

**A Cyber-Physical System (CPS) Approach to Support Worker Productivity based
on Voice-Based Intelligent Virtual Agents**

Daniel Antonio Linares García

Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State
University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

in

Environmental Design and Planning

Nazila Roofigari-Esfahan, Chair

Chimay Anumba

Farrokh Jazizadeh Karimi

Sang Won Lee

August 1st, 2022

Blacksburg, VA

Keywords: Cyber-Physical Systems, CPS, Voice-Based, Productivity, Worker Support,
Interoperability, VIVA, Human-System Interaction

© 2022 by Daniel Linares

A Cyber-Physical System (CPS) Approach to Support Worker Productivity based on Voice-Based Intelligent Virtual Agents

Daniel Antonio Linares García

ABSTRACT

The Architecture, Engineering, and Construction (AEC) industry is currently challenged by low productivity trends and labor shortages. Efforts in academia and industry alike invested in developing solutions to this pressing issue. The majority of such efforts moved towards modernization of the industry, making use of digitalization approaches such as cyber-physical systems (CPS). In this direction, various research works have developed methods to capture information from construction environments and elements and provide monitoring capabilities to measure construction productivity at multiple levels. At the root of construction productivity, the productivity at the worker level is deemed critical. As a result, previous works explored monitoring the productivity of construction workers and resources to address the industry's productivity problems. However, productivity trends are not promising and show a need to more rigorously address productivity issues. Labor shortages also exacerbated the need for increasing the productivity of the current labor workers.

Active means to address productivity have been explored as a solution in recent years. As a result, previous research took advantage of CPS and developed systems that sense construction workers' actions and environment and enable interaction with workers to render productivity improvements. One viable solution to this problem is providing on-demand activity-related information to the workers while at work, to decrease the need for manually seeking information from different sources, including supervisors, thereby improving their productivity. Especially, construction workers whose activities involve visual and manual limitations need to receive more attention, as seeking information can jeopardize their safety. Multiple labor trades such as plumbing, steel work, or carpenters are considered within this worker classification. These workers rely on knowledge gathered from the construction project documentation and databases, but have difficulties accessing this information while doing their work. Research works have explored the use of knowledge retrieval systems to give access to construction project data sources to

construction workers through multiple methods, including information booths, mobile devices, and augmented reality (AR). However, these solutions do not address the need of this category of workers in receiving on-demand activity related information during their work, without negatively impacting their safety.

This research focuses on voice, as an effective modality most appropriate for construction workers whose activities impose visual and manual limit actions. To this end, first, a voice-based solution is developed that supports workers' productivity through providing access to project knowledge available in Building Information Modeling (BIM) data sources. The effect of the selected modality on these workers' productivity is then evaluated using multiple user studies. The work presented in this dissertation is structured as follows: First, in chapter 2, a literature review was conducted to identify means to support construction workers and how integration with BIM has been done in previous research. This chapter identified challenges in incorporating human factors in previous systems and opportunities for seamless integration of workers into BIM practices. In chapter 3, voice-based assistance was explored as the most appropriate means to provide knowledge to workers while performing their activities. As such, Chapter 3 presents the first prototype of a voice-based intelligent virtual agent, aka VIVA, and focuses on evaluating the human factors and testing performance of voice as a modality for worker support. VIVA was tested using a user study involving a simulated construction scenario and the results of the performance achieved through VIVA were compared with the baseline currently used in construction projects for receiving activity-related information, i.e., blueprints. Results from this assessment evidenced productivity performance improvements of users using VIVA over the baseline. Finally, chapter 4 presents an updated version of VIVA that provides automatic real-time link to BIM project data and provides knowledge to the workers through voice. This system was developed based on web platforms, allowing easier development and deployment and access to more devices for future deployment.

This study contributes to the productivity improvements in the AEC industry by empowering construction workers through providing on-demand access to project information. This is done through voice as a method that does not jeopardize workers' safety or interrupt their activities. This research contributes to the body of knowledge by developing an in-depth study of the effect of voice-based support systems on worker

productivity, enabling real-time BIM-worker integration, and developing a working worker-level productivity support solution for construction workers whose activities limit them in manually accessing project knowledge.

A Cyber-Physical System (CPS) Approach to Support Worker Productivity based on Voice-Based Intelligent Virtual Agents

Daniel Antonio Linares García

GENERAL AUDIENCE ABSTRACT

The Architecture, Engineering, and Construction (AEC) industry is currently challenged by low productivity trends and labor shortages. At the root of productivity, the improving productivity of construction workers is of critical essence. Therefore, academia and industry alike have shown great interest in research to develop solutions addressing construction worker productivity. For this purpose, monitoring systems for construction worker support have been developed, but productivity trends do not seem to improve, while labor shortages have increased productivity concerns.

Other approaches to address productivity improvements have explored active means for productivity support. These include monitoring systems that also interact with the user. Construction workers performing activities that require allocating immense attention while using both hands, e.g. plumbers, steel workers, carpenters, have not been the focus of previous research because of the challenges of their conditions and needs. The activities performed by these workers require access to construction project data and documentation. Still, it is difficult for these workers to access information from the documents while doing their work. Therefore, previous researchers have explored methodologies to bring project data and documentation to the field but providing workers on-demand access to this data and documents have not been thoroughly studied.

This research focuses on identifying the most appropriate method to provide workers access to information during activities that require more visual and manual attention. Worker support is provided by developing a solution that provides workers access to knowledge during their activities without being disruptive. The study then evaluated the effect of providing non-disruptive access to information sources enabled through the developed solution on the productivity for workers. First, in chapter 2, this study reviews the literature on approaches to connect construction project databases, a.k.a. Building Information Modeling (BIM), and workers. This review identified system types, integration approaches, and future research trends for linking BIM sources and with

workers. In addition, this chapter's outcomes highlight system interoperability challenges and challenges in developing interactive systems involving humans. In chapter 3, a voice-based support system was developed as the most appropriate method for worker support during work activities that limit visual and manual worker capabilities. Then, the performance benefits of using a voice-based support system for construction workers was evaluated through a user study involving simulated construction activities. Finally, in chapter 4, this study provided a new integration method to connect BIM and workers in real-time. This system allows workers to interact with information from BIM through voice. The system was developed based on web platforms, allowing easier development and deployment and access to more devices for future deployment.

This study contributes to the productivity improvements in the AEC industry by empowering construction workers through providing on-demand access to project information. This is done through voice as a method that does not jeopardize workers' attention or interrupt their activities.

ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. Nazila Roofigari-Esfahan, for her guidance, patience, and support during my Ph.D. program. Nazila has been an exceptional mentor, and I am immensely grateful for the significant time and effort she has invested in me. Nazila's office door has always been physically and virtually open for me. I can genuinely say that I would not have prevailed throughout my graduate studies without her support, trust, and patience. The passion for research and education that Nazila shares are admirable and contagious. I hope she continues to be a long-life mentor after my Ph.D. program.

My committee members have also been essential during my Ph.D. program. Dr. Anumba's feedback reflects his ample experience in Knowledge Management, Cyber-Physical Systems, and overall research in construction. I want to thank Dr. Jazizadeh for his supportive feedback and mentoring that started even before I started my Ph.D. program at Virginia Tech. Last but not least, I would like to thank Dr. Lee, whose insights into human subject research greatly influenced improvements to my experimental work.

I would like to thank the Myers Lawson School of Construction (MLSoC) for all the support I received during my graduate studies. I want to acknowledge the support I received from Dr. Georg Reichard and Dr. Josh Iorio. I want to acknowledge that I have benefited from Dr. Reichard's leadership and support throughout the Ph.D. program. I am incredibly grateful to Dr. Iorio for her support and academic advice. Finally, I acknowledge Dr. Tanyel Bulbul, Dr. Abiola Akanmu, and Dr. Annie Pierce's support and guidance.

I would like to thank the Vecellio Construction Engineering and Management Program (VCEMP) for the formative support I received during my Master studies and the support I continue receiving during My Ph.D. Program. I would like to thank Dr. Jesus M. de la Garza, Dr. Michael Garvin, and Dr. Farook Jazizadeh. I learned so much from Dr. de la Garza's experiences; I consider him my first mentor. Dr. Garvin's personality and teachings were inspiring. Dr. Jazizadeh's patience and concise feedback significantly impacted my life and research work.

I also would like to thank the Department of Computer Science at Virginia Tech for all the knowledge shared with me in this area of expertise. I want to thank Dr. Sang Won Lee, Dr.

Myounghoon "Philart" Jeon, Dr. Doug Bowman, and Dr. Scott Mccrickard. I always found extremely helpful the feedback I received from Dr. Lee. The help and support I received from Dr. Jeon during my experimental work were vital for my success. Dr. Bowman's classes and work were always inspiring. Finally, Dr. Mccrickard's virtual classes were engaging and inspirational.

During my Ph.D. program, I had the opportunity to meet other students who contributed to my doctoral studies. I would like to thank former and current students in the MLSoC department, Zack Dowel, Srijeet Halder, Poorvesh Dongre, Wenjun Han, and Jeremy Withers. I would also like to thank former students at the VCEMP department, including Diana Franco Duran, Wooyoung Jung, Miguel Andres Guerra, Vanessa Guerra, and Jose Guevara. I would like to extend my gratitude to fellow students that further contributed to my Ph.D. journey: David Villacis, Jose Francisco García, and Kristina Pratt.

Finally, I would like to thank my family, who have supported me throughout my Ph.D. Special gratitude goes to my wife, Gabriela, who has been supportive all the time and has taken well care of our son, who eventually joined us on this journey. I value every effort she makes, and I also keep learning from her. I have enjoyed all the moments with my son, Elliot, he brings light to our life, but it has not been easy. Finally, I want to thank my parents and sister. I am thankful to them for the countless hours they listened to me when asking for advice, for their monetary support, and for constantly looking out for me. All of them have contributed more than they can imagine. I also want to acknowledge my sister-in-law, Lily and family, our Uncle Manual and Aunt Francisca for supporting us from afar, and our friends at the LDS church. Thank you so much.

CONTENTS

LIST OF FIGURES	xv
LIST OF TABLES	xvii
Chapter 1. INTRODUCTION.....	1
1.1 Background	2
1.1.1 Productivity in the AEC Industry	3
1.1.2 Knowledge Management and Knowledge Adaptation	5
1.1.3 Cyber-Physical Systems (CPS).....	6
1.1.4 Human-Computer Interaction	8
1.2 Research Gaps and Point of Departure	10
1.3 Literature Findings and Proposed Solution to Develop	10
1.4 Research Objectives and Goals.....	11
1.5 Research Methodology and Dissertation Structure.....	12
1.6 Expected outcomes, contributions, and impacts	13
Chapter 2. REVIEW OF BUILDING INFORMATION MODELING (BIM) AND HUMAN CYBER-PHYSICAL SYSTEM (CPS) INTEGRATION APPROACHES TO SUPPORT CONSTRUCTION WORKER PRODUCTIVITY IN THE AEC INDUSTRY	15
2.1 Abstract	15
2.2 Introduction.....	16
2.3 Point of Departure, Scope, and Context of Application	17
2.4 Research Methodology	18
2.5 Summary of Reviewed Articles for Integration Approaches.....	19
2.6 BIM and Worker (BIM-worker) Integration Approaches for Productivity Support	25

2.6.1 Type A Systems: Knowledge Retrieval CPS Systems	26
2.6.1.1 Approach A1: Systems for Text-based Knowledge Retrieval.....	27
2.6.1.1.1 Description of this Approach	27
2.6.1.1.2 Examples of this Approach.....	28
2.6.1.1.3 Discussion of this Approach	29
2.6.1.2 Approach A2: Systems for Voice Knowledge Retrieval	30
2.6.1.2.1 Description of this Approach	30
2.6.1.2.2 Examples of this Approach.....	31
2.6.1.2.3 Discussion of this Approach	33
2.6.1.3 Approach A3: System for Visual and Multimodal Knowledge Retrieval ...	33
2.6.1.3.1 Description of this Approach	33
2.6.1.3.2 Examples of this Approach.....	35
2.6.1.3.3 Discussion of this Approach	36
2.6.2 Type B Systems: Bi-directional CPS Systems.....	37
2.6.2.1 Approach B1: Systems for Multimodal integration of BIM, sensor data, and workers	38
2.6.2.1.1 Description of this Approach	38
2.6.2.1.2 Examples of this Approach.....	40
2.6.2.1.3 Discussion of this Approach	41
2.6.2.2 Approach B2: Systems for Multimodal BIM, sensors, and Workers Integration Based on Web-Assisted Data Processing.....	42
2.6.2.2.1 Description of this Approach	42
2.6.2.2.2 Examples of this Approach.....	43
2.6.2.2.3 Discussion of this Approach	46
2.7 Reviewed Articles outside the scope of this study.....	47
2.7.1 Reviewed Articles Not Focused on the Construction Phase.....	47
2.7.2 Reviewed Articles Not Integrating BIM.....	47
2.8 Discussion	47
2.8.1 Integration Approaches	48

2.8.2 Cyber-Physical Systems.....	49
2.8.3 System Interaction with workers and managers	49
2.9 Future Research Directions.....	50
2.9.1 Human Factors and System Interactions.....	50
2.9.2 Voice Interaction with Construction Workers	51
2.9.3 Knowledge Management	51
2.9.4 Web Interoperability	52
2.9.5 Definition of the characteristics of CPS in the AEC industry	52
2.10 Conclusions.....	52
Chapter 3. DESIGN AND ASSESSMENT OF VOICE-BASED INTELLIGENT VIRTUAL AGENTS (VIVA) TO SUPPORT CONSTRUCTION WORKER PRODUCTIVITY	54
3.1 Abstract.....	54
3.2 Introduction.....	54
3.3 Background.....	56
3.3.1 Factors Impacting Construction Worker Productivity.....	56
3.3.2 Construction Worker Support	57
3.3.3 Knowledge delivery impact on worker productivity	59
3.3.4 Voice-Based Support System in Other Domains.....	60
3.3.5 Voice-Based Worker Support Systems.....	61
3.4 Research Methodology	62
3.4.1 Contextual Inquiry	63
3.4.2 Voice-based Intelligent Virtual Agent (VIVA) System Development	66
3.4.3 Usability Study.....	70

3.4.3.1 Participants	70
3.4.3.2 Experiment Tasks	70
3.4.3.3 Assemblies	71
3.4.3.4 Experiment Setup, Scenarios, and Tasks	72
3.4.3.5 Interventions.....	74
3.4.3.6 Perceived Workload.....	75
3.4.3.7 Semi-Structured Interviews	75
3.4.3.8 Procedures	75
Voice-based Procedures.....	75
Paper-Based Procedures	75
3.5 Results.....	76
3.5.1 Support Method Effect.....	77
3.5.1.1 Completion Time.....	77
3.5.1.2 Assembly Errors	78
3.5.1.3 Interventions.....	78
3.5.1.4 Workload.....	79
3.5.2 Order Effect	80
3.5.3 Post-Experiment Feedback	80
3.5.3.1 Support Method Assessments.....	81
3.5.3.2 Support Method Comparisons	83
3.6 Discussion	83
3.6.1 Performance Findings	84
3.6.2 Perceived Workload Findings.....	84
3.6.3 Participants' Feedback.....	85
3.6.4 Impact of environmental noise and face coverings on worker activities.....	85
3.6.5 Targeted Workers' Experience	86
3.6.6 Radio Communication during Assembly Tasks	86

3.6.7 Contributions.....	87
3.7 Limitations	87
3.8 Conclusions and Future Work	88
Chapter 4. DEVELOPMENT OF A REAL-TIME VOICE-BASED INTELLIGENT VIRTUAL AGENTS (VIVA) BASED ON SYSTEMS INTEGRATION TO SUPPORT CONSTRUCTION WORKER PRODUCTIVITY	90
4.1 Abstract	90
4.2 Introduction.....	90
4.3 Background	92
4.3.1 Cyber-Physical Systems (CPS) in the AEC Industry	92
4.3.2 BIM-Web Interoperability	94
4.3.3 BIM and Natural Language Processing (NLP) Systems.....	96
4.4 Research Methodology	99
4.5 Case Studies	100
4.5.1 Case Study 1: Specify the installation location of objects during crane operations	100
4.5.2 Case Study 2: Identifying the number of construction elements at a specific location.....	100
4.6 VIVA Implementation Framework.....	101
4.6.1 Development Setup	102
4.6.2 Data Sources	102
4.6.3 BIM Parser	103
4.6.4 Information Hub.....	103
4.6.5 Communication Hub.....	104
4.6.6 Interaction Hub	105

4.7 Data Flow and Stages.....	105
4.8 Interaction with VIVA	107
4.8.1 On-site User Interaction	107
4.8.2 Office User Interaction	109
4.9 Evaluation	109
4.9.1 Interoperability and Natural Language Understanding Test.....	109
4.9.2 Spoken Instruction Recognition and Matching Test.....	110
4.9.3 Summary of Evaluation Results.....	111
4.10 Discussion	111
4.11 Conclusions and Future Work	113
Chapter 5. CONCLUSIONS	115
5.1 Summary	115
5.2 Contributions.....	117
5.2.1 Productivity effect of voice-based support systems on construction workers	117
5.2.2 BIM-worker system integration approaches	118
5.2.3 Voice-based systems based on web platforms for the AEC industry	118
5.3 Limitations and Future Research Work	119
5.3.1 Taxonomy of CPS for the AEC industry	119
5.3.2 Further evaluation of voice-based systems in construction applications.....	120
5.3.3 Performance of voice systems on multilingual target users.....	120
REFERENCES	121

LIST OF FIGURES

Figure 1.1 Historical productivity of multiple industries compared. Source: (Barbosa et al. 2017)	2
Figure 1.2. Schema of Productivity affectation and its levels	4
Figure 1.3. Identified research gap in this study	10
Figure 1.4. Overview of Research Design	13
Figure 2.1. Article Selection Methodology.....	18
Figure 2.2. Hierarchy of Approaches for BIM-Worker Integration	25
Figure 2.3. Diagram for Approach A1: Systems for Text-based Knowledge Retrieval... ..	28
Figure 2.4. Diagram for Approach A2: Systems for Voice Knowledge Retrieval	32
Figure 2.5. Diagram for Approach A3: System for Visual and Multimodal Knowledge Retrieval.....	34
Figure 2.6. Diagram for Approach B1: Systems for Multimodal integration of BIM, sensor data, and workers	39
Figure 2.7. Diagram for Approach B2: Systems for Multimodal BIM, sensors, and Workers Integration Based on Web-Assisted Data Processing.....	44
Figure 3.1. Research Framework	63
Figure 3.2. Experimental Assemblies	65
Figure 3.3. Development System Diagram for the VIVA	66
Figure 3.4. VIVA (Voice-Based) Experimental Setup	72
Figure 3.5. Baseline (Paper-Based) Experimental Setup.....	73
Figure 3.6. Comparison of completion time among participants based on support method. * shows significance at $p=0.0218 \leq 0.05$ and Effect Size of -0.755.....	77
Figure 3.7 Comparison of # of required interventions among participants based on support method. * shows significance at $p=0.0266 \leq 0.05$ and Effect Size of -0.280	78

Figure 3.8. Comparison of Workload parameters among voice and paper support methods. ns shows no significance found	79
Figure 3.9. Comparison of time completion among participants based on assembly order. * Shows significance at $p=0.0454 \leq 0.05$ and Effect Size of 0.654.....	80
Figure 3.10. Results from Semi-Structured Interviews	82
Figure 4.1. Context of Application of VIVA within CPS in the AEC Industry	94
Figure 4.2. BIM IE based on NLP algorithm development.....	97
Figure 4.3. BIM IE based on Systems Interoperability	99
Figure 4.4. Research Methodology Diagram.....	100
Figure 4.5. System Implementation Diagram	101
Figure 4.6. 3D Model used to develop and evaluate VIVA.....	102
Figure 4.7. BIM Model Zones Diagram	104
Figure 4.8. Designed Revit Add-in to automatically update the VIVA database.....	109
Figure 4.9. Interoperability Test Platform and Execution Example on Case 1	110

LIST OF TABLES

Table 2.1. Summary Table of Reviewed Articles for Integration Approaches	20
Table 3.1. Summary of experiment scenarios by support method, order, and assembly..	74
Table 3.2. Summary of Statistical Data for Performance Measures.....	76
Table 3.3 Participants subjective feedback about support systems comparisons	83
Table 4.1. Example of Data Flow and Stages for two BIM Objects	108
Table 4.2. Summary of Evaluation Results for VIVA.....	111

CHAPTER 1. INTRODUCTION

The management of construction projects is a complex and challenging task. From the beginning to the end, cyber resources, such as BIM, documents, specifications, and physical resources, such as the management team, laborers, equipment, and tools, must be efficiently monitored and used to achieve the intended goal of safely delivering the construction project on time and within budget (Yates 2014). In order to attain these goals, it is critical to quantify, monitor, and support project productivity by effectively managing resources.

