3.01	🟦 3.28	🟦 3.34
Improving quality	🟥 3.98	🟩 3.64	🟩 3.78	🟩 3.56
Educating the workforce (improve their understanding of the project)	🟩 3.78	🟩 3.73	🟩 3.61	🟥 3.89
Allowing real-time data collection	🟦 3.45	🟦 3.33	🟩 3.80	🟩 3.64
Providing additional resources for problem solving	🟩 3.79	🟩 3.85	🟩 3.84	🟥 3.92
Enhancing spatial cognition	🟩 3.82	🟥 4.20	🟥 4.12	🟥 3.94
Enhancing decision-making	🟥 4.04	🟩 3.95	🟥 4.12	🟥 3.96
Improving growth and success by creating new business models	🟦 3.44	🟦 3.54	🟦 3.31	🟦 3.17
Improving corporate image	🟦 3.62	🟩 3.81	🟥 3.94	🟩 3.63

Key:

🟥 cluster 1 🟩 cluster 2 🟦 cluster 3

Appendix D: Clustered Table of AR Obstacles by Company Type

Obstacle	Category	OP GC	OP Trades	OP AE	OP OOR
Integration with existing technology	Technological	🟥 3.33	🟩 3.29	🟥 3.43	🟩 3.56
Data privacy and security	Technological	🟦 2.88	🟦 2.53	🟦 2.54	🟦 3.50
Maturity of the technology	Technological	🟥 3.86	🟥 3.60	🟥 3.35	🟥 4.02
Hardware compliance with safety standards	Technological	🟦 2.94	🟦 2.40	🟦 2.86	🟦 3.42
No AEC industry standard for hardware	Technological	🟩 3.02	🟥 3.35	🟩 3.08	🟦 3.32
No AEC industry standard for software	Technological	🟩 3.08	🟥 3.55	🟩 3.32	🟦 3.49
Lack of management support	Organizational	🟩 3.00	🟩 3.18	🟩 3.14	🟩 3.64
Uncertain of its benefits	Organizational	🟩 3.01	🟥 3.48	🟥 3.49	🟩 3.79
Cultural resistance	Organizational	🟩 3.14	🟩 3.15	🟥 3.56	🟩 3.61
Disruption to the rest of the organization	Organizational	🟦 2.69	🟩 3.11	🟦 2.71	🟦 2.65
Lack of skilled personnel	Human	🟥 3.68	🟩 3.29	🟥 3.64	🟥 3.91
Lack of IT resources	Human	🟥 3.36	🟥 3.39	🟩 3.30	🟩 3.86
Resistance to change	Human	🟩 3.24	🟥 3.73	🟩 3.23	🟦 3.41
The need of specialists' assistance	Human	🟥 3.46	🟥 3.33	🟥 3.37	🟥 3.96
Discomfort with prolonged use (headset tightness, dizziness, etc)	Human	🟩 3.06	🟦 2.56	🟩 3.01	🟩 3.72
Cost of implementation	Financial	🟥 3.42	🟥 3.59	🟥 3.56	🟥 4.17
Cost of maintenance	Financial	🟦 2.88	🟩 3.14	🟩 3.07	🟩 3.70
Time and cost required to train existing staff	Financial	🟥 3.35	🟥 3.49	🟩 3.05	🟥 4.18
Actual in-field applications	Financial	🟥 3.36	🟩 3.22	🟥 3.73	🟩 3.84
The fragmented nature of the construction industry	Others	🟩 3.12	🟥 3.61	🟥 3.47	🟩 3.76
Lack of standards (to describe data and support interaction and collaboration)	Others	🟩 3.09	🟥 3.48	🟩 3.09	🟦 3.50
Lack of existing BIM workflow to augment	Others	🟦 2.92	🟩 3.23	🟩 3.31	🟩 3.70

Key:

🟥 cluster 1	🟩 cluster 2	🟦 cluster 3