Productivity stagnation in the construction industry remains one of the biggest challenges to overcome. Even though some technological and methodological advancements toward productivity improvement have been developed and implemented, data still shows that productivity improvements are insufficient (Eastman and Sacks 2008; Goodrum and Haas 2002; Goodrum and Haas 2004; Hasan et al. 2018). However, progress can be achieved when proper means for productivity measurement are available. Monitoring productivity focuses on monitoring workers, equipment, and material resources to quantify the ratio of units developed (output) per unit of work and the resources needed (input) during a measured period of time (Ashuri et al. 2014; ASTM International 2016; Azzam et al. 2019; Chang et al. 2005; Gurm and Ongkowiyo 2020; Hwang and Soh 2013). Likewise, another approach to improving productivity is proactively supporting project resources' productivity. However, there are few academic and industry investments in developing tools to support proactive solutions.

At the core of possible solutions, proactive productivity enhancement solutions have been provided in the areas of knowledge management, cyber-physical systems (CPS), and human-computer interaction. On the knowledge management side, solutions aim to provide construction workers with information so that they can access knowledge as information from BIM (Brathen and Moum 2016; Junbok et al. 2017), spatial-temporal coordination among different project resources (Mirzaei et al. 2018), and virtual augmentation of the digital resources to support workers' activities (Wang et al. 2014). As a systematic approach, CPS has actively supported project resources when coordination between humans and machines is needed. Examples of these interactions include equipment operations (Goodrum and Haas 2004) and crane operations (Kan et al. 2018).

Human-computer interaction in the context of workers' impact on labor activities and productivity was first explored in other fields, such as manufacturing. Zuboff (1988) manifested that the job itself changes from skills-based physical work to analytical control-based and operational when computationally mediated means are incorporated alongside human workers. In the architectural, engineering, and construction (AEC) industry, developing CPS that supports humans on construction sites requires further consideration of multiple factors, including the environment, activity performed, tools, visual constraints, context, BIM, knowledge delivery, and human factors (e.g., cognitive, workload perception). Therefore, investigating methodologies to support workers addresses the productivity challenges faced by the AEC industry and is the focus of this study.

1.1 Background

In the last decades, productivity trends show that current practices of managing construction productivity are ineffective (Barbosa et al. 2017). As a consequence, previous research efforts focused on tackling this problem by exploring the use of emerging technologies and methodologies to increase the efficiency of the project resources (Linares et al. 2019). However, these solutions have not been effective in improving the industry's low rate of productivity due to their fragmentation and poor integration. More specifically, human resources' productivity has remained unchanged because research on labor productivity mainly focuses on monitoring, and the active support of labor resources is not broadly considered. Previous research efforts to actively support worker productivity have been made in the areas of knowledge management, CPS, and human-computer interaction. These areas been found as the most influential areas to tackle the problem identified in this research and are explained in detail in the following sections.

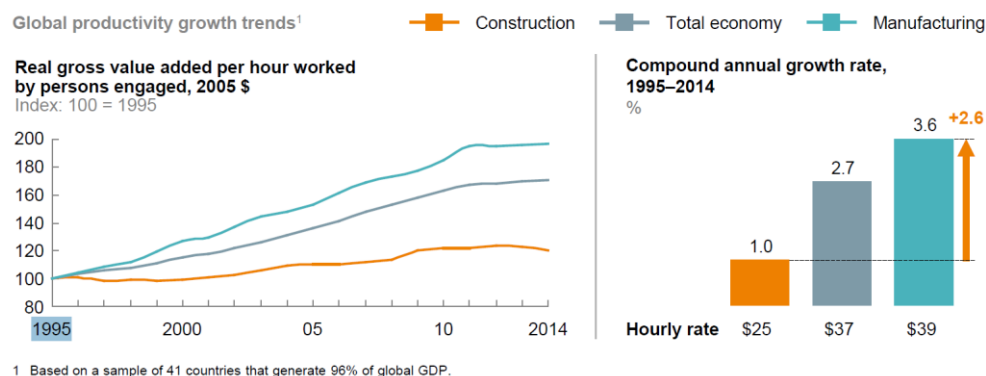


Figure 1.1 Historical productivity of multiple industries compared. Source: (Barbosa et al. 2017)

1.1.1 Productivity in the AEC Industry

In other industries such as manufacturing, tackling the productivity issue has been addressed in multiple ways, including simplified manufacturing processes, improved logistics, modularization, and digital approaches. The latter has proven to successfully increase productivity by increasing automation, delivering optimized processes, and supporting workers by providing relevant knowledge to them and assisting them in performing their intended tasks efficiently (Al-Ali et al. 2018; Kim and Park 2017). Digital approaches, such as Cyber-Physical Systems (CPS), are considered the most promising approaches to holistically integrate technological advances with current standard practices (Rüßmann et al. 2015) to support efforts that improve productivity actively, given their smartness, bi-directionality, and connectedness (Klötzer et al. 2017).

Compared to other industries, the AEC industry is known to have decreasing productivity rates and a sizable gap in productivity improvements, see Figure 1.1 (Barbosa et al. 2017). Because of this, in the last years, technology-based approaches such as BIM, automated monitoring systems, and connected devices were more conventionally implemented in the AEC industry to support the evolution towards overcoming the current industry challenges of productivity stagnation (Kim et al. 2009; Teo 2016). For example, BIM is now widely used and even considered a best practice for buildings and infrastructure development (Junbok et al. 2017; Shan et al. 2012). Using sensors, location systems, and intelligent systems-based approaches to monitor workers and construction equipment promises to sustain productivity and safety efforts (Akhavian and Behzadan 2015; Lee et al. 2017; Li et al. 2016). However, these approaches are fragmented, limited to specific applications, and within closed platforms; therefore, integrated digitalization approaches such as CPS, are a potentially better solution, as observed in advances made in other industries (Chuah et al. 2019; Monisha and Rajasekhara Babu 2019; Nagorny et al. 2018; Nikolakis et al. 2019; Romero et al. 2020).

Productivity tracking is a need and a challenge for the efficient usage management of the physical and digital resources (Prastianing Atas Kasih and Joko Wahyu Adi 2019). From the management perspective, productivity is considered at three levels: industry, project, and task (Huang et al. 2009). When considering productivity in a construction project, productivity at the project and task levels are critical and largely dependent on the efficient management of the physical project resources and how the digital project resource are appropriately delivered to them (Hasan et al.

2018). At the task level, productivity is more directly affected by labor productivity, where multiple factors such as environment, site, management, and project design play an essential role (Thomas and Yiakoumis 1987). On the other hand, project management directly establishes how knowledge and decisions are transferred and communicated to the laborers (Ozturk and Yitmen 2019; Park et al. 2005). Consequently, project management also indirectly affects productivity at the task level and directly at the project level, as shown in Figure 1.2.

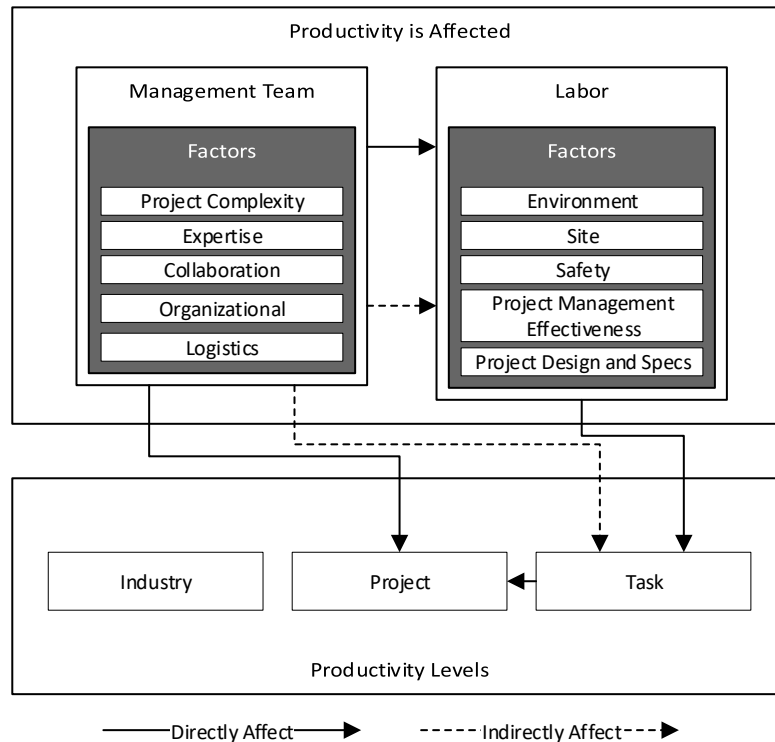


Figure 1.2. Schema of Productivity affectation and its levels

Measuring productivity is a daunting task; therefore, using automated technologies to monitor and track productivity is of great interest (Gurmu and Ongkowijoyo 2020). Research efforts have been made toward getting quantifiable insights about the inputs, quantifying the number of outputs used, and estimating productivity ratios. As a result, recent research efforts focus on monitoring various resources, including labor, equipment, and material (Park et al. 2005). The results of resource tracking is an additional digital project resource, which will then be analyzed with data analysis methodologies to generate insights into an even higher value for multiple construction resources used to increase project productivity. According to Neve et al. (2020), the quantified benefits of

improving labor productivity resulting from slight trade productivity improvements are estimated to be billions of dollars.

The experience of construction workers is also a factor that takes time to build up and mature. In this direction, Ha et al. (2020) studied worker's experience and identified a direct linear relationship between workers productivity and years of experience until worker's productivity becomes constant at 12 years of experiences. Also important, Ha et al. (2020) highlight that a baseline worker productivity is reached until worker's experience reaches seven years. Therefore, supporting workers productivity while their skill trades matures is a lasting process. As a result, any effort to support workers at these early stages have potential to address the gap of experience while their skills mature.

1.1.2 Knowledge Management and Knowledge Adaptation

Knowledge management (KM) describes knowledge's effective creation, interpretation, distribution, and manipulation as easily and readily interpretable information (Guodong et al. 2018). KM is an important productivity aspect that is often neglected in construction projects. Timely knowledge management is essential for keeping productivity goals and increasing the productivity of resources. It can inform what needs to be done, when, what dimensions and quantities of resources to use, or what amount of work should be completed. KM also helps efficiently manage the supply chain, equipment and materials, and the selection and assignment of worker teams to activities.

In the past, explicit knowledge was delivered through blueprints, written instructions, memos, or in-person communication. However, these methodologies impose an imbalance on the effort made between the knowledge provider (e.g., project management personnel or site superintendent) and receiver (e.g., foremen). As a result, the knowledge provider is burdened with the additional tasks of translating raw knowledge to be understandable and usable by the receiver, while the receiver becomes a passive knowledge consumer. Research also indicates that delivering knowledge to specific resources is more complex or has been done inefficiently in the AEC industry (Calvetti et al. 2020). As such, providing knowledge to construction resources such as labor is more challenging because of the limitation on their cognitive abilities to retrieve information while performing their trade tasks and the surrounding conditions they perform (Solis et al. 2015). Direct

knowledge delivery to end-user, e.g., workers, can cause additional barriers and inefficiencies if ineffectively implemented.

Recently, researchers and industry moved towards placing information booths on the job site to enable direct knowledge delivery to workers (Ruwanpura et al. 2012). In such approaches, the workers will have to search for the information they need through multiple documents, i.e., digital assets, which might be time-consuming. Consequently, all the workers that need to access information must be trained to use digital assets, platforms, and devices. Besides, the workers will have to stop their activity and move to a specific location where they can use a device to access digital construction assets (Ruwanpura et al. 2012). This research example highlights how challenging knowledge management is and why knowledge delivery alternatives need to be analyzed to effectively deliver information to the end-users in a human-centered system approach.

Given the complexity of knowledge management, ontologies (Anumba et al. 2008), and architectures (Fang et al. 2018), and technological approaches such as the use of Information and Communication Technologies (ICT) (Demian et al. 2015; Gürdür et al. 2018; Lin et al. 2016; Linares et al. 2019) have been explored. Industry solutions have incorporated Knowledge Management Systems (KMS) that integrate information from multiple sources and visualize them through mobile and web applications (e.g., Autodesk solutions and Procore). However, these solutions' focus is to offer non-semantic file-sharing platforms, allowing users to access digital project resources when requested, but not proactively nor semantically in the sense that users will not be able to be easily understandable and use the information available on these platforms while simultaneously doing their jobs. This non-proactive information is then of little use for hands-on resources such as trade workers that do not have the computational tools or training to retrieve knowledge from the files distributed by KMS. Based on the previous research findings, *this research will address the gap identified concerning how efficient knowledge management can improve labor productivity in construction projects.*

1.1.3 Cyber-Physical Systems (CPS)

CPS bidirectionally connects physical and digital assets to achieve automated processes such as optimization, monitoring, and knowledge management. Given the current status of knowledge delivery and productivity described in the previous section, a CPS-based approach to bridge the

existing gap in knowledge delivery from digital to physical resources to improve construction projects' productivity is explored in this research.

Multiple efforts have been undertaken to solve the AEC industry challenges through a CPS-based approach, including monitoring equipment operations (Kan et al. 2017; Kan et al. 2018), object recognition of construction project elements (Srewil and Scherer 2017), progress monitoring (Omar et al. 2018), safety (Li and Leung 2020; Wang and Razavi 2019), and worker ergonomics (Akanmu and Olayiwola 2019). However, productivity has not improved significantly, suggesting that monitoring is insufficient to achieve productivity improvements effectively. Following the last statement, *this research hypothesizes that actively supporting workers' activities helps increase productivity during construction projects besides productivity monitoring.*

Research also suggests that within CPS and similar schemas (such as IoTs and Industry 4.0), the establishment of the interoperability between digital and physical resources has been more emphasized in the development of the physical-to-cyber direction, neglecting the cyber-to-physical direction (Puri and Turkan 2018; Son et al. 2017; Turkan et al. 2013). Industry solutions are on the same page and focus on monitoring the physical project assets or the physical-to-cyber direction of CPS (Ozturk and Yitmen 2019; Wang and Meng 2019). Such examples include monitoring solutions such as Reconstruct®, and KMS such as Autodesk® solutions. These solutions help define productivity boundaries, thresholds, issues, and gains; however, neglecting the other direction, i.e., conveying knowledge from cyber assets to the respective physical resources, creates a gap in digital construction management practices and leaves incomplete automated solutions. Therefore, better addressing the cyber-to-physical direction in CPS, bring the potential of digital project resources to fruition. Based on the literature, few cyber-to-physical solutions within the context of CPS have been developed to support workers' productivity actively. Consequently, fully automated CPS-based solutions need critical consideration of the cyber-to-physical aspects of CPS.

On the other hand, the CPS-based approach introduces challenges associated with interoperability among different components, platforms, and subsystems that already exist. Research efforts explored the interoperability of CPS-like systems in the AEC industry (Muñoz-La Rivera et al. 2020). Tang et al. (2019) proposed various approaches to develop interoperable processes between IoTs and BIM; their scope is limited to communications with the sensors, and its scope does not

include human-centric knowledge interoperability. This study reveals how complex the management of the multiple data types currently used in the AEC industry is and how challenging it can be to transfer data among system components such as physical technology and technical components. The previous works show how CPS is used in the context of system design for solutions aimed at aspects of construction productivity, such as digital technologies and frameworks for interoperability. Therefore, *these approaches do not address cyber resources from other sources, such as humans.*

1.1.4 Human-Computer Interaction

Human-Computer Interaction (HCI) studies humans' use of computational systems in their daily activities. This field seeks to understand the factors that affect human and computer collaboration, such as cognitive, contextual, experiences, interfaces, etc. (Rogers 2012). The HCI theories have been widely applied in multiple industries, e.g., human-robot interaction in manufacturing environments (A-lHamouz et al. 2019). However, the discoveries from HCI in other industries cannot be fully translated to applications in the AEC industry because of its industry peculiarities and the level of integration of humans and robots in the AEC context. Consequently, the factors involved in workers' active support based on HCI principles have not been fully established in the AEC industry. Modalities of knowledge delivery to the workforce are an essential factor that needs to be carefully studied when tending to improve human workers' productivity, ensure minimized distraction, and increase the employed approaches' effectiveness. These modalities are varied and can include paper-based instructions, voice interaction, visual interaction, hybrid interactions, etc. For example, a computer or a mobile device is not optimal for searching through specific information on the construction site while the worker is carrying out activities particular to their trade. For example, the worker may need information about the location or quantity of the material required for the activity at hand. Getting this information from a device might negatively impact his/her productivity and safety because he/she will need to stop his activities and divert his attention to the search for the required information in the device.

The interaction between construction workers and information systems is challenging because of workers' dynamic conditions, characteristics, and needs on a construction site. Researchers have explored multiple alternatives for interaction to achieve this goal. Physical information booths have been explored to be placed onsite (Hewage and Ruwanpura 2009; Murvold et al. 2016;

Ruwanpura et al. 2012). In such a system, the user has to interrupt their productive activities and mobilize to the location of the information station. Apart from being disruptive and needing activity stoppage, these systems are not intuitive and need exclusive training because they are based on computer-like interfaces that require the user to be comprehensively trained to use the system.

Other interaction approaches have been explored through virtual environments, such as Augmented Reality (AR), to visualize information where the user is working without needing to move (Wang et al. 2014). However, the technologies' current state does not allow for a non-disturbing experience and usually cannot be used in conjunction with conventional personal protection equipment (PPE). As a result, AR devices negatively impact users' comfort while using them, and it might also obstruct workers' Field of View (FOV) during their tasks and cause safety issues. These bring productivity and safety issues that interdict the intended benefits. However, future development of AR devices promises to overcome some of the current technical limitations; yet integration with the user's PPE might be a challenge. Other potential HCI approaches to deliver information to workers include voice assistant systems to provide helpful information to the user (Kondratova 2003). In the past, these have been explored to be used for applications such as scheduling information (Abdel-Monem and Hegazy 2013) and BIM (Lin et al. 2016). However, the scope of these research efforts is developing interoperability frameworks without considering a specific purpose and are not on an "on-demand" basis.

Therefore, establishing and evaluating effective modalities to efficiently deliver knowledge to human resources is a gap not currently addressed in the literature. Nevertheless, these modalities are expected to support the efficiency of knowledge management systems significantly. *As a result, this research will investigate knowledge delivery through voice interaction modality to enable "on-demand" information retrieval and delivery to human resources on construction worksites.* As such, this research will analyze, evaluate, and develop a prototype system that effectively supports workers' productivity when receiving essential information from digital project resources.

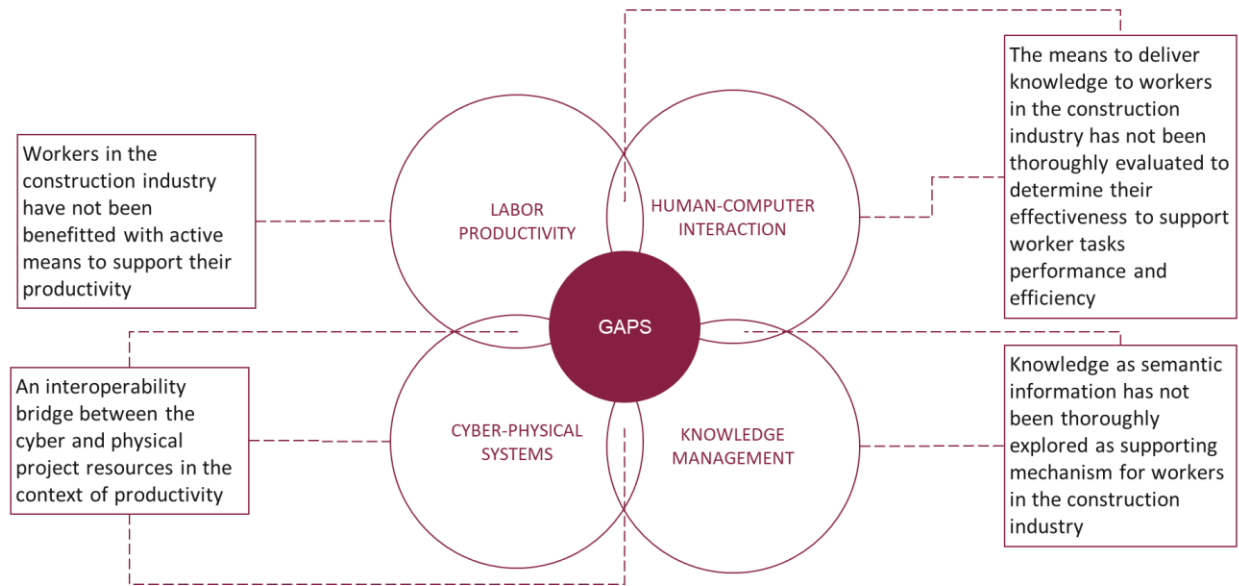


Figure 1.3. Identified research gap in this study

1.2 Research Gaps and Point of Departure

Figure 1.3 presents the research gaps in the context of the main literature research areas of labor productivity, CPS, KM, and Human-Computer Interaction. The preliminary gaps from the intersection of multiple of these research areas can also be reviewed in Figure 1.3. The literature review and the aforementioned gaps are then summarized as follows:

- Efficient knowledge management can improve labor productivity in construction projects,
- Actively supporting workers' activities has the potential to increase productivity during construction projects, and
- Current CPS approaches do not fully link cyber resources from the AEC industry and workers in the field.

As a result, the point of departure of this study is the need to investigate the methodologies that support workers onsite through modalities that are appropriate for their conditions and needs. From the literature, using the workers' voices to give them access has significant potential for improvements but needs to be evaluated for effectiveness and systems interoperability.

1.3 Literature Findings and Proposed Solution to Develop

This research project aims to address the aforementioned gaps identified in the literature by developing an integrated, CPS-based knowledge-sharing system that bridges the cyber and

physical construction assets, which can significantly improve current productivity deficits in the construction industry. This system primarily supports critical human resources (e.g., labor, management team) to carry out their activities more efficiently, increasing their productivity (Correa 2018).

As a result, the current document presents a systematic approach to developing the fundamentals and a support system that connects cyber and humans on the construction site. The system is expected to significantly improve labor and project productivity by promptly delivering knowledge from digital sources in construction to workers. This will be achieved by developing and evaluating an interoperable system that receives and processes laborers' requests for information through a non-disruptive interaction. As such, the present solution improves productivity through (1) establishing the required mechanism to bridge the cyber construction assets and the project's physical resources and (2) providing precise and timely knowledge to project resources.

To summarize, the following research questions will be addressed to fill the gaps identified in the literature review: (1) How can a direct bridge between cyber assets and physical resources help improve productivity in a construction project? What are the requirements to enable this bridge? (2) How can knowledge from the project be proactively used to improve the productivity of resources? (3) What system and interaction factors enable effective delivery of knowledge to project resources that supports their productivity?

1.4 Research Objectives and Goals

The purpose of this study is to investigate, develop, and evaluate a methodology to support the productivity of construction workers by means of efficiently providing knowledge that they can use while they do their work activities. Based on the gaps identified in the literature, the following objectives were proposed for this study to improve labor productivity through voice-based systems to promptly deliver customized knowledge from cyber sources to construction workers:

1. Investigate the integration approaches used in the literature to link BIM (cyber resources) and construction workers (physical resources) during construction projects to support productivity improvements.
2. Identify the most appropriate methodology to support workers in construction projects based on the modality for knowledge delivery.

3. Evaluate the performance and workload perception effect and benefits of using the identified methodology in the context of construction workers.
4. Develop and evaluate an interoperability solution to link BIM and human workers that supports the productivity of construction workers based on knowledge retrieval.

1.5 Research Methodology and Dissertation Structure

The dissertation is organized into five chapters. The proposed structure of the document is as follows:

- **Chapter 1:** Introduction. This chapter introduces the general topics of CPS, KM, HCI, and project productivity and introduces the main problems and justification of this research undertaking. Also, this chapter presents the objectives of the dissertation, as well as the structure of the document.
- **Chapter 2:** Review of Building Information Modeling (BIM) and human cyber-physical system (CPS) integration approaches to support construction worker productivity in the AEC industry. As presented in Figure 1.4, this chapter addresses objective 1 of this dissertation. Its point of departure is the investigation of the integration approaches to link BIM and construction workers to increase their productivity. A literature review is the main research method used to analyze and synthesize previous research works. This chapter's outcomes include identifying the system types, integration approaches, and future research directions.
- **Chapter 3:** Design and assessment of a Voice-based Intelligent Virtual Agents (VIVA) to support construction worker productivity. As presented in Figure 1.4, this chapter addresses objectives 2 and 3 of this dissertation. This chapter's point of departure considers the outcome from the previous chapter's future research directions on human factors in construction systems applied to the more specific case of voice-based systems for productivity support. This study first identifies the voice as the most appropriate modality to support workers in construction. Then, it develops a prototype system that provides workers with instructional information for completing their work activities. The research methods used in this chapter include developing a contextual inquiry to identify the best modality for construction workers. Then, a prototype system is developed and evaluated based on its effectiveness on performance and cognitive workload perceived by workers.

- **Chapter 4:** Development of a real-time voice-based intelligent virtual agent (VIVA) based on systems integration to support construction worker productivity. As presented in Figure 1.4, this chapter's point of departure is the findings from Chapters 2 and 3 to develop an interoperable voice system that links BIM and workers in construction. For this purpose, the developments in this chapter create a prototype for a system that connects BIM sources and workers in real time through a smart speaker that interacts with the user vocally. This article provides a functional system based on two case studies, and it proposes a framework for interoperability and evaluation based on different target users.
- **Chapter 5:** Conclusions. This chapter summarizes the previous chapters' findings and provides an in-depth discussion about their relevance and contributions to the body of knowledge. Future research directions are highlighted.

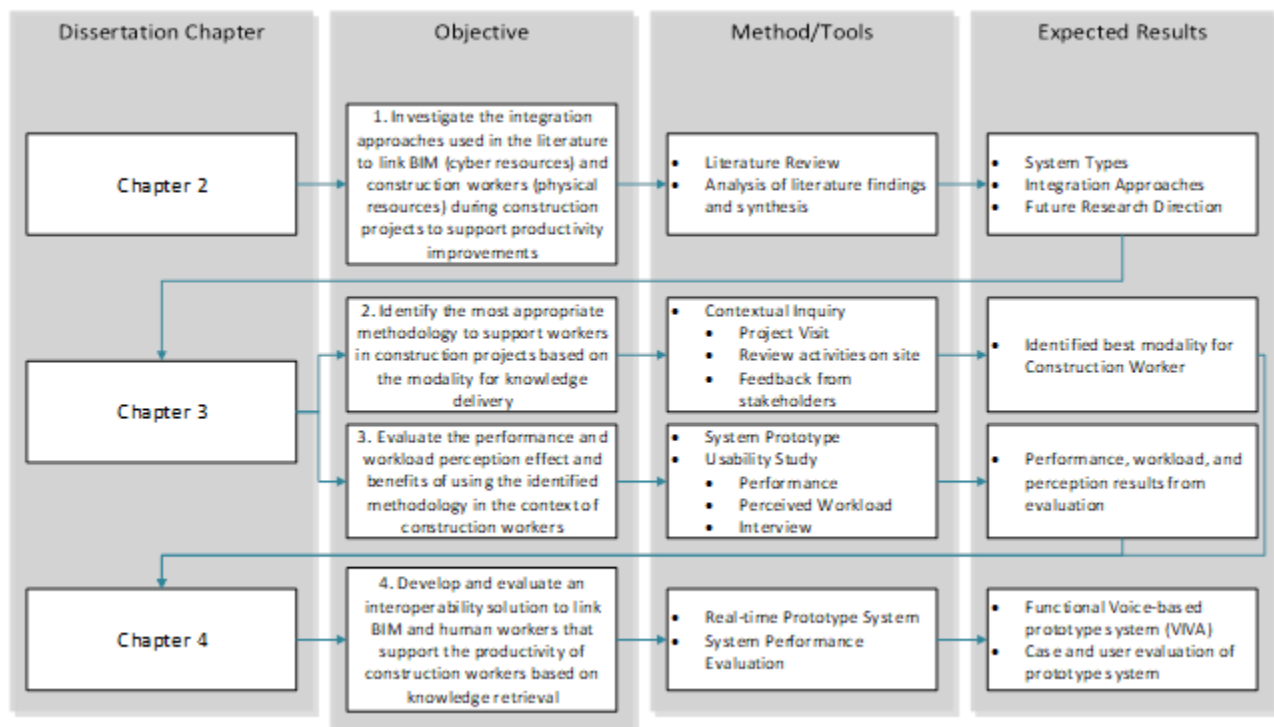


Figure 1.4. Overview of Research Design

1.6 Expected outcomes, contributions, and impacts

Efficient knowledge delivery to specific project resources presents specific challenges, and the lack of such efficient knowledge delivery is proven to impact human resources' productivity negatively. The proposed research tackles this productivity issue at its root by proposing a system

to efficiently deliver knowledge from the digital project assets available to human resources in an “on-demand” approach. By doing this, this research is expected to increase productivity at the task level by allowing workers to access knowledge intuitively when they need it, without disrupting their work activities.

On the other hand, knowledge management is challenging in the AEC industry because the information sources are highly heterogeneous and lack integration. Therefore, this research takes a CPS approach to bridge the cyber assets available with the resources that need knowledge from these assets. This way, this research presents an innovative approach to address the mentioned knowledge delivery gap by completing the bidirectional communication loop among cyber and physical construction assets through an evaluation of a knowledge delivery modality most appropriate to construction workers.

Finally, this research contributes to the body of knowledge in construction management and automation by developing and applying a methodology to manage information from cyber sources and effectively communicate it to workers. The contributions are expected to help develop an integrated system that captures information from the construction site and automatically communicates it to the targeted end-users.

CHAPTER 2. REVIEW OF BUILDING INFORMATION MODELING (BIM) AND HUMAN CYBER-PHYSICAL SYSTEM (CPS) INTEGRATION APPROACHES TO SUPPORT CONSTRUCTION WORKER PRODUCTIVITY IN THE AEC INDUSTRY

2.1 Abstract

The Architecture, Engineering, and Construction (AEC) industry is undergoing a digital shift toward integrating physical and cyber resources that is fueled by technological innovation, building information modeling (BIM), sensing technologies, and modernization of industry practices. However, the AEC industry is currently facing challenges including low productivity and labor shortages, impacting construction project productivity that is heavily dependent on the productivity of workers. As a result, human-in-the-loop cyber-physical systems (CPS) approaches that aim to support workers through connecting them with project sources, including BIM, have great potential to generate productivity improvements in the industry. Accordingly, multiple research efforts have been made to develop system architectures and prototypes that benefit workers' productivity. However, there has not yet been a synthesis of these worker support integration approaches or an identification of this area of interest's current status and challenges. To address this gap, we performed a review of the articles that develop architectures and prototype systems to support construction workers' operations or their managers in the field during projects' construction phase. After the research articles were vetted, 38 were reviewed and analyzed in depth. This analysis revealed two primary types of CPS systems and five integration approaches. First type is knowledge retrieval system that includes three integration approaches including articles focusing on text-based knowledge retrieval (A1), voice knowledge retrieval (A2), and visual and multimodal knowledge retrieval (A3). The second system type are activity monitoring and context aware CPS systems that includes two integrations approaches including systems that integrate multimodal BIM, sensor data and workers (B1) and BIM and sensor data integration for worker support assisted by web platforms (B2). These developments shed light on the challenges of including humans in the loop of CPS systems in the construction industry and demonstrates how effective such systems can be in supporting worker productivity. The article discusses each approach's challenges and benefits and suggests future research directions.

2.2 Introduction

The AEC industry is undergoing a digital shift toward systems integrating cyber and physical construction elements, cyber-physical systems (CPS). Such change is enabled by emerging technologies (Linares et al. 2019), building information modeling (BIM) (Maskuriy et al. 2019), sensing integration methodologies (Tang et al. 2019), and modernization of industry practices. At the same time, the AEC industry is challenged by a lack of productivity (Barbosa et al. 2017; Hasan et al. 2018) and labor shortages (Kim et al. 2020) that affect its outcomes. Therefore, research studies that develop aspects of workers lack of productivity are of significance. As a result, several of these previous research developments have taken advantage of CPS to boost some aspects of worker productivity in construction projects is relevant to addressing those issues. These aspects have included health and safety, knowledge retrieval, monitoring, and others.

CPS in construction establish information-rich knowledge processes that enable bi-directional information flow between the physical world and its cyber representation (Akanmu and Anumba 2015). CPS researchers in construction domain have developed systems with different levels of integration between cyber and physical elements. Some CPS obtain insights from the physical construction projects through sensor data capturing and analysis and transfer data to BIM databases (physical-to-cyber) (Tang et al. 2019). Other systems use BIM sources to provide support to physical construction resources (cyber-to-physical) (Li et al. 2018; Rezgui et al. 2011). Other closed-loop systems provide bi-directional integration of both cyber and physical resources e.g., Kiani et al. (2014) and Kan et al. (2018). However, the integration of humans within CPS, especially in the cyber-to-physical CPS direction, which enables human worker support, has not been a research priority despite its importance in the AEC industry (Eskandar et al. 2020).

Understanding the integration approaches that enable connecting cyber and physical construction elements is important to gaining insight into the benefits and challenges of these developments and further supporting the use of related CPS research in construction. Because of this, previous researchers developed CPS interoperability architectures and prototype systems for BIM-human integration (Dave et al. 2018; Niu et al. 2019; Rezgui et al. 2011). However, the multiple integration approaches used in these studies need to be further understood and synthesized. Researchers have reviewed previous literature to identify the established integration approaches to link CPS resources such as BIM and sensors (Tang et al. 2019). Their developments have greatly

supported the research direction of BIM-sensors interoperability and have supported other researchers' integration approaches ahead. Likewise, further understanding of integrating other construction elements is also essential to address all facets of CPS in the AEC industry.

Understanding the role of humans and their integration with other elements in CPS systems addressed towards construction is critical. By understanding previous researchers' approaches and identifying the benefits and drawbacks of previous integrations, future research can take advantage of productivity improvements developed in previous studies. However, no such synthesis of integration approaches between BIM and workers has been found in the literature. Based on this gap, this study reviews the literature pertinent to integrating BIM and humans, particularly workers and managers in construction projects, during project development phases. By developing such a literature review, this article seeks to identify trends in systems that link BIM and human workers and the benefits, challenges, tools, and interaction devices and modalities used by previous research works.

2.3 Point of Departure, Scope, and Context of Application

Previous research works have developed systems that integrate BIM and human workers through multiple integration approaches and purposes that have not been synthesized. Therefore, the point of departure of this study is the need to identify the integration approaches between BIM and humans and identify its benefits and challenges, as well as future research directions.

While the benefits of integrating BIM and human workers can be traced to multiple stages of development in construction projects, developing solutions for the construction stage of project development has the greatest effect. Previous research also documented that efforts to support the productivity of construction workers produce significant project productivity improvements (Barbosa et al. 2017), among other benefits such as project cost and schedule. As a result, the scope of this study was defined to be the integration of BIM and workers' productivity support during the construction phase of project development. This definition also includes systems that target construction workers' managers, who indirectly affect the workers' performance. In sum, this study's objectives are (1) to identify primary system types that integrate BIM and humans; (2) to identify and analyze the integration approaches to link BIM and workers in construction with emphasis on interoperability of processes, data, and user interaction; and (3) provide insights for future research.

2.4 Research Methodology

A comprehensive review of studies that integrate BIM and worker support was developed based on the review of articles in the AEC discipline and journals in other related fields that develop computational systems and user interactions applied to the AEC industry. Figure 2.1 presents the research methodology for article selection and analysis. The methodology steps are the following:

1. Query the Web of Science and Google Scholar databases in search for articles based on key phrases that include multiple combinations of the terms related to BIM, human, and worker support (e.g., BIM, Building Information Modeling, worker, construction, human interaction, cyber-physical systems, CPS, system, interaction, human, interoperability, integration, computational, integration, smart, cloud-based, IoT, Internet of Things, technology, construction, knowledge).
2. Define article candidates by eliminating irrelevant articles or duplicates based on reading the article title and abstract.
3. Select articles to be reviewed by eliminating those outside the defined scope based on the complete review.
4. Categorize reviewed articles based on content analysis and discussion
5. Define integration approaches and development of diagrams
6. Identify future research directions
7. Write summary, discussion, and conclusions.

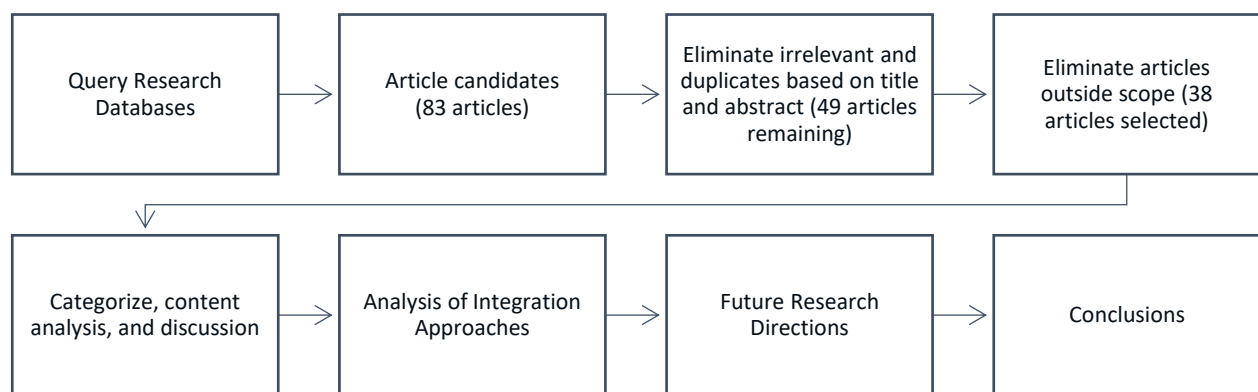


Figure 2.1. Article Selection Methodology

2.5 Summary of Reviewed Articles for Integration Approaches

Table 2.1 shows the summary of the 38 reviewed articles considered to define the five approaches for integrating BIM and workers for productivity support. Table 2.1 presents the literature item next to a description of the article's contribution to BIM-worker productivity support, the description of the human interactions presented in the developments of each literature item, and the data sources and target users considered.

Table 2.1. Summary Table of Reviewed Articles for Integration Approaches

Approach	Literature Item	Description of Article Contribution to BIM-User Support	Description of Human Interaction with System	Productivity Factor(s) in Article	Data Sources	Target Users
A1	(Fan et al. 2015)	Develop Information Retrieval algorithm system for construction documents	Search queries based on text	Knowledge Management	BIM Documents	Any Construction Worker
	(Lin et al. 2016)	Develop Information Retrieval system based on MapReduce for BIM data	Search queries based on text	Knowledge Management	IFC Data from BIM Model	Construction Managers
	(Park et al. 2013)	Develop Information Retrieval System based on ontologies for construction documents	Search queries based on text	Knowledge Management	BIM documents	Construction workers and managers
	(Wang et al. 2021; Wang et al. 2022)	Develop algorithm to extract information from BIM through text-based queries	Workers ask for information about the location of construction elements. Text-based	Knowledge Management	IFC Data from BIM Model	Construction Workers
A2	(Shin and Issa Raja 2021)	Develop architecture and prototype to enable interaction between BIM data sources and workers through voice	Manager use his voice to ask for information about the project. Interaction can produce a response to the manager and changes to BIM Model	Knowledge Management	BIM data	Project managers
A3	(Yeh et al. 2012)	Develop a system that uses a projector and a mobile device to visualize construction drawings on site	Visual Information is projected onsite. User Interacts with System through mobile device	Productivity, Knowledge Management	BIM model	Workers on site
	(Rezgui et al. 2011)	Develop architecture to retrieve knowledge in the AEC industry	Workers request knowledge through multimodal device interaction	Knowledge Management	IFC Data from BIM Model	Any Construction Worker
	(Hewage and Ruwanpura 2009;	Develop architecture and prototype for information booths on the construction site	Worker interaction with information on site about knowledge needs	Knowledge Management	BIM Model, BIM data, construction documents	Construction workers on the field

Table 2.1. Summary Table of Reviewed Articles for Integration Approaches

Approach	Literature Item	Description of Article Contribution to BIM-User Support	Description of Human Interaction with System	Productivity Factor(s) in Article	Data Sources	Target Users
	Ruwanpura et al. 2012)					
	(Alsafouri and Ayer 2019)	Develop architecture and prototype system to retrieve the 3D model from 2D drawings to increase understanding during constructability meetings	Workers and managers use a mobile app to scan 2D drawings to visualize 3D models on a mobile device	Productivity, Knowledge Management	BIM model	Workers and managers on site
	(Lin et al. 2015)	Develop architecture and prototype of a collaboration platform based on physical objects and multiple visualization devices	Worker interact with mobile app and show 3D visualization over scanned objects	Knowledge Management	BIM Model and BIM data	Worker and manager in the onsite office
	(Linares-Garcia et al. 2022)	Develop architecture for users to interact with virtual objects through physical objects	Worker interacts with mobile device to show visualization after scanning objects	Knowledge Management, Productivity	BIM Model and construction documents	Construction workers, managers, and clients
	(Mirzaei et al. 2018)	Develop architecture and prototype system for identification of workspace conflicts and optimization of workers groups activities	Managers query activities from Revit Plugin. Worker receives feedback from Revit UI	Progress Monitoring, Productivity, Coordination	BIM Model, BIM data, project schedule	Workers and managers on site
	(Wang et al. 2014)	Develop architecture and prototype system to retrieve 3D models and data onsite based on scanning 2D drawings	Worker scans 2D drawings on the field with a mobile app to retrieve 3D models	Productivity	BIM Model, BIM data	Workers and managers onsite
	(Yang et al. 2016)	Develop mobile app to retrieve 3D models in the field	Worker scans 2D drawings on the field with a mobile app to retrieve superimposed 3D models	Knowledge Management	BIM Model, 3D Model	Workers and managers onsite

Table 2.1. Summary Table of Reviewed Articles for Integration Approaches

Approach	Literature Item	Description of Article Contribution to BIM-User Support	Description of Human Interaction with System	Productivity Factor(s) in Article	Data Sources	Target Users
	(Zaher et al. 2018)	Develop architecture and prototype system to retrieve BIM model from 2D drawings	Worker provides and receives feedback through mobile app. Feedback is based on superimposing 3D models through Mobile AR	Knowledge Management, Progress Monitoring	BIIM model, BIM data	Construction workers and managers
B1	(Kan et al. 2018)	Develop architecture and prototype system for equipment monitoring	Operator receives visual information and audio feedback. System provides feedback to users about operations and hazards	Health and Safety, Productivity	BIM Model, BIM data	Crane Operators and managers
	(Golzarpoor et al. 2018)	Develop architecture to enable process interoperability based on proposed process schema	Process schema included example of user interaction through User Interfaces	Knowledge Management, Interoperability	BIM Model, BIM data	Any Construction Worker
	(Kiani et al. 2014)	Develop architecture and system prototype to track the conditions onsite through a mobile app	Audio and visual feedback through mobile device	Health and Safety	BIM Mode, BIM data	Workers onsite, H & S Managers
	(Ham et al. 2016)	Develop system prototype for progress monitoring with data from UAVs	Visual Feedback in web platform	Progress Monitoring	BIM Model, 3D Model	Project Control and Management Personnel
	(Schweigkofler et al. 2018)	Develop architecture and system prototype for 3D model retravel based on mobile app and Bluetooth localization beacons	Onsite navigation and visualization of 3D models with Mobile AR App	Knowledge Retrieval	BIM Model, BIM data, sensor data	Workers on site
	(Son et al. 2017)	Develop architecture and system prototype for automatic progress monitoring updating based on data from UAVs	Manager reviews project progress updates on dashboard	Progress Monitoring	BIM Model, BIM data, project schedule	Project Managers

Table 2.1. Summary Table of Reviewed Articles for Integration Approaches

Approach	Literature Item	Description of Article Contribution to BIM-User Support	Description of Human Interaction with System	Productivity Factor(s) in Article	Data Sources	Target Users
	(Srewil et al. 2016; Srewil and Scherer 2017)	Develop architecture for an automatic link between physical and digital objects based on sensors from the field	Worker scan objects in the field, then managers review information in a simulation dashboard	Interoperability	BIM Model, BIM data	Any construction worker and management
	(Zhou et al. 2019)	Develop architecture and framework to support machine blind hoisting through sensors	Worker in the field interacts with the system through mobile. Manager interacts with dashboard	Productivity, Progress Monitoring	BIM Model, BIM data, sensor data	Construction workers on site and managers
B2	(Koseoglu and Nurtan-Gunes 2018)	Develop prototype system to evaluate the support of mobile AR app on lean construction support	Worker interacts through mobile app. Managers interact with the system through web dashboard	Progress Monitoring, Productivity	BIM Model, 3D Model and data.	Workers onsite and managers
	(Han et al. 2022)	Develop architecture and prototype for monitoring and supporting road compaction operations	Worker receive warnings and information through mobile device. Manager reviews web dashboard	Progress Monitoring	BIM Model, BIM data, sensor data	Equipment Operators, Construction Managers
	(Li et al. 2018)	Develop architecture and prototype to support prefabricated construction supply chain and assembly	Worker interact through mobile app. Manager reviews web dashboard	Progress Monitoring, Productivity, Coordination	BIM Model, BIM data, sensor data	Workers onsite, Construction Managers
	(You and Feng 2020)	Develop architecture and prototype to support construction operations through sensing and dashboards	Manager reviews project dashboard	Productivity, Interoperability	BIM Model, BIM data, sensor data, project schedule	Project Managers
	(Teizer et al. 2017)	Develop architecture and prototype to track user's location onsite and notify them about planned work	Worker interacts through mobile app to receive warnings and information. Manager reviews web dashboard	H&S, progress tracking	BIM Mode, BIM data	Workers onsite, and managers
	(Liu et al. 2016)	Develop architecture for construction monitoring	Worker interaction with mobile and manager with web dashboard	Interoperability	BIM Mode, BIM data	Construction workers and managers

Table 2.1. Summary Table of Reviewed Articles for Integration Approaches

Approach	Literature Item	Description of Article Contribution to BIM-User Support	Description of Human Interaction with System	Productivity Factor(s) in Article	Data Sources	Target Users
	(Moreira et al. 2021)	Develop architecture and prototype for risk identification and warning through mobile app on the field	Worker use an AR through mobile device to be warned and visualize H&S risks	Interoperability, H&S	BIM Mode, BIM data	Workers on Site
	(Park and Cho 2018)	Develop architecture and prototype to help workers navigate the field and get warned about hazards	Worker use the mobile AR app to navigate and receive warnings	H&S	BIM Model, BIM data, sensor data	Workers on site
	(Niu et al. 2019)	Develop architecture to manage physical assets, including tracking resources across multiple construction sites	Uncertain type of system interaction with the worker. Managers monitor project in dashboard	Interoperability	BIM Model, BIM data, sensor data	Construction workers and managers
	(Yuan et al. 2016)	Develop architecture and system to monitor temporary structures such as scaffolding for the sake of H&S of construction workers	Worker receive sound alerts about H&S hazards through mobile app	H & S	BIM Model, BIM data, sensor data	Construction workers on site
	(Calvetti et al. 2020)	Develop architecture of envisioned future construction worker	General framework about the future worker in AEC, worker 4.0	Productivity	BIM Model, BIM data, sensor data	Construction workers
	(Anumba et al. 2020)	Develop architecture for monitoring construction activities. This is based on a review of applications of CPS in construction	Workers and managers interact with UIs or warnings on the field	Interoperability, progress monitoring	BIM Model, BIM data, sensor data	Construction workers and managers

2.6 BIM and Worker (BIM-worker) Integration Approaches for Productivity Support

This section details the approaches identified in the literature for research developments that integrate BIM and workers for productivity support during the construction phase of project development. Five integration approaches were identified from the reviewed articles that proposed, developed, and implemented systems in this research area, see Figure 2.2. Here, each integration approach is described in detail based on various literature examples and approaches characteristics, processes, and system elements. Analyses of the benefits and drawbacks of each integration approach and its applicability to the productivity support of workers are presented.

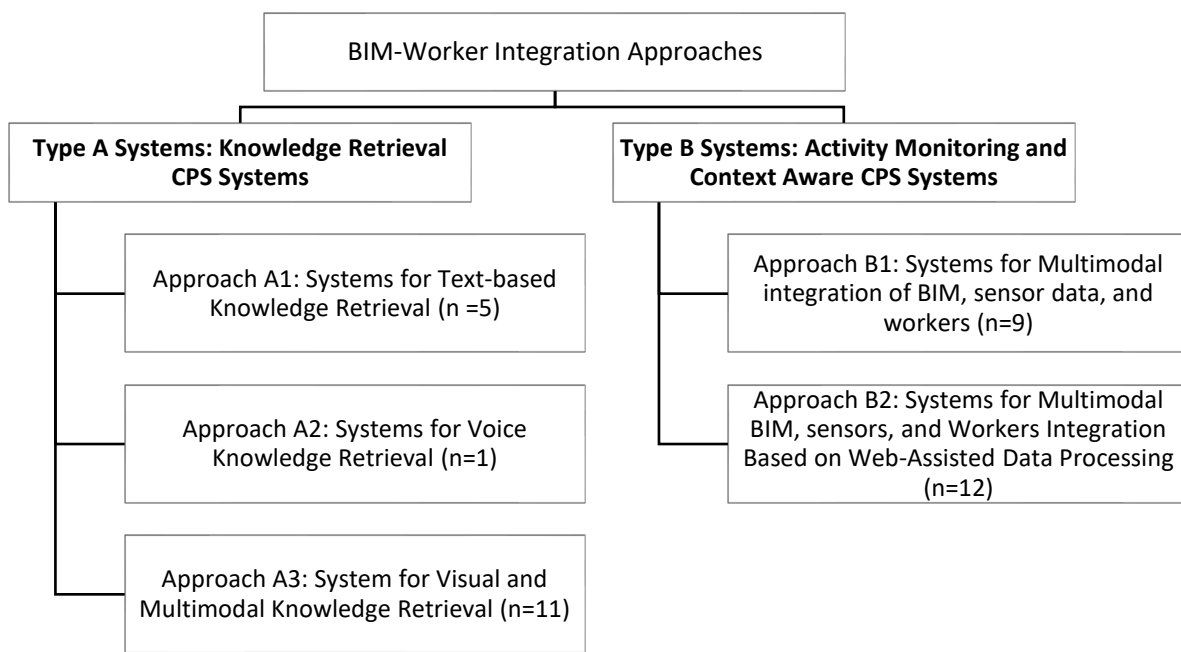


Figure 2.2. Hierarchy of Approaches for BIM-Worker Integration

The integration approaches are analyzed from a CPS perspective by considering cyber and physical integration components. When appropriate, integration approaches also include components of physical-to-cyber linking to the cyber-to-physical direction to enable bi-directional sensor integration of CPS. This additional physical-to-cyber context addresses the literature example cases that further integrate sensor data into the BIM-Worker integration approaches. As a result, the integration approaches hierarchy is based on major system types including knowledge retrieval CPS systems and Activity Monitoring and Context Aware CPS Systems developed for BIM-worker integration.

The first component of each integration approach is the BIM context which serves as the repository of data and information present during the construction phase of projects. This database usually contains a BIM model from the project's design phase and information created before and during construction, such as schedules, as-built project updates, documentation, sensor data, specifications, and other information collected to manage the construction project. This data and information are usually stored within virtual models, IFC formats, or BIM platforms. The addition of unstructured documents (documents not linked to BIM) are also included in databases, cloud storage platforms, document management systems (e.g., Procore® or Autodesk®), FTP servers, and local files present in this context.

The second component is the worker context. This component relates to the methodologies that the reviewed research works have used to develop interoperable systems and interact with the target user of the system. Within productivity support, the main actor is the construction worker; however, multiple cases were found in the literature where reviewed articles also targeted managers' work, which also affects workers' productivity. Furthermore, some reviewed systems also targeted both workers and managers. In addition to the target system user, interaction devices are also experienced within the human context. This interaction also encompasses user experience components (UX) such as user interfaces (UI) and modalities (e.g., voice, visual, haptic, or combinations of these) for interaction with the system.

The third component is the integration context that links both the BIM context and the worker context. The integration context summarizes the different system processes and elements employed to make this integration possible, and it is the focus of this study. It is further detailed in the following sections.

2.6.1 Type A Systems: Knowledge Retrieval CPS Systems

Worker and manager access to knowledge from the BIM project context has been shown to improve their productivity significantly (Wang and Meng 2019). Therefore, integration approaches that developed architectures and prototype systems to support knowledge retrieval from BIM were found in the literature. These types of systems transfer data from BIM sources to the user through various system processes and elements.

These types of systems are identified with the approaches that start with the letter "A." Three approaches are included in this type of systems: (A1) articles focusing on text-based knowledge

retrieval, (A2) voice and multimodal knowledge retrieval, and (A3) Visual and Multimodal Knowledge Retrieval for Construction Worker Support. These approaches are further discussed in the following sections.

2.6.1.1 Approach A1: Systems for Text-based Knowledge Retrieval

2.6.1.1.1 Description of this Approach

In this approach, researchers employ text-based queries to interact with the user for knowledge retrieval applications in construction projects. User interactions include using input devices for text-based queries and screens to present text responses to the user.

In total, five articles fit this approach that distinguishes themselves as unidirectional CPS systems where the authors developed or proposed such systems, see Figure 2.3. As Figure 2.3 shows, the following system processes and elements are included in this approach:

- i. The types of data in the BIM context include data and information from BIM databases, along with documents, specifications, and regulations that pertained to the project in development. Given the different types of documents that are sought to be included for knowledge extraction, methodologies to retrieve such information include (1) exporting BIM data to industry foundation classes (IFC) or resource description frameworks (RDFs) with exporting tools such as Revit, DB Link or schedules. Then, data is usually integrated into a single database parsed in the integration context.
- ii. The integration context in this approach includes the process of knowledge extraction from the BIM database based on the development of algorithms. The algorithms for knowledge extraction have included Natural Language Processing (NLP), tokenization, and MapReduce. Once knowledge has been extracted, a web or mobile application is developed to present the extracted knowledge to the user in a friendly manner. The app developed is also a bidirectional communication hub between the knowledge extraction module and the user.
- iii. The worker context in this approach moves forward from the developed web or mobile application developed in the integration approach. Methods for the user to interact with the integration approach through user interfaces (UI) or text responses from the system are developed for this purpose and in this context. Knowledge extraction also requires a

developed system to know the user's intentions, and to enable that, text-based queries or interactions through input devices (mouse and keyboard) are obtained from the user in this context.

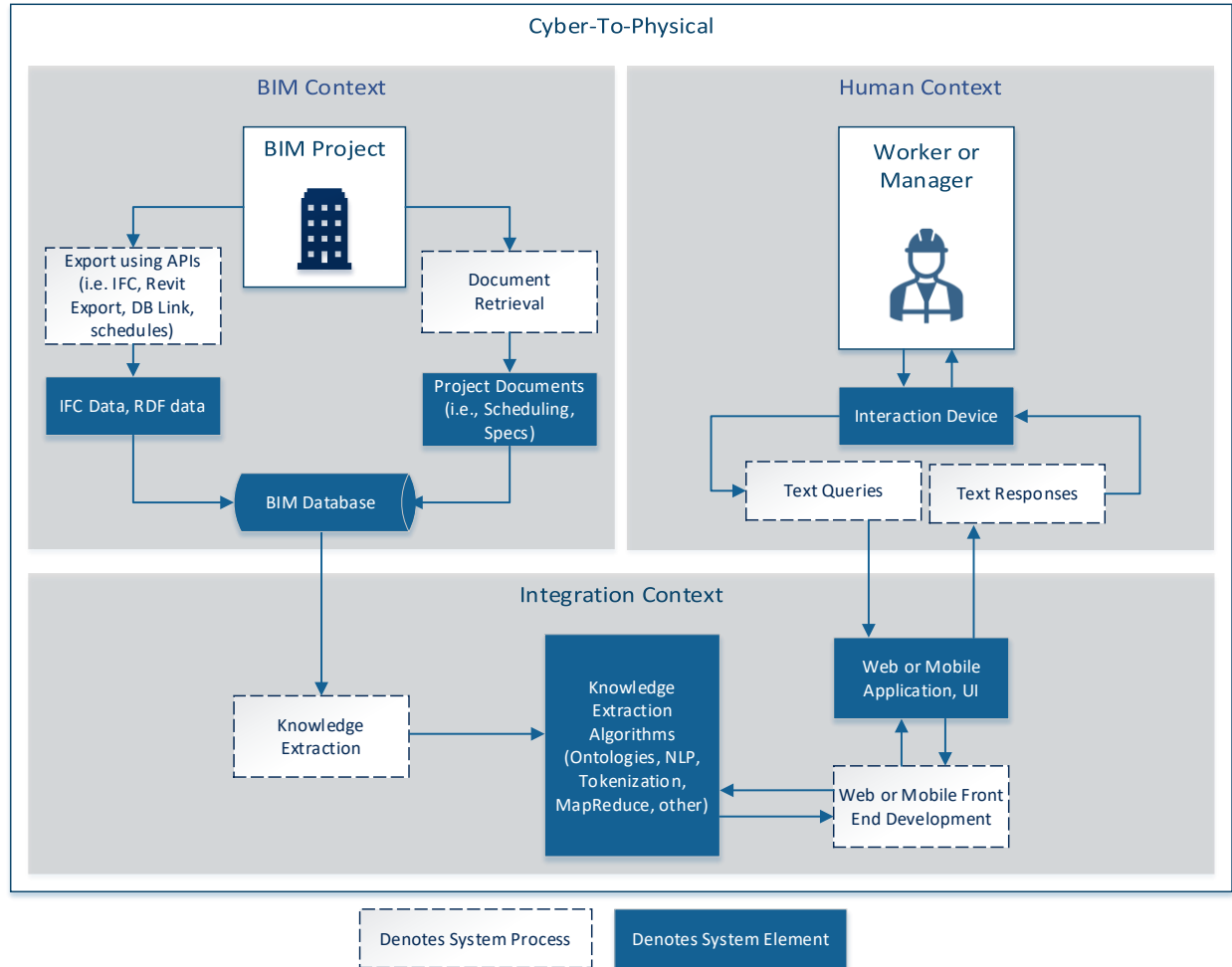


Figure 2.3. Diagram for Approach A1: Systems for Text-based Knowledge Retrieval

2.6.1.1.2 Examples of this Approach

Developments by Hewage and Ruwanpura (2009) and Ruwanpura et al. (2012) envisioned information extraction would happen at a higher level, allowing users to retrieve documents and files and allow user interaction with screens to show information.

However, researchers in this field have noted that knowledge extraction at a finer level (i.e., questions about project elements instead of documents) is needed to be helpful to construction workers in such dynamic environments. As a result, text-based information extraction methodologies have been explored to bring knowledge from BIM project sources to a finer level. Research by Park et al. (2013) used ontologies to parse IFC documents and match knowledge extraction requests, as well as Lin et al. (2016) used MapReduce algorithms, and Fan et al. (2015) used natural language processing (NLP) algorithms to link BIM project documents to users' information requests. Their work produced system solutions that allow users to ask for more specific information about BIM project data, e.g., the number of construction elements in a specific location through text-based queries. Further developments in this area have also added domain-knowledge characteristics, such as construction elements relationships and parameters, to the developed knowledge extraction solution to provide more adequate responses for the construction industry (Wang et al. 2022; Wang et al. 2021; Wang et al. 2022). Although these research works provide better results to the user, they do not carefully address the issues of user interaction with the worker, developing text-based solutions through the web, or mobile app interfaces.

2.6.1.1.3 Discussion of this Approach

This approach to BIM-worker integration is specifically used for knowledge retrieval to match BIM project information of different types to workers' queries through text-based interaction. Developments in this area are divided between addressing the issue of knowledge extraction and the issue of worker interaction through text queries and their responses. Research works focused on developing algorithms for information extraction based on machine learning, data integration, and ontological methodologies while delivering knowledge responses in screens or mobile interfaces for text-based responses. Given the characteristics of the AEC industry, both knowledge extraction and user interaction are challenging to address.

The main advantage of this approach is that the solution can address some needs of the AEC domain based on the development of the knowledge extraction algorithms. Another advantage is that algorithms have been able to get knowledge from BIM models and other AEC documents, thus making broader knowledge available to the construction worker. The biggest drawback of this approach is the low effectiveness of text-based system interactions with the user in the current stages of development.

This approach is suitable for workers or managers whose environment and activities do not limit their visual modalities and can be obstructed. It is also suitable for workers or managers who manage a large number of knowledge sources and need to process information queries promptly to accomplish their work quickly.

2.6.1.2 Approach A2: Systems for Voice Knowledge Retrieval

2.6.1.2.1 Description of this Approach

This integration approach supports knowledge extraction from BIM and provides basic voice interaction. However, the current status of the articles in this approach only enables the user to ask questions but the system response is not through voice but through text or changes in the BIM model.

Only one article fit this approach that distinguishes themselves as CPS systems where the authors developed or proposed such systems, see Figure 2.4. As Figure 2.4 shows, the following system processes and elements are included in this approach:

- i. Data sources from the BIM project context focus on BIM model data transformed to RDF format and integrated with a relational database. The formatting of this database was due to the communication with the web platform present in the integration context for Natural Language Understanding (NLU). The relational database is read following the integration approach and can be updated based on processing user queries from the integration approach. In this approach, data is transformed from and into the relational database based on scripts made in Dynamo or data export and a pre-determined data schema that is part of the knowledge extraction module.
- ii. The integration context is based on two main modules. First, a web platform processes voice queries by the user and transforms them into the text to be processed in the knowledge extraction module. Shin and Issa Raja (2021) developed a prototype system that used a web platform used for a speech-to-text NLP tool based on the Google Actions service. This tool converts voice queries to text. The knowledge extraction algorithm then matches text queries to information queries and instructions to modify the BIM model. The knowledge extraction is based on relational database management systems (RDBMS), Dynamo scripts, and ontology schemas. Once knowledge has been extracted, the system either goes

back to the BIM project context through the relational database to update the BIM model, or the system responds to the user based on the Revit interface.

- iii. In this approach, the worker context includes the user feedback to the system through voice or other envisioned multimodal approaches and responses of the system to the user based on information shown on the Revit interface. The intermediate mechanism for interaction is the device that registers the user's voice feedback and the PC that runs the AEC software (Revit). There is no voice-based feedback from the system to the user in the systems reviewed.

2.6.1.2.2 Examples of this Approach

Only one article belongs to this approach. Shin and Issa Raja (2021) developed a system that interacts with the user with voice to provide knowledge from BIM model sources and make changes to the same BIM model based on voice queries. This article is unique among those included in this approach as the authors developed a prototype system that connects back to the BIM model and make changes back to it. It is also unique in the integration approach as it combines data schemas, data integration, and web-based systems. However, responses from the system are only provided based on visual feedback in the Revit software as showing text messages or making the desired changes to the BIM model parameters.

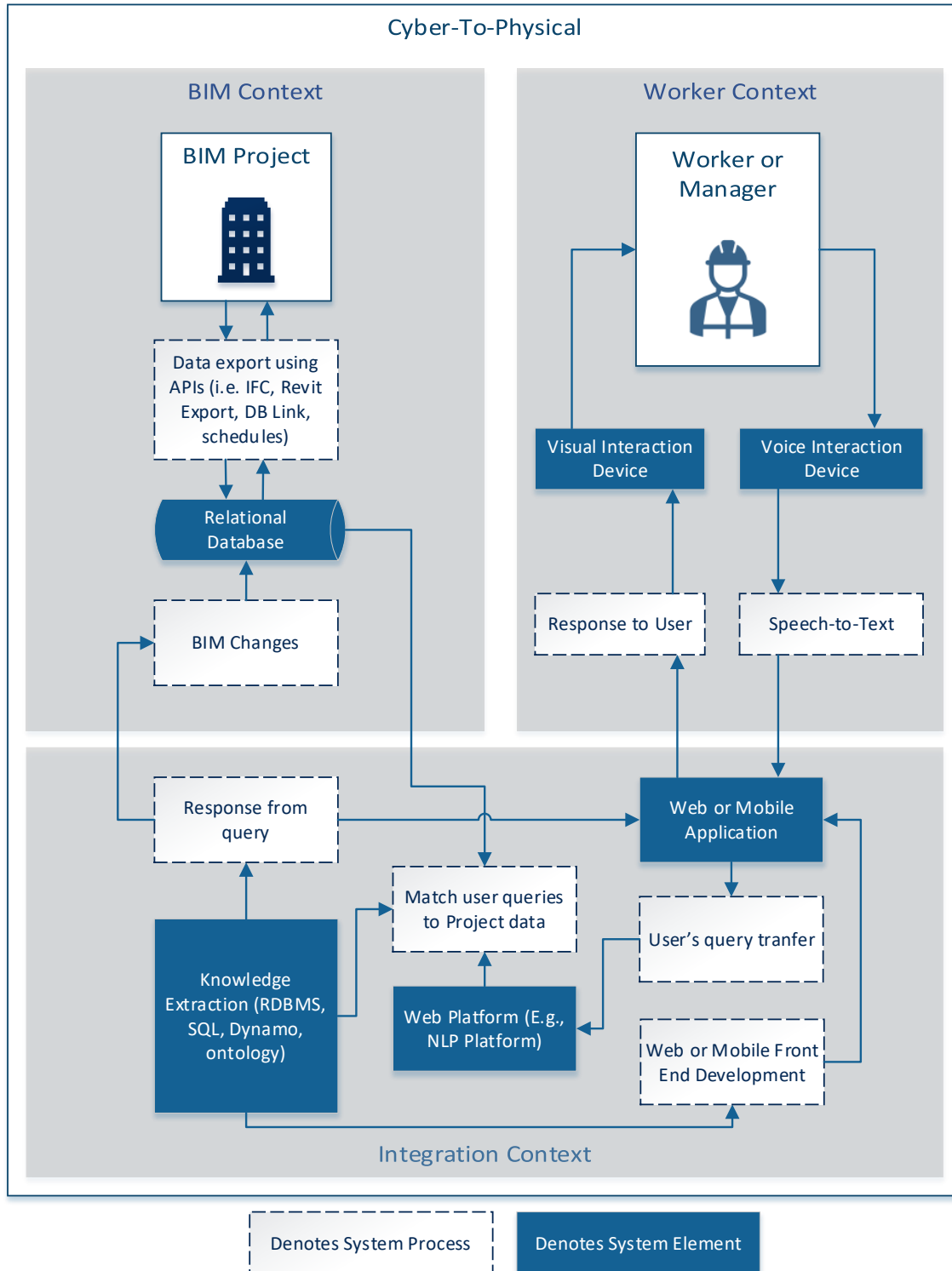


Figure 2.4. Diagram for Approach A2: Systems for Voice Knowledge Retrieval

2.6.1.2.3 Discussion of this Approach

This approach for BIM-worker interaction has examples that goes beyond knowledge extraction and can update the BIM model based on the user interaction. Given that this article addresses knowledge extraction and user interaction, these articles seem to provide a more holistic solution for construction workers. Reviewed articles from approach A2 lack non-visual feedback to the user, thus limiting the approach's use in construction contexts, particularly for construction workers. Approach A2 is also adequate for managers to retrieve project information or for BIM managers to update the model.

The main advantage of this integration approach is that it provides an alternative to visual interaction for knowledge extraction. This allows users limited in this regard to access knowledge that was not available otherwise. Workers in the field could benefit from this approach to access knowledge during their work, but they would still need to receive visual feedback which is not an ideal modality for them. However, a drawback is that using voice interactions for worker activities still needs further research to evaluate its effectiveness. Another advantage of this integration approach is that using web-based voice processing algorithms relieves the developer of the need to create an algorithm to recognize voice feedback from the user. With this in mind, the developer can focus on polishing the processes for knowledge extraction. Another drawback of this approach is that the integration among different processes, including data schemas, matching, algorithm creation, and linking and managing to the web platform and the BIM model, can become complex.

2.6.1.3 Approach A3: System for Visual and Multimodal Knowledge Retrieval

2.6.1.3.1 Description of this Approach

The construction worker activities noted here have been found to be supported based on feedback through varied visual and multimodal support through knowledge retrieval. Researchers in this area have developed integration approaches based on data transformation from BIM sources to interfaces that can be used during construction activities or to support managers in increasing the efficiency of the construction process performed by workers. As a result, integration methods that have envisioned solutions and developed systems to support worker activities through visual and multimodal interfaces have been found in the literature and summarized in this approach.

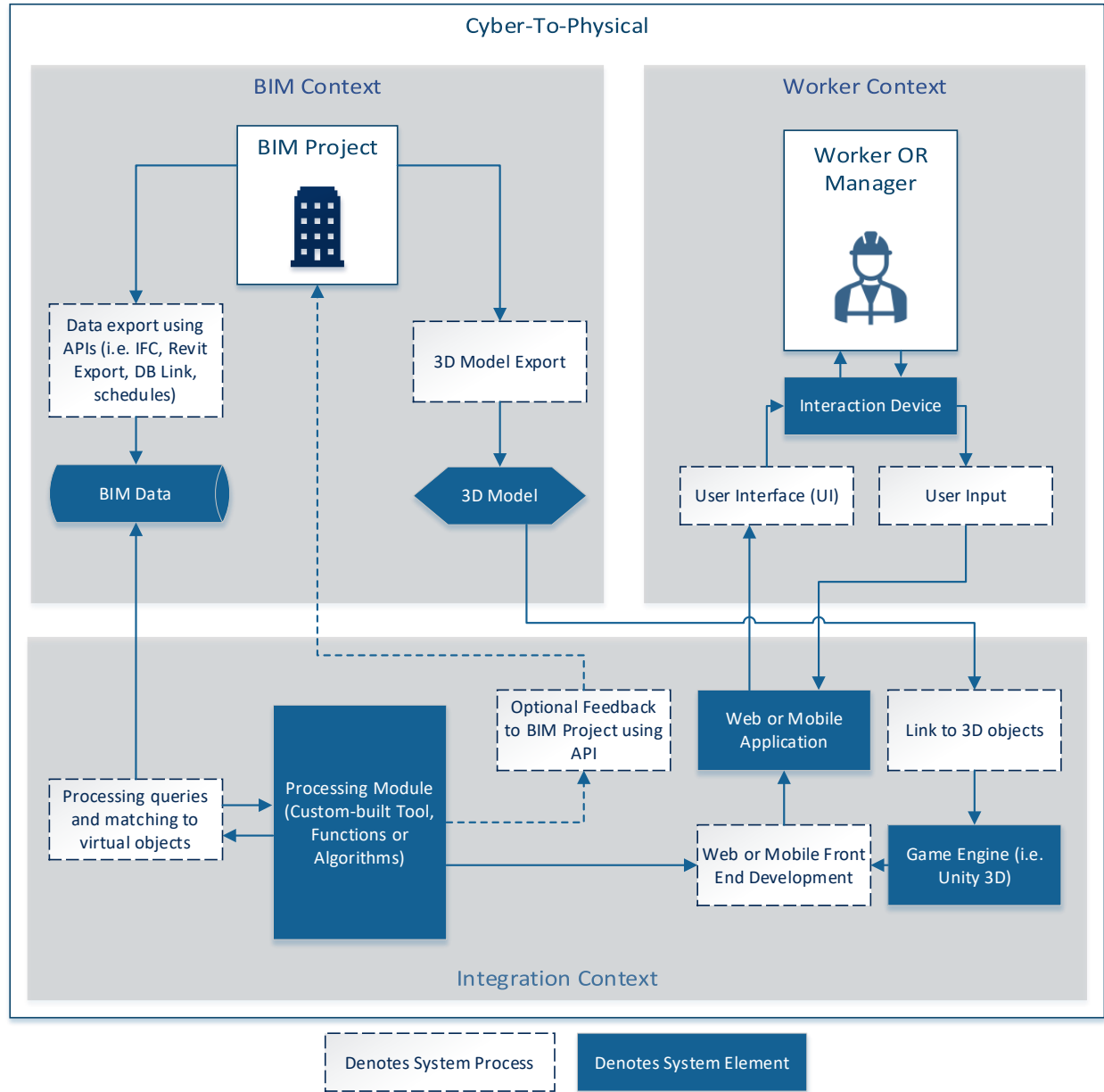


Figure 2.5. Diagram for Approach A3: System for Visual and Multimodal Knowledge Retrieval

In total, 11 articles fit this approach that distinguishes themselves as CPS systems where the authors developed or proposed such systems, see Figure 2.5. As Figure 2.5 shows, the following system processes and elements are included in this approach:

- i. The data types within the BIM context have included data from BIM sources stored in BIM databases and 3D models from the virtual model. The BIM database has resulted from the export of data from the BIM model in IFC and XML done with APIs. The virtual model

has included variants of static 3D models or dynamic 4D models exported from the Revit APIs (i.e., FBX file format) or open standards (e.g., OBJ).

- ii. The integration method in this approach relies mainly on managing the 3D model data transfer through a game engine (e.g., Unity 3D) that serves as the primary enabler of the user visualization. The game engine has also been used to develop web or mobile applications to be used by the user. However, other web or device interfaces have also been created based on web or desktop application development. In some cases, the integration method has also included a processing module that adds functionality to the systems based on data analysis in the BIM context or from feedback from the user, which would produce updates to the BIM model. Finally, the web, desktop or mobile application is the gateway for user interaction.
- iii. Most of the reviewed articles have relied on a single device for interaction within the worker context including smartphones, tablets, computers, and even physical objects. Interactions have usually been multimodal and have included haptics, visual, and augmented reality (AR). Multiple interactions through AR based on mobile devices have been developed within this approach.

2.6.1.3.2 Examples of this Approach

Early developments to increase workers' productivity by improving their access to knowledge brought information booths to the construction site (Hewage and Ruwanpura 2009; Ruwanpura et al. 2012). These booths were conceptualized to be connected to BIM sources of multiple data types, including BIM data and project documents, information about supply chain and project progress, and to connect the field and office. Nevertheless, these booths were envisioned to have fixed locations, so workers needed to interrupt their work and relocate to the location of the booth for information about the project.

More recent research using this approach has primarily developed interactions to provide feedback by showing visual information to the user in their work context. For this purpose, previous research works have sought to visualize information to workers, including drawings and model visualization on the field (Linares-Garcia et al. 2022; Wang et al. 2014; Yeh et al. 2012), to help support coordination meetings (Alsafouri and Ayer 2019; Lin et al. 2015; Linares-Garcia et al. 2022), navigation (Yang et al. 2016), and project progress and coordination (Mirzaei et al. 2018;

Zaher et al. 2018). The methodologies to interact with the workers have included projectors embedded in helmets (Yeh et al. 2012), mobile devices (Alsafouri and Ayer 2019; Lin et al. 2015; Linares-Garcia et al. 2022; Wang et al. 2014; Yang et al. 2016; Zaher et al. 2018), and web dashboards (Mirzaei et al. 2018).

Alsafouri and Ayer (2019) and Lin et al. (2015) created mobile apps that interacted with multiple users based on scanning objects in the environment and projecting visual information on mobile devices. Both used reality augmentation based on the recognition of predefined target images. Their applications supported coordination meetings and increased cognitive understanding of 2D objects through 3D augmentation. In the construction field, research by Linares-Garcia et al. (2022), Wang et al. (2014), and Zaher et al. (2018) used similar integration methods based on the development of mobile apps with reality augmentation features to scan objects in the field and allow construction workers to increase the understanding of 2D drawings or their environments.

Different types of works including that by Yeh et al. (2012), who integrated BIM and BIM data that were then shown to the user through a projector embedded in the safety helmet. Their approach to integrating BIM and workers included using a mobile device to interact with drawings on the screen to select location parameters and projection parameters. The integration method included the development of the mobile app through SDK from apple. Finally, as a by-product of a methodology to dynamically detect and solve the time-space conflict of construction activities resources, Mirzaei et al. (2018) provided an overview of these conflicts and solutions to users through a desktop user interface in Revit for interaction.

2.6.1.3.3 Discussion of this Approach

This approach to BIM-human interaction enables project feedback through multiple visualization options that support their users' work activities and coordination meetings. Developments that use this approach have mainly employed mobile AR developments to enable user interaction, including some examples of reality augmentation where the user also scans objects or drawings to obtain a visualization of 3D models. The interactions in this approach have also included touch interaction with the devices used.

The integration methods in this approach have transferred data through interoperable processes. Data have been transferred among different processing steps to conclude with an interaction with the user through visual modality. In this integration process, game engines, such as Unity 3D, have

served as enablers for 3D integration with data and enable reality augmentation through reality augmentation scanning APIs (e.g., Vuforia).

The advantages of this approach are that the resulting user interaction is usually straightforward, allowing the user to scan objects with the mobile device and receive project feedback through 3D visualization on the mobile screen. Another advantage is that mobile apps also allow for easier deployment to multiple users, as exemplified by Alsafouri and Ayer (2019) and Lin et al. (2015). One drawback of this approach is the need for previous knowledge about using a game engine and programming language to create the 3D visualizations and interactions for the mobile app. Another drawback is that the 3D models are static once deployed and cannot be updated unless the mobile app is updated.

This approach is suitable for construction workers who need quick information in the field through visual modality. This helps them increase their understanding of construction outcomes. Similarly, this approach is helpful for workers and managers who want to share visual information in a collaborating environment.

2.6.2 Type B Systems: Bi-directional CPS Systems

Researchers have also focused on integrating data from BIM sources and sensors to support workers' activities. Outcomes of this integration approach have developed bi-directional CPS architectures and prototype systems that support user interaction between BIM, sensors, and workers. The access of workers and managers to the data fusion of BIM and sensor data supports multiple application domains, including knowledge management, progress monitoring, collaboration, context understanding, and health and safety (H&S). See applications domains in Table 2.1.

In total, 21 reviewed articles include bi-directional CPS systems, named Type B Systems in this article, and are identified with the approaches that start with the letter “B.” Two approaches of this type: (B1) Bi-directional Integration Based on Interoperable Data Transfer, (B2) Bi-directional Integration Based on Web-Assisted Data Processing. These approaches are further discussed in the following sections.

2.6.2.1 Approach B1: Systems for Multimodal integration of BIM, sensor data, and workers

2.6.2.1.1 Description of this Approach

Integrating BIM data and sensors support user activities in application domains such as progress monitoring and context awareness. By developing systems to manage both cyber-to-physical and physical-to-cyber data integration, the worker receives a complete picture of their work activities. For example, sensor data about work activities' progress integrated with BIM data for visualization of 4D models or progress monitoring allows workers to identify productivity issues or improvements.

In total, nine articles fit this approach that distinguished themselves by bi-directional CPS systems where the authors proposed or developed a custom-built architecture or prototype processing module, see Figure 2.6. As shown in Figure 2.6, the following system processes and elements are included in this approach:

- i. Within BIM context in this approach, data types have included data from BIM sources stored in BIM databases and 3D models from the virtual model. The BIM model has included variants of static 3D models or dynamic 4D models. Databases in this approach are usually created from exporting IFC or XML schemas. In this approach, communication between the BIM project and BIM databases is only unidirectional from BIM to databases.

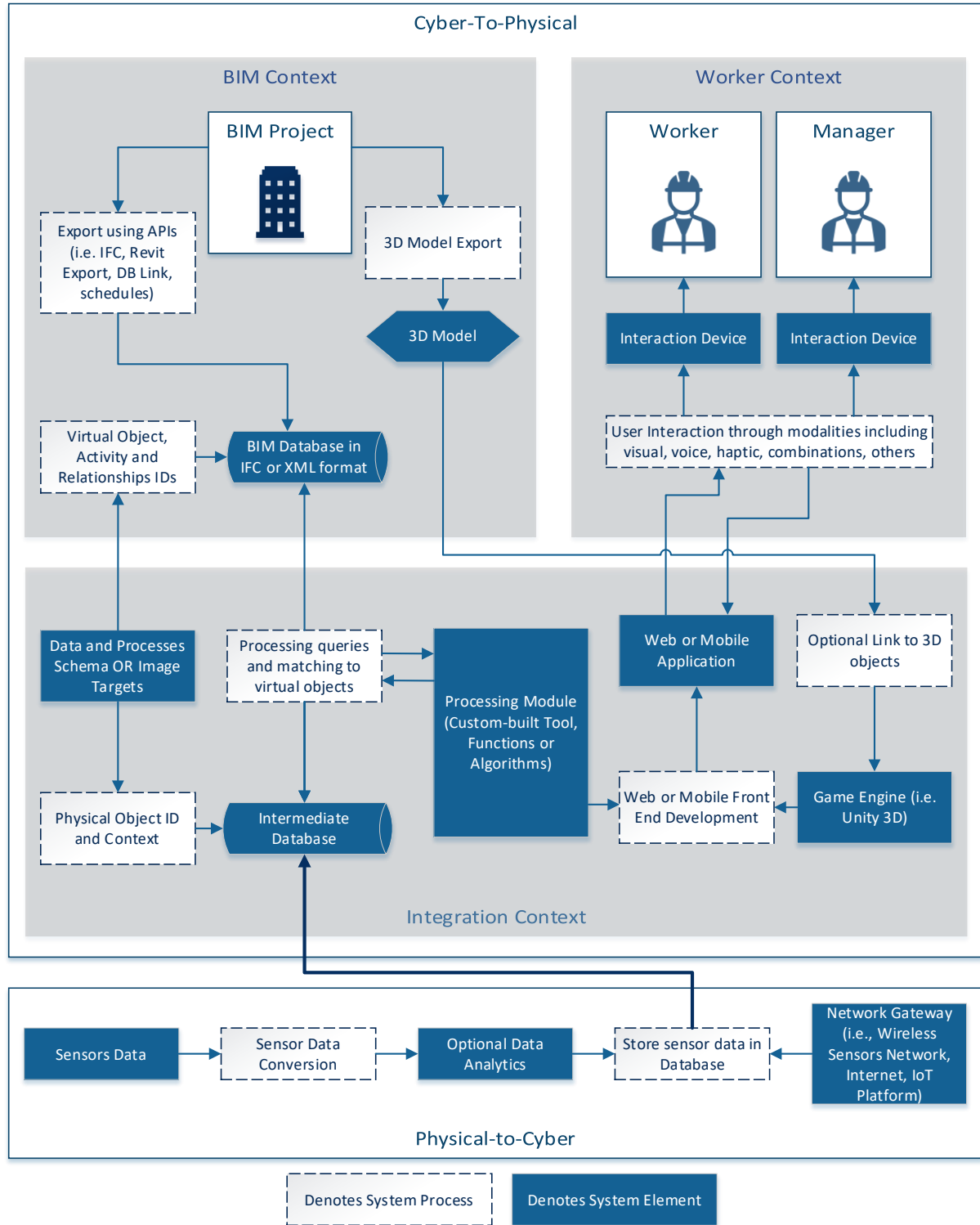


Figure 2.6. Diagram for Approach B1: Systems for Multimodal integration of BIM, sensor data, and workers

- ii. Following the BIM context, the integration context in this approach connects the BIM database from the BIM context and an intermediate database that includes sensor data from the physical-to-cyber direction. Connecting these two databases is a process of query processing based on data schema, process schema, or image targets to match IDs of virtual and physical elements. These data and process schemas were part of the reviewed article proposals. Then, matched data is transferred to the processing module based on custom-built tools, including developed algorithms or proposed functions. After processing, data is transferred to a web or mobile front end for worker interaction. In this approach, 3D objects are linked to the processed data based on game engines, such as Unity 3D, for worker interaction. The web or mobile application is usually created based on the game engine or web development.
- iii. Within the human context, reviewed articles have relied on multiple types of devices to interact with the user or manager or both through single or multimodal interaction methods. These methods have included showing information on screens, enabling interaction with mobile apps, web dashboards, Mobile Augmented Reality applications, and simulations on screens.

2.6.2.1.2 Examples of this Approach

The articles that have adopted this approach have been based on two main research trends. Most researchers have developed systems with sensing capabilities that include the user in the loop of system functioning to provide them with activity monitoring or context awareness feedback. The second group of researchers has focused on proposing methodologies to integrate data from sensors and BIM and make this information available to humans.

Various researchers using the first approach began by focusing on developing the sensing capabilities of the proposed system. They subsequently developed an interactive system to provide the system's user activity or context feedback or provide monitoring capabilities to managers that benefited the workers. For example, Kan et al. (2018) developed a system to monitor the operations of mobile cranes in the field and used sensors to track the movement of the moving parts of the crane. Their system could track hazards to other users produced by the crane's movement while adding the context of the BIM model. As a result, their system interacts with the crane operator by

visualizing his activities and providing multimodal warnings to the operator if the system detects any hazards.

Similarly, Zhou et al. (2019) also did equipment monitoring for blind hoisting of tunneling equipment. In line with the health and safety domain, Kiani et al. (2014) used temperature sensors and BIM models to track workers' conditions in the field and notify the user through a mobile app about hazardous working conditions. Their system was also able to allow managers to track working conditions within the spaces in the field.

For construction progress tracking, researchers have used laser scanner data from the construction field to feed into systems that match information to existing 3D or 4D models. Ham et al. (2016) and Son et al. (2017) have provided examples of this methodology; Ham et al. (2016) produced a superimposed visualization of the updated model, while Son et al. (2017) analyzed data and produced a dashboard for progress monitoring. Other researchers have also sought to use this approach to enable the navigation of BIM models (Schweigkofler et al. 2018).

Work using the second approach included research that proposed data and process schemas for linking BIM, sensors data, and platforms for user interaction. However, this group of studies has presented system architectures that still need to be tested. Golzarpoor et al. (2018) proposed that the interoperability of systems in construction needs a definition of baseline schema of processes, named Industry Foundation Processes (IFP). They indicated that allowing this baseline would further integrate construction data and tools. However, other researchers have focused instead on defining the schema for construction objects and how their virtual and physical versions can be better intertwined (Srewil et al. 2016; Srewil and Scherer 2017).

2.6.2.1.3 Discussion of this Approach

This approach is characterized by BIM-to-worker systems that integrate data from the physical world through sensors and supporting construction workers with activity monitoring or context awareness as feedback for their activity in progress. Developments related to this approach have primarily included workers receiving feedback from the developed sensing systems and managers able to monitor processes and environmental conditions. Because of the added interoperability with data from sensing, data linking includes methodologies for connecting BIM and sensor data and providing a visualization to the user afterward. The integration approach is based on the development of the processing module and developments in the user front end for interaction,

having, in some instances, 3D visualizations. Depending on the processing module's complexity, each solution's ease of implementation varies.

Despite the difficulty of developing custom processing modules, this approach might allow more flexibility in the features developed. However, this requires the developer to be more capable of developing the processing module based on data manipulation that might include programming in one or multiple programming languages. As shown in the examples, this approach is suitable for workers and managers capturing sensing data and adding feedback to the user will provide better productivity or increased health and safety.

2.6.2.2 Approach B2: Systems for Multimodal BIM, sensors, and Workers Integration Based on Web-Assisted Data Processing

2.6.2.2.1 Description of this Approach

As it is related to approach B2, this approach has also produced examples where users received activity monitoring and context awareness feedback from sensor data. This feedback supports their productivity by receiving progress updates, productivity insights, health and safety warnings, and improving coordination with other stakeholders and project elements. However, this approach differentiates itself based on the integration method to include web-assisted data integration to enable data linking and user interaction.

In total, 12 reviewed articles fit this approach that also enables bi-directional CPS systems and where the authors used web platforms to improve their system data processing and user interaction. As a result, integration methods that develop architectures and prototype systems for this purpose were found in the literature, see Figure 2.7. As shown in Figure 2.7, the following system processes and elements are included in this approach:

- i. The BIM context in this approach is similar to that of B1. Still, it differs in how BIM databases are integrated into the system to enable bi-directional feedback in the BIM model. As a result, some system examples have developed solutions that change data parameters back in the BIM model. Another difference in comparison to B1 is that BIM databases in this approach have been of RDF format to address compatibility with web platforms.

- ii. The integration context in this approach is similar to approach B2, but the processing is supported by web tools used to process data or user interaction. The communication of this web-assisted processing is bi-directional to enable changes back to the BIM model. The web tools found in the literature include Microsoft Azure, IoT-based platforms, Autodesk platforms, and other cloud-based services. Another difference from previous integration methods is that intermediate databases become relational databases in RDF format to better communicate with web tools based on web standards. In this approach, linking to 3D models is optional, so it is using a game engine for development or data processing.
- iii. This approach has allowed interaction with the system for more than one target user within the worker context. As a result, some reviewed examples have simultaneously provided interactions between workers and managers. Interaction devices have been varied, and have included mobile devices, screens, and web dashboards through multiple modalities.

2.6.2.2.2 Examples of this Approach

Reviewed articles in this category have focused on proposing architectures and prototype systems for enabling integration with BIM and sensor data for various applications. However, as part of their developments, researchers have also thought about how their systems were able to interact with target workers or managers. Consequently, most of the reviewed articles using this approach proposed prototype systems for construction applications, including equipment operations (Anumba et al. 2020; Han et al. 2022; Yuan et al. 2016), progress monitoring (Li et al. 2018; You and Feng 2020), prefabrication (Li et al. 2018), localization (Teizer et al. 2017), and health and safety (Moreira et al. 2021; Park and Cho 2018). Researchers have used multiple interaction methods such as monitoring screens, mobile devices, and web dashboards to maximize BIM and sensor data synergy.

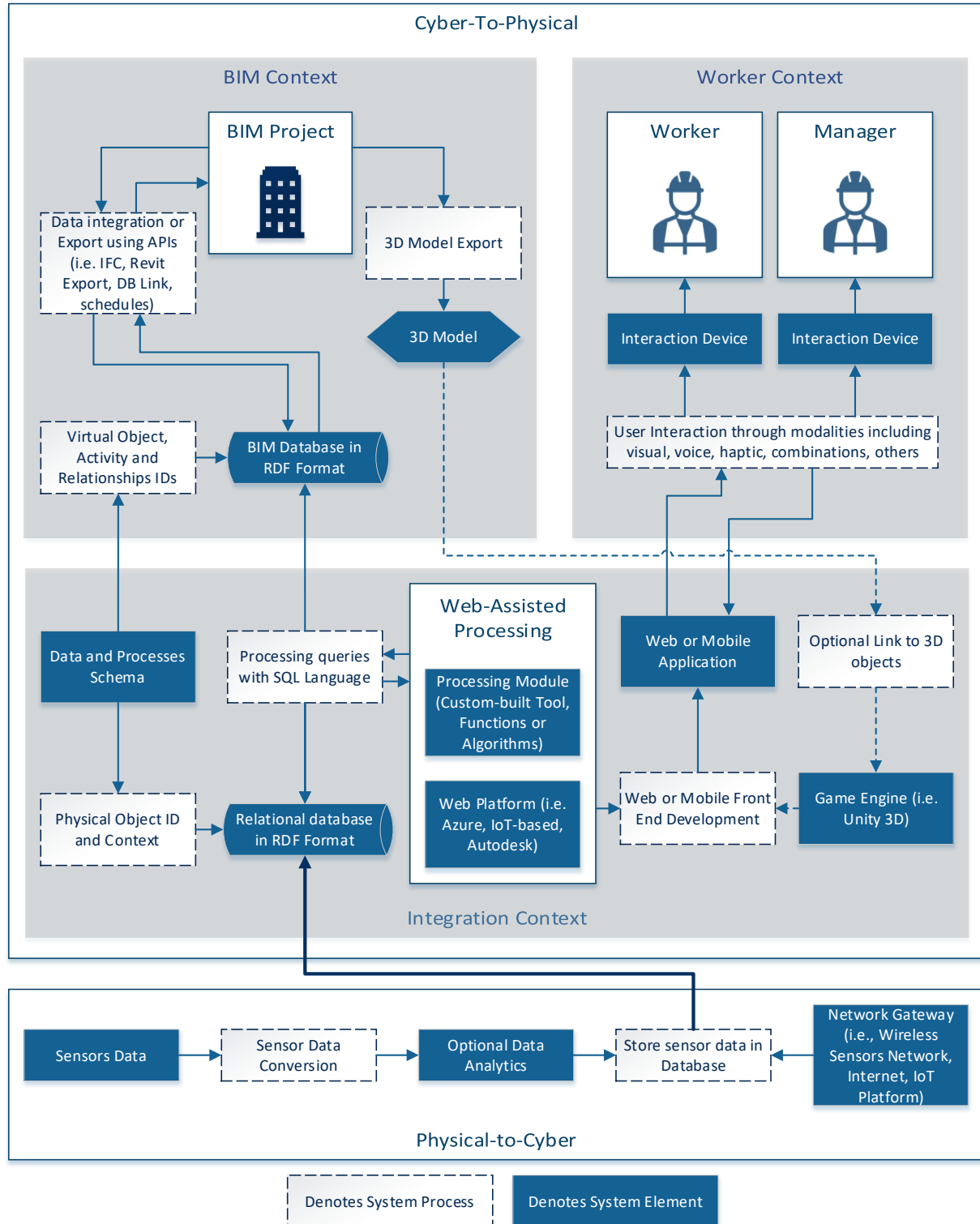


Figure 2.7. Diagram for Approach B2: Systems for Multimodal BIM, sensors, and Workers Integration Based on Web-Assisted Data Processing

Han et al. (2022) used sensors to monitor compaction equipment operations IoT platforms to manage data in their proposed system. Interactions with the system then happened on a real-time dashboard that presented progress monitoring and quality parameters for compaction activities. The web-assisted platform supported the networking aspects of the system while also feeding data to the processing module based on data analytics. Similarly, Anumba et al. (2020) presented multiple applications where data and humans interacted to create equipment operations that show visualizations to improve health and safety. In this article, the integration method used web-connected platforms. Moreira et al. (2021) and Park and Cho (2018) also explored improving hazard identification on the construction site by using sensor data to identify hazards and their severity, then visualizing these hazards to the user through a mobile application.

Other researchers have also tracked construction elements to monitor the progress monitoring of traditional construction methods and prefabricated construction elements. You and Feng (2020) used UAVs to capture data from the field and used web platforms and data analytics to create progress monitoring dashboards for construction management. Similarly, Li et al. (2018) tracked prefabricated construction elements and a data schema so workers could scan sensors in the elements with mobile devices. Information was then transferred to web platforms for visualization and tracking.

Teizer et al. (2017) used mobile apps to allow workers to provide their feedback about installing construction elements and register their status back to the BIM model and a monitoring dashboard to the management personnel. The researchers developed a solution that integrates lean management principles to allow more efficient operations and safer environments on the construction site. Koseoglu and Nurtan-Gunes (2018) also used a cloud platform and mobile device to track users' feedback about project progress.

Other researchers have focused on understanding the synergy between BIM, data, and human support. For example, Niu et al. (2019) proposed that smart construction objects (SCOs), or construction objects with pre-determined networking characteristics might improve interoperability in the AEC industry, including addressing user interaction. Liu et al. (2016) instead, proposed that interoperability between web platforms and construction objects might be improved based on a smart construction cloud platform that addressed the AEC industry's needs

and characteristics. At the same time, Calvetti et al. (2020) proposed a paradigm of a connected worker, worker 4.0, enabled by sensors and interaction devices.

2.6.2.2.3 Discussion of this Approach

This approach is related to approach B1 as it also includes systems that incorporate sensor data but differs in that web platforms and tools assist the custom-made processing tools in linking BIM, sensor data, and user interaction. Developments in this approach have provided solutions for multiple construction applications, such as equipment operations, progress monitoring, and health and safety. Reviewed studies using this approach have developed sensing solutions that provide feedback to workers and management, and systems that seek user interaction with BIM and sensor data. At the same time, these research works have proposed integration approaches that use web solutions. By using web platforms, their authors have created systems with interactions to multiple users, including construction workers and managers on the field and at the office.

The advantages of this approach are that because they use web-assisted integration methods, solutions are easier to develop, given that there is an established baseline to work with and build over. Using web platforms allows developers to include features that otherwise would be unfeasible to develop based on custom-built tools. Another benefit of this approach is that some web services have already incorporated more streamlined user interfaces while accessing these services through multiple devices. For example, web platforms by Autodesk® can be accessed from multiple devices including web, mobile app and desktop apps.

Drawbacks to this approach are that to use web platforms, the developed solutions have to be linked through APIs and data schemas that the web platforms can handle. Web platforms might restrict the developed solutions to the processes and outcomes that the web platforms allow. Lastly, by using web tools, the deployment of a given solution can be more widespread through the devices and services that have access to such web platforms, e.g., IoT platforms.

This approach is suitable for support solutions for workers but also support the operations of managers that affect workers activities. It is beneficial for applications in which interaction with the user is encouraged, or feedback about the sensing system capabilities is possible through visual modality. In addition, this approach enables coordinated feedback for construction and managers, thus creating collaborative environments in construction that stimulate productivity and health and safety improvements.

2.7 Reviewed Articles outside the scope of this study

The scope of this article was defined as the integration methods between BIM and humans to be used by construction workers and managers during the construction phase of projects. Therefore, articles not fitting into this scope were reviewed but not included in this study's approaches definitions. Nevertheless, these articles are summarized in this section to clarify the reasons why they were omitted from the definition of the approaches.

2.7.1 Reviewed Articles Not Focused on the Construction Phase

Multiple reviewed articles integrated BIM and humans for worker support, but they did not focus on the construction phase as defined in the scope of this article. Several of these articles were addressed towards the design phase (Boechat and Corrêa 2021), facility management (Ensafi et al. 2021; Vivi et al. 2019), or building operations (Chen et al. 2021; Dave et al. 2018; Pasini et al. 2016). As a result, these articles were not considered for the definitions of the approaches for integration methods.

2.7.2 Reviewed Articles Not Integrating BIM

Other reviewed articles integrated humans to support systems for workers, but they did not link BIM information. Some of these articles discussed systems that communicate with sensors and transfer that information to workers for compaction work zone safety and equipment operations (Kanan et al. 2018; Seo et al. 2015) or applications to obtain health and safety feedback from sensors (Akanmu et al. 2020; Hasanzadeh et al. 2020). As a result, these articles were not considered for the definitions of the approaches for integration methods.

2.8 Discussion

This article established the current status of systems that integrate BIM and workers for productivity support during the construction phase of project development. Multiple applications are benefited of this integration including knowledge management, safety, progress monitoring, and others. To this end, the relevant literature works were identified, vetted, reviewed, analyzed, and categorized into five integration approaches. This section discusses this study's developments and findings and their implications for the theories and practices in this area of research.

2.8.1 Integration Approaches

Section 2.6 is the outcome of the literature review, analysis, and categorization of BIM and worker integration approaches for productivity support. In total, 38 articles were included to define the integration approaches. Two main system types were identified from this classification based on the scope of the scientific contributions in these articles. These are further explained as follows:

- The first trend in system development is focused on Knowledge Retrieval CPS Systems. Two approaches are included in this research trend.
 - Approach A1 outlines developments in knowledge retrieval from BIM sources and construction documents for workers and managers based on text-based queries. The integration methods included in this approach have mainly focused on developing knowledge extraction algorithms and have provided user interaction as a secondary outcome. As a result, most are designed for text-based queries through mobile apps, desktop applications, or web front ends. This is a limitation of this approach, as some workers cannot make text-based queries because of the nature of their activities, health and safety concerns, or environment. Still, the developments made under this approach have clear benefits for managers' access to knowledge, and the approach has great potential to further support workers and managers based on solving system interaction methods with the worker in the field.
 - Approach A2 includes enhanced developments in knowledge extraction that provide an adequate interaction with the user based on voice. The integration approaches of the reviewed articles fit this category based on the voice modality's knowledge extraction. The relevance of this approach is that enabling voice interaction for BIM and humans can potentially support construction workers' activities in the field without disruptions of their activities.
 - Approach A3 includes developments focused on providing feedback to users from BIM sources through visual and multimodal modalities. Most of the reviewed articles in this area visualize BIM models for workers and managers through user interactions such as mobile AR applications, screens, and software UIs. The integration methods collected under this approach have primarily used game engines to visualize the BIM models. Algorithms have also been used to change aspects of the visualized 3D models. In

addition, multiple reviewed studies have presented interactions by scanning physical objects to trigger BIM visualization through mobile apps.

- The second trend in system development is focused on CPS systems that provide activity monitoring and context aware feedback to workers based on BIM and sensor data. Three approaches are included in this research trend.
 - Approach B1 relates to developments that provide feedback to workers or managers, and integrate sensor data, thus enabling bi-directional system integration. Integration methods used in this approach have included custom-built tools, functions, or algorithms that perform data fusion through data and process schemas. Game engines have also been used to develop visualizations, apps, and web front ends. As a result of integrating BIM, sensor data, and users, systems in this approach have primarily focused on developed sensing solutions and provided feedback to workers and managers as a by-product of the developed solution.
 - Approach B2 is similar to B2, as it also integrates BIM, sensor data, and workers to enable sensor data integration. However, it differs from B2 in that the integration method is supported by a type of web platform or tool that is essential for the developed solution. By using web platforms, developments in this approach can provide interactions to multiple users simultaneously based on web platforms.

2.8.2 Cyber-Physical Systems

The reviewed articles in these studies support efforts for digital transformation in the AEC industry based on system developments that adds workers in the loop of virtual and physical construction elements. Most of the approaches in this study only cover the cyber-to-physical CPS direction, as they only connect BIM sources to workers. These developments can potentially be used with other systems that developed the physical-to-cyber direction, thus closing the loop of CPS bidirectionality. Clear identification of the system elements and processes to enable degrees of unidirectionality or bidirectionality needs further research.

2.8.3 System Interaction with workers and managers

The studies reviewed in this article have enabled multiple types of interaction with workers and managers for productivity support. Interactions with users have included those with mobile devices, achieved by utilizing mobile apps, screens or projectors, voice, and combinations of these

modalities. Interactions with managers have included those with dashboards that provide visual support and user interactivity. Managers have also been able to interact through mobile apps, and text-based interactions have been common for knowledge extraction. Other interaction methodologies addressed to workers or managers have included AR for scanning objects from physical construction 2D drawings or objects.

The human factors for effective interaction of systems with workers are also an area of concern for the researchers whose work is reviewed here. For example, the effectiveness of using touch interfaces in mobile apps was disputed by Yang et al. (2016), and was considered not accurate enough for mapping applications. When considering AR interactions, developing an effective user interaction is also critical for effective system interaction with the user and with physical objects (Lin et al. 2015; Linares-Garcia et al. 2022). Nevertheless, the consideration of these human factors embedded into the system design is being proposed by researchers (Calvetti et al. 2020; Rahimi Movassagh et al. 2021).

2.9 Future Research Directions

The previous sections provided a synthesis of the literature on BIM and human CPS integration methods for the development phase of construction projects. This section provides potential research directions based on the reviewed articles.

2.9.1 Human Factors and System Interactions

The reviewed articles presented multiple alternatives for interaction considering devices and different user interactions. Recently, mobile devices, including smartphones and tablets, have been commonly used to read and get information from projects. Mobile devices have also been used to enable AR interactions through their screens. This type of interaction has been based on using a device's camera to scan paper drawings and 3D objects and show the user superimposed 3D models through the smartphone screen. However, further research in this area is needed to enable interactions in other contexts, such as interactions with or between visually constrained construction workers and managers.

In the latest years, other devices have been explored as ways to support BIM-human cooperation, including AR head-mounted display (HMD) devices. However, using these devices in dynamic environments such as construction sites is challenging because usability and safety issues arise

from workers involved in construction activities using AR HMD devices. As a result, a future research direction is to identify appropriate AR user experiences for users on the construction site. For example, research by Linares Garcia et al. (2021) proposed user interfaces for workers for dynamic environments that include manufacturing, but these proposed interfaces can also be translated into construction applications.

Wearables also have the potential for future BIM interactions with the user. Some literature examples were identified during the article selection process but were omitted because they did not integrate BIM sources. However, this area of future research can be considered for future BIM-human interactions. For example, Roofigari-Esfahan et al. (2021) developed a smart vest for integrating work zones and construction workers. This research direction presents challenges such as user interaction and device development but can significantly support the productivity of construction workers.

2.9.2 Voice Interaction with Construction Workers

Approach A2 presented voice systems to interact with BIM, e.g., Shin and Issa Raja (2021). However, this system was adequate only for managers to retrieve knowledge from BIM sources. Voice interaction with construction workers has significant potential to enable workers to access BIM information in visually limited construction activities and environments, but researchers need to evaluate the related performance benefits for and cognitive effects on construction workers. Proposed solutions tend to assume English-speaking origins, but construction sites may include workers for whom English is not their first language. As a result, another aspect to consider in voice interaction for workers is the language barriers of such system. Therefore, research in this direction also needs to evaluate the effect of different levels of English proficiency on voice systems.

2.9.3 Knowledge Management

Knowledge in the construction industry involves different levels of human perception. Knowledge can be provided as documents, phrases, or words with a particular meaning. Therefore, it is important to provide the appropriate level of knowledge to humans for BIM-human systems to be developed. For example, when providing knowledge through voice to workers in the field, the worker might want to receive instructions about work processes instead of technical information.

This kind of knowledge, referred to as semantic knowledge, needs to be better understood in the context of work activities for the workers to benefit from such interactions and allow productivity improvements. Otherwise, the proposed systems risk becoming disruptive. Therefore, this is an important area of future research.

2.9.4 Web Interoperability

Approach B2 included approaches integrating BIM, humans, and sensor data using web tools and platforms. web tools include cloud computing, cloud storage, web services, and platforms that have been integrated with construction systems. In our review, it was also common that other approaches included web platforms to show information to users as the front ends of user interaction. Therefore, the role of the web in the CPS processes cannot be neglected, and it will continue to be an area of research development, especially given the interoperability of processes and data fusion. Other researchers have already made inroads in this area by proposing data schemas and processes, e.g., Afsari et al. (2017) and Afsari et al. (2017).

2.9.5 Definition of the characteristics of CPS in the AEC industry

CPS needs to be better in the AEC industry based on a taxonomy identifying its characteristics and relationships. Any development in this area needs to clarify the different terms, processes, and ontologies for CPS in the AEC industry. Research in this direction also needs to consider the integration of CPS in the AEC industry with systems in other industries and contexts (Griffor et al. 2017). By developing such taxonomy, academia and industry can define a common direction for CPS interoperability, processes, and applications for the future.

2.10 Conclusions

This study presents an in-deep review of the integration approaches between BIM and workers in the AEC industry for productivity support. The scope was defined to consider developments specifically for the construction phase of project development and includes developments that target managers as system users as their work indirectly affects workers' productivity. In total, 83 articles were reviewed, but 38 were considered to develop the integration approaches. This in-depth review further contributes to the body of knowledge in this research direction and sheds light on the integration status of BIM and workers, as well as the limitations and challenges ahead. The

objectives of this study were to identify system types, analyze integration approaches and provide future research directions.

The combination of the integration approaches to advance the development and interoperability of systems in the AEC industry was also encountered in the course of this study. Type B systems provide a more complex interaction with sensors to enable activity monitoring and context-aware feedback to the worker to support productivity improvements. System interaction with the user was multimodal. The knowledge retrieval systems present for type A systems were focused on developments that retrieved data from BIM sources and then provided it to the user through text-based queries, voice queries, and multimodal modalities. The integration approaches included custom tools, algorithms, data and process schemas, game engines, web platforms, and combinations. The interactions between BIM, workers and managers were enabled through multiple devices such as screens, mobile devices, AR devices, the web, and modalities that included vision, voice, touch, or a combination.

Finally, the third study objective was to define future research directions for BIM-human CPS for worker support. In this regard, five prominent research directions were identified: human factors and system interaction, voice interaction with construction workers, knowledge management, web interoperability, and the definition of the characteristics of CPS in the AEC industry.

As presented in this article, the AEC industry seeks to address systems to incorporate humans in the loop of productivity systems. This is an industry need based on its lack of productivity and labor shortage. However, much work needs to be done in this research direction to define baselines that integrate humans into current and future CPS in the AEC industry. Furthermore, considering the human factors in the system, the development would provide better holistic approaches to incorporate humans in construction systems more seamlessly.

CHAPTER 3. DESIGN AND ASSESSMENT OF VOICE-BASED INTELLIGENT VIRTUAL AGENTS (VIVA) TO SUPPORT CONSTRUCTION WORKER PRODUCTIVITY¹

3.1 Abstract

The Architecture, Engineering, and Construction (AEC) industry in the United States faces a scarcity of skilled labor workers. Previous efforts in academia and industry have investigated various approaches to improve worker productivity. Voice-based systems present opportunities to improve worker productivity, but their usability and applicability in unstructured and noisy occupational settings such as those inherent in construction projects have not been explored. This study develops a prototype Voice-based Intelligent Virtual Agent (VIVA) and evaluates its impact on construction worker productivity. A usability study was conducted involving 20 students to evaluate VIVA's support on workers' performance and cognitive workload. The results corroborated performance gains with VIVA. Results from workload demonstrate that intervention through voice assistance does not impose a cognitive burden on workers. The proposed solution provides a novel use of voice-based agents, in a dynamic and noisy occupational setting, compared to the conventional use of voice assistants in stationary or structured settings.

3.2 Introduction

The Architecture, Engineering, and Construction (AEC) industry in the United States is currently facing a critical shortage of skilled labor shortages (EHS Today Staff 2021; Karimi et al. 2018; World Economic Forum and The Boston Consulting Group 2016). However, the nation's aging infrastructure and increasing housing demand, in addition to the projected economic growth for the industry, mandates the industry to hire more people, almost 61,000 per month, requiring access to more qualified workers (Kim et al. 2020). Such skilled labor shortage is one of the main

¹ This technical article was co-authored with Dr. Nazila Roofigari-Esfahan, Kristina Pratt, and Dr. Myounghoon Jeon, and has been submitted to an academic journal that address computational and information technology in the Construction Industry

contributors causing project cost overruns and schedule delays (Gomar et al. 2002). In the absence of skilled workers, the industry has to hire new novice and low-experienced workers to address the demand. Novice/low-experienced laborers tend to have low productivity, needing more time to complete the project, and consequently leading to delays in the construction schedule (Allmon et al. 2000). Given the significant role of laborers in overall construction productivity, hiring low-skilled workers can aggravate the current descending state of productivity gains in construction (Nasirzadeh and Nojedehe 2013).

Therefore, there is a need to build the next generation of skilled workers in construction to address industry's current worker shortage and the resulting productivity shortfalls. Developing methods to support worker productivity has been investigated in previous research efforts. Previous efforts made use of different technologies/methods, e.g., wearables (Ahn Changbum et al. 2019), cyber-physical systems (CPS) (Anumba et al. 2020), knowledge management (KM) (Constantinescu 2009; Elghamrawy and Boukamp 2010), environmental sensing (Kiani et al. 2014), individually or in tandem, towards augmenting construction workers (Calvetti et al. 2020).

Voice-based support is a viable solution to improve productivity of construction workers at all skill levels, as it is intuitive and works well with construction environments. In addition, most commercial voice interaction devices possess noise-canceling capabilities, another strength of using these devices for construction environments. Voice can be especially useful in providing digital instructional/informing knowledge (Kondratova 2003) to workers while at work without causing disruption in their on-going activity. Despite voice assistants' widespread use at home and various occupational settings, its benefits to improve worker productivity in construction have not been investigated. As such, for the voice-based methods to be effective in supporting construction worker productivity, there is a need to define the stepping stones for its implementation in the industry. This will include establishing a clear pathway for its development based on the construction work environment's requirements/barriers, measuring its performance and evaluating its impact on workers' perceived workload, among others. This paper aims to contribute to achieving this goal and add to the current body of knowledge through taking the first steps towards quantifying and analyzing the effects of voice-based support on the productivity of construction workers. To this end, a prototype Voice-based Intelligent Virtual Agent (VIVA) was developed. VIVA aims to support worker productivity through providing ad-hoc semantic knowledge, the

specific task/context-related knowledge that is pre-processed to be understandable by workers, when they need it.

To this end, this article first provides an in-depth review of voice-based support systems in different industries from the perspectives of design, development, and assessment. The effectiveness of semantic knowledge provided through VIVA is evaluated through a usability study and collecting subjective feedback from participants.

The results seek to deepen the understanding of how construction productivity can benefit from applications of voice-based systems, and evaluate their effectiveness for onsite worker productivity support. It also seeks to elucidate the users', i.e., workers', experience while receiving support during onsite task performance. Finally, it further contributes to widening the application and development of voice-based systems from stationary settings to highly noisy and dynamic settings.

3.3 Background

3.3.1 Factors Impacting Construction Worker Productivity

Construction worker productivity is affected by multiple factors that determine their work outcomes and safety behaviors. These factors include mental, physical, environmental, experiential, technological, and social factors, each of which impacting the workers differently. The multitude of involved factors complicates the understanding and addressing of productivity issues. Previous research has focused on studying these factors individually or jointly, and providing different insights on improving construction productivity.

Rodriguez et al. (2020) highlight that non-physical factors such as perceptual, cognitive, psychomotor, and social factors coupled with physical demands significantly affect construction worker productivity. Rodriguez et al. (2020) also concluded that non-physical factors, especially increased cognitive demands, are being exacerbated by current efforts towards increasing industry digitization.

The worker's aptitude to do the job at hand was studied by Johari and Neeraj Jha (2020). Their study described aptitude as the ability to perform a certain job or task in terms of physical and mental demand. This study describes that physical aptitude plays a more important role in construction worker productivity than mental aptitude; meaning the productivity of the workers

lacking physical traits adequate for the completion of their job, such as manual dexterity, eye coordination, and physical response, is more negatively impacted than mental aptitudes, such as intelligence, numerical skills, communication skills or perception.

Ha et al. (2020) studied workers' experience and identified a direct linear relationship between worker productivity and years of experience until their productivity becomes constant at 12 years of experiences. More importantly, Ha et al. (2020) highlighted that a baseline worker productivity is reached until workers' experience reaches seven years. This study highlighted how essential it is to support inexperienced workers' productivity which accounts for a considerable period of maturing worker productivity.

Johari and Neeraj Jha also proposed that motivation is another factor that affects productivity and should not be neglected in improving construction worker productivity (Johari and Jha Kumar 2020). Similarly, Rouhanizadeh and Kermanshachi (2021) posited that an inverse relationship exists between workers productivity and their emotional health. Lastly, the Covid-19 pandemic has been recognized as an important cause, affecting workers' welfare (Pamidimukkala and Kermanshachi 2021) and negatively impacting their productivity. Other factors included workers' perception of health and safety practices at the job site. Hashiguchi et al. (2020) examined these factors and identified a varying degree of health perceptions among construction workers depending on age. According to their study, by addressing workers' safety misperception, their productivity can increase. Prioritizing these competing factors introduces a challenge to construction industry stakeholders. Consequently, researchers have also proposed methodologies such as fuzzy decision-making and mapping, to prioritize productivity factors (Kazerooni et al. 2021). All these factors make addressing productivity issue a complex task. Therefore, the current study focuses on assessing voice-based task assistance, as a method to minimize the negative effects of some of the previously mentioned factors on workers productivity and support the productivity of inexperienced workers.

3.3.2 Construction Worker Support

Providing support to construction workers is investigated for multiple purposes, including productivity (Yeh et al. 2012), health and safety (Park and Cho 2018), efficient communication (Alsafouri and Ayer 2019), training (Akanmu et al. 2020), and operation management (Teizer et al. 2017). Numerous approaches were proposed to support workers, categorized here as passive

and active methods. Passive methods provide industry best practices, while active methods provide interventions to change the working dynamics or workers' perceptions during work activities.

Workers' tendency to take safety risks in construction activities jeopardizes productivity gains. Hashiguchi et al. (2020) demonstrated that improving workers' health and safety perception positively impacts their productivity. Because of this, health and safety support for workers is of high priority and has received significant attention in previous research. Hasanzadeh et al. (2020) investigated risk-taking behaviors of construction workers and recommended interventions to avoid safety hazards and injuries (Hasanzadeh et al. 2020). Active worker support has also been explored using wearables, including exoskeletons. The use of exoskeletons can potentially support workers by providing physical support during repetitive or heavy lifting activities that might provoke short or long term health issues/injuries for workers (Okpala et al. 2022), which affect their productivity and the project productivity.

Worker support through providing contextual understanding and knowledge delivery is another area of significant interest in previous research works. In this area, Augmented and Virtual Reality (AR/VR) interventions have been explored to present information and augment the user's context understanding. These interventions used multiple types of AR/VR devices such as Head-Mounted Displays (HMDs) (Ensafi et al. 2021), and smartphones and tablets (Alsafouri and Ayer 2019), and wearables such as smart watches (Lee et al. 2017) to provide workers with contextual information. Effective and safe use of these devices in construction requires a better understanding of the interaction between user and the provided intervention including the device, information, and interface. As such, researchers have focused on developing system concepts and user interfaces, and evaluating their impact on workers' performance (Kim et al. 2020; Linares Garcia et al. 2021; Yang et al. 2019). Knowledge transfer through intervened training was also investigated to improve construction productivity. AR has been used for teleoperations, and off-site and on-site support (Li et al. 2018), knowledge transfer for worker support (Sappelli 2016), and access to project information and Building Information Modelling (BIM) databases (Brathen and Moum 2016). BIM has been used together with AR to provide information to workers (Schweigkofler et al. 2018), support human-robot collaboration (Liu and Wang 2017), and improving project operations (Shan et al. 2012; Teo 2016).

Although these worker support strategies can increase worker productivity, they may be limited in practice, when implemented in everchanging and hazardous construction environments. In addition, most current interventions require tailored training to prepare the workers to use the technology, especially for less tech savvy workers. As such, a readily implementable worker support system should take into account the combination of workers' limitations, nature of construction activities and environmental constraints. Based on this, voice-based worker support has the following advantages over current interventions: it needs less training due to its intuitive application; and it does not block workers' field of view or disrupt worker's task. These characteristics make voice-based agents a viable, readily implementable intervention to support construction workers with their tasks.

3.3.3 Knowledge delivery impact on worker productivity

The effective creation, interpretation, delivery, and manipulation of knowledge as easily and readily interpretable information is described as knowledge management (KM) (Guodong et al. 2018); however, it is an aspect often neglected about productivity. Timely knowledge management is essential for keeping productivity goals and increasing the productivity of resources. It can inform what needs to be done, when to do it, what dimensions and quantities of resources to use, or what amount of work should be completed.

In the past, explicit knowledge was delivered through blueprints, written instructions, memos, or in-person communication. However, research shows that delivering knowledge to specific resources is more complex or has been done inefficiently in the AEC industry (Calvetti et al. 2020). Direct knowledge delivery to end-users, e.g., workers, when improperly implemented, can cause additional burden and inefficiencies. Providing contextual information to construction workers during performing their tasks is more challenging (Solis et al. 2015) due to multitude of personal, activity and environment factors. First, workers' cognitive abilities are limited and used primarily to perform the task at-hand. As a result, the information should be provided in a way not adding cognitive burden on them. Second, the intervention provided for information retrieval should not distract workers, thereby exposing them to safety hazards. Finally, the dynamics of the surrounding environment should be taken into account. Recently, placing information booths on the job site has been used to deliver direct knowledge to workers (Ruwanpura et al. 2012). In such approaches, the workers search through multiple documents, i.e., digital assets, to find the information they

need, which might be time-consuming. Consequently, all the workers required to access information need to be trained to be able to use digital construction resources, e.g., BIM platforms and devices. Besides, the workers will have to stop their activity to move to a specific location to use the device to access digital construction resources (Brathen and Moum 2016). This highlights how challenging KM is and why knowledge delivery alternatives need to be analyzed to ensure effective information delivery. Given the complexity of knowledge management, ontologies (Anumba et al. 2008), architectures (Fang et al. 2018), and technological approaches (Demian et al. 2015; Gürdür et al. 2018; Lin et al. 2016; Linares et al. 2019) have been explored. Industry solutions have incorporated Knowledge Management Systems (KMS) that integrate information from multiple sources and visualize it through mobile and web applications (e.g., Autodesk solutions and Procore). However, these solutions focused on offering non-semantic file-sharing platforms, allowing users to access digital project resources when requested, but neither proactively nor semantically. In other words, users will not be able to be easily understand and use the information available in these platforms while simultaneously performing their tasks. This non-proactive approach to information delivery is therefore of no use for hands-on resources such as trade workers that do not have the computational tools or training to retrieve knowledge from the files distributed by KMS. As a result, other means to provide knowledge to workers while doing their work activities are needed. The current study investigates voice assistants as a viable solution to address this KM gap and develops a platform to transfer semantic knowledge to workers while performing their activities.

3.3.4 Voice-Based Support System in Other Domains

Voice-based systems have been used in other domains to support humans in multiple environments, such as home and workplace, and for different purposes, such as cognitive support, device control, and enabling access to information.

Voice-support systems are being used nowadays to retrieve information about the environment, personal user information, from different sources, including internet. This has been enabled through commercial systems, including Amazon Alexa, Google Assistant, Apple Siri, and others (Jimenez et al. 2021). Other uses of voice-based systems include device control in smart homes/spaces to increase user comfort. In these applications, the user interacts with a voice interaction device to actuates an action in other device that the user (Chan and Shum 2018).

Voice-based systems have also been explored to be enhanced workspaces. With the increasing popularity of unconventional workplaces that are being held at home or even in vehicles, voice-based systems have also been designed to support these spaces (Chan and Shum 2018; Lee and Jeon 2022). These systems are intended to be used by any users and provide information to users through smartphones and other devices specially designed for user interactions through voice, e.g., smart speakers.

In the future, voice-based systems are envisioned to support elderly and people with disabilities for basic daily activities such as washing hands or using the toilet (Salai et al. 2021). These are also being explored to affect energy behaviors of users in buildings and homes (He et al. 2022).

In light of developments and applications in the domains presented, voice-based support systems are proved to increase human capabilities, including cognitive capabilities, and provide facilitated access to information from multiple sources. Therefore, this study explores the possibilities and challenges of using voice assistants in a more dynamic environment, i.e., construction sites, and seeks to identify the opportunities for supporting construction worker productivity.

3.3.5 Voice-Based Worker Support Systems

Previous research works that explored voice-based solutions in different industry settings concluded that these solutions can reduce cognitive workload and consequently increase performance during work activities (Brachten et al. 2020). However, the drawbacks of voice-based solutions in domain-specific applications were identified as domain knowledge extraction and correct identification of users' utterances (Shalaby et al. 2020).

Despite its benefits, the full potential of voice-based systems to provide proactive worker support in construction, has not been realized. Recent research explored tailored voice agents for the construction industry from the ground up (Sangyun 2020; Shin and Issa Raja 2021), considering an algorithmic approach. In a previous work, the authors investigated the human factors relevant to workers using voice-based support on the job site and developed a framework for bringing construction knowledge to workers (Rahimi Movassagh et al. 2021).

In a similar direction, other approaches investigated interoperability methods between construction sources and IoT platforms (Ghosh et al. 2021). Tang et al. (2019) also proposed multiple methodologies to address BIM and IoT interoperability to provide researchers with interoperable

heuristics for the future development of IoT systems. These approaches focused on the required infrastructure for any worker support system, and shed light on the requirements and barriers of developing IoT-based infrastructure for designing pro-active worker support systems. This research takes benefit from the existing higher-level research and develops a specific intervention to address the identified gap.

3.4 Research Methodology

From the literature review, it was identified that construction workers need user-centric approaches to receive proactive information while performing their activities. Therefore, the present study aims to explore the benefits of voice-based support systems to address this need. The main objective of this study is to develop a prototype platform for voice-based worker support and evaluate its impact on the performance of construction workers through a usability study. A simulated steel connection activity was designed as steelwork represents a critical trade whose productivity and safety are a vital contributor to construction projects [60]. A voice-based information delivery framework was developed to provide instruction during assembly tasks.

Multiple research methods were integrated to develop and evaluate a Voice-based Intelligent Virtual Agent (VIVA) framework to enable proactive knowledge delivery to construction workers (See Figure 3.1). The developed voice-based system was evaluated for its effectiveness and implications on workers' performance and cognitive workload. The effectiveness of the developed platform on performance and cognitive load of the users was tested and compared to a traditional paper-based information retrieval baseline.

The study was initiated by conducting a contextual inquiry visit to identify the context and needs of the stakeholders. To this end, the research team visited an under-construction project on Virginia

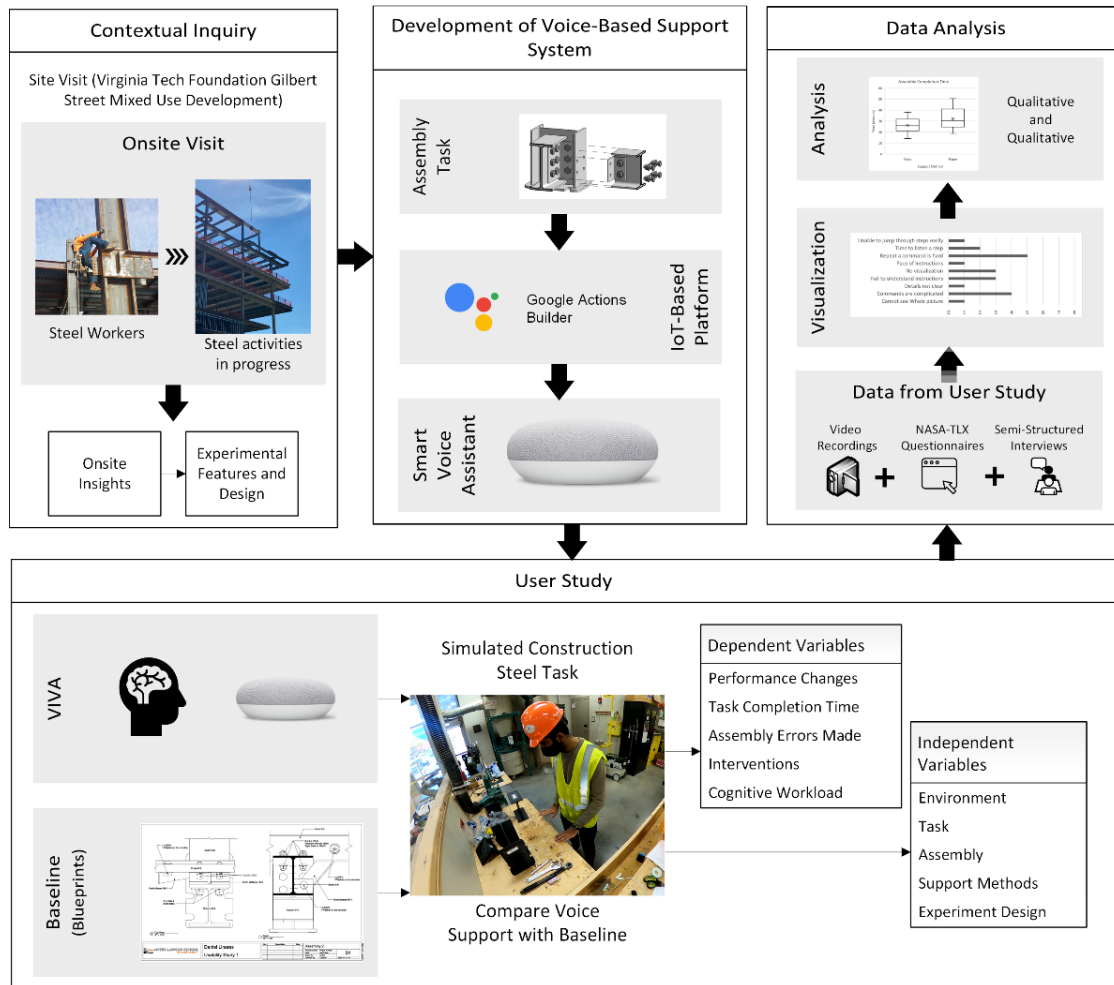


Figure 3.1. Research Framework

Tech's Campus and collected practical insights through observations and communications with project managers and steel workers. The information gathered during the contextual inquiry was used as the foundation to develop VIVA and the system was further evaluated through a usability study involving students with little to no experience in construction. This group was selected to eliminate the preference and performance bias caused by experience. Subsequently, the data gathered were analyzed to compare and find statistical significance. Finally, results were reviewed, and conclusions were given.

3.4.1 Contextual Inquiry

A contextual inquiry is a means to obtain users' feedback about a particular phenomenon through an observation and verbal feedback at the location of the phenomenon (Hartson and Pyla 2012). In order to incorporate users' experience and knowledge related to the steelwork in the

development of the VIVA, a contextual inquiry was conducted. Gilbert Street Mixed-Use Complex project on Virginia Tech Campus was selected and was visited during its steel erection operations. The coordinated visit allowed us to observe the worksite and workers during steel erection of building structure and talk with stakeholders. Project engineers were asked about the process they follow to coordinate work with steelworkers. The following insights were gathered during the contextual inquiry:

Steel erection work is considered one of the most hazardous jobs in building construction sites, so safety precautions during these activities are critical.

- During the steel erection process, multiple roles are involved in providing steelworkers with the information they need. These roles include supervisors who directly have audio communication through radio with the workers on site. They are not necessarily located where the steel erection is conducted and observe the process from afar. Another role is the spotter, who is constantly tracking the location of the steel elements being transported by the crane to assure clearances. The spotter coordinates with steelworkers, supervisors, and the crane operator and notifies them about deviations from the intended erection plan. Finally, the crane operator is another actor in the steel erection process.
- Regarding steelworkers' safety considerations, workers are encouraged to avoid distractions at all times. Visual distraction cues are especially considered dangerous. The only way to ask/receive information is through radio communication or stopping their activity and going to a safer location where the information they need is available.
- The steel erection team, which includes the labor workers, the site superintendent, and the project engineer from the subcontractor, has a pre-task meeting where workers can review the information about the tasks they will do during a certain period. After that, workers will rely on memory and understanding of the instructions and knowledge acquired in the erection team meeting.

The mentioned insights obtained from the contextual inquiry were taken into account in our system development and usability study to address the actual conditions governing construction sites. In the usability study in particular, the following features were included to ensure realistic simulation of actual processes:

- Although collaborative crane operations processes for steel erection involves more than one worker's activity, this study focuses on the steelworkers' efforts to complete the steel assembly as a part of the whole process. The information needs of the rest of the involved workers in process of crane operations are not within the scope of this article
- Two adequately similar steel connection assemblies were designed, and 3D printed to enable each participant to complete the task both based on paper and voice instructions. See Figure 3.2.
- The baseline uses a paper-based scenario including construction blueprints to address the on-site condition where workers have to retrieve information from paper drawings in a different location than the work location i.e., construction trailer. At the blueprints' station that was located 15 ft apart from the work station, the participants had to look at and understand the paper drawings and go back to the work station to complete the assembly. In the usability study, we provided unlimited opportunities to the participants to go back and forth between the blueprints' locations and the work location, i.e., where assembly job is performed. This allowed fair comparison with the voice-based scenario where participants could ask VIVA unlimited questions. The experimental procedures for both scenarios are described in detail in section 3.4.3.4.
- The voice-based scenario uses conversation between workers and the database without causing distraction or stopping the undergoing activity. This case is similar to the current onsite practices where the workers verbally ask their supervisor the updated information about their task through

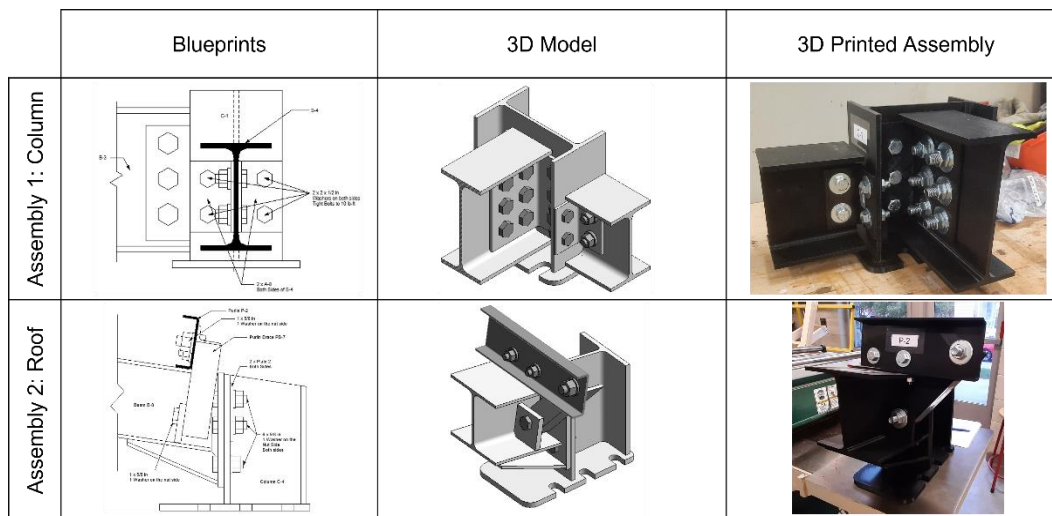


Figure 3.2. Experimental Assemblies

radio.

- In both scenarios, the participants were given the option to ask the research team to intervene and answer questions, or the team intervened when observing a problem. The number of required interventions were recorded for both scenarios to enable comparison.

3.4.2 Voice-based Intelligent Virtual Agent (VIVA) System Development

VIVA worker support system was developed to investigate how providing prompt semantic information through voice-based interaction can impact worker productivity. Figure 3.3 presents the system development. The system was developed based on Google Actions, an IoT platform for voice agents, and available voice assistants, i.e., Google Nest Smart Speaker, with embedded Natural Language Processing (NLP). An app was developed to enable interaction between the user and the information hub. The app works with a Google Nest smart speaker that was used as the interaction device to receive user inquiries and provide responses. The system shown in Figure 3.3 was built based on three integrated layers to enable effective voice interaction with the user.

The first layer is the information hub. This layer presents a manually developed repository of essential information relative to the instructional information needed to conduct the assigned activity, i.e., complete the given assembly in this case. Two primary sources of information were

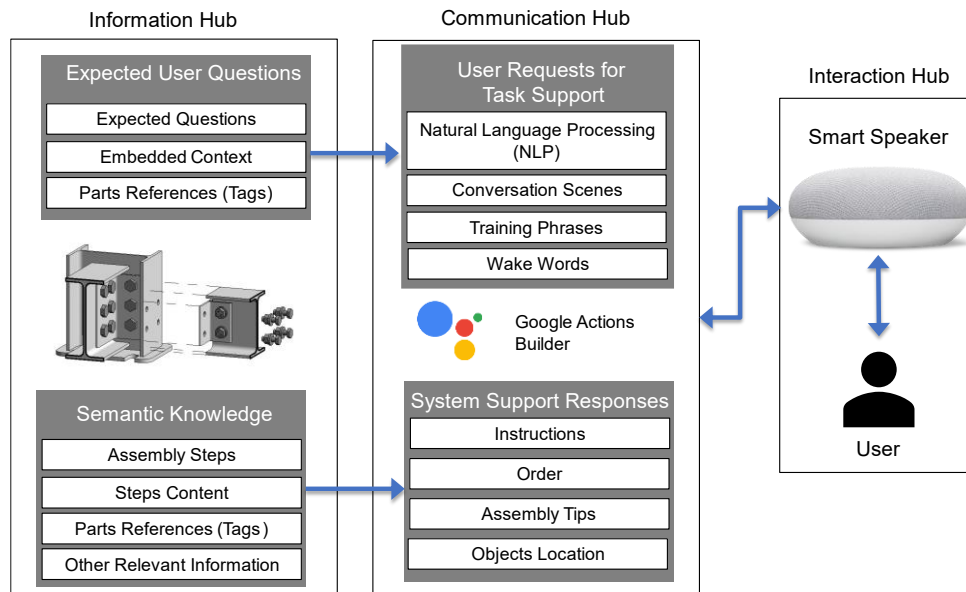


Figure 3.3. Development System Diagram for the VIVA

developed in this system layer, expected questions and semantic knowledge.

I. **Expected user questions** have the following data features:

- The questions that participants were expected to ask were identified thoroughly, taking into account language usage variations that users might use to refer to each step in the assembly process. For example, participants used multiple verbs to refer to how to bring together assembly pieces, including join, put together, connect to, etc. By providing these training questions to the NLP algorithms, VIVA can understand users' questions about steps without needing fixed keywords or sentence structure after the app has been called.
- All the assembly parts had a paper tag with a unique ID used as the part reference in the system. The tag was used as an identifier that the participants could refer to when asking for instructions. VIVA also used part tag IDs as a reference to guide users on what specific parts are used in the instructions.
- The context was embedded into the users' questions by asking them to refer to the previous step in the assembly process as explained in the examples below. This was used to address the limitation of the NLP in the Google Actions platform, as other alternatives such as step numbers and ordinals did not provide enough differentiation among steps to identify each step correctly, and the system could get confused between steps, providing incorrect instructions. To this end, phrases that include context were added to the expected user questions, such as *"after joining pieces PS-3 and B-8"*. For example, participants needed to say what assembly parts they previously joined or where they picked the last pieces of materials to receive information about the following steps. Users were asked to use the assembly pieces' tag IDs or location of items in previous steps as part of the context addition. However, this embedded context information was not fixed, and users were encouraged to add as much information as possible.

For example, the first step of the column assembly asked the participants to get tools from a red container at the entrance door. Therefore, examples of expected questions by the user with embedded context would be a phrase such as: *"After getting the tools, what would be the next step?"*, *"Once I get items from the red container, what should I do next?"* or *"I got the stuff located at the entrance. What do I do now?"*.

As another example, step 5 of the roof assembly was to connect assembly pieces PS-3 and B-8. Therefore, the expected user's questions for step 6 would be: *"After connecting PS-3 and B-8, what should I do next?"* or *"B-8 and PS-3 are now joined. What follows?"*.

These examples highlight that the embedded context in the user's responses were not fixed to key phrases or specific sentence structures. Still, some information, such as the assembly pieces'

tag ID, would naturally be expected by the VIVA app to recognize the context embedded into the questions and provide the correct instructions.

- For the first step, the participants can ask “*What is the first step?*” or “*What do I need to do first?*” or other variations of these phrases.

II. **Semantic knowledge** in the information hub has the following data features:

- Semantic knowledge in the context of this research refers to the translation of knowledge contained in the blueprints and other relevant information sources to the instructions provided to the worker through voice. Semantic knowledge also includes other knowledge needed for completing the assembly steps, such as the location of assembly objects and tools used. Creating the semantic knowledge and the translation of assembly information to voice instructions was a part of the scope of this research. However, the scope at this point was limited to the translating the information required for the assembly completion. Translation of more complex information is an area of future work.
- The assembly steps were devised from the logical assembly process for each of the two steel-connection assemblies. Both assemblies involved seven assembly steps to be completed.
- The assembly step contents varied in complexity, but they tended to be simpler at the beginning of the assembly and gradually becoming more complex towards the end. This pattern was the same for the two assemblies used in the experiment. These steps helped participants to identify assembly parts, gather material, and then provided stepwise instructions to complete the assemblies. For example, the following is the first step for the column assembly used in the experiment: “*First, you need to get the tools. These are located in the Red Container near the entrance door.*” While the following is the last step in the roof assembly as used in the experiment: “*With the leg of the angle PB-7 looking down, first connect PB-7 to the beam B-8 with one bolt of 5/8-inch diameter. The head of this bolt should be on the PB-7 side. Then, put a washer only on the nut side and do not tighten this bolt completely. Then, connect PB-7 and P-2 with one bolt of 5/8 diameter. The head of the bolt should be on PB-7 side and put a washer only on the nut side. Then tighten both bolts completely. This is the last step.*”
- Other relevant information was included in the voice instructions to provide additional support to the user verbally, given the lack of visual support. For example, some steps required identifying what side of the pieces needed to be connected; for these steps, the instructions added phrases like: “*The head of the bolts goes on the PS-3 side*”.

The second system layer is the communication layer. This communication layer was developed entirely in the web version of the Google Actions platform, and was used as a middleware program between the user and the information hub. As the first step towards enabling the interaction, the system needs to understand user questions. The following processes were used to enable this step:

- The communication hub made use of Natural Language Processing (NLP) algorithms embedded in the Google Actions platform. The algorithms were trained using the information relative to contextual steps as well as language usage variations, and conversation flow, to enable correct interpretation of user questions. The training phrases were obtained from the information hub.
- Wake words are phrases used to activate the smart speaker and start interaction with the user. Because two versions of the system were used, one for each assembly, two different wake words were used. For the column assembly, the wake words are: “*Hey Google. Call the Assistant*” or variations of this phrase. For the roof assembly, the wake words are: “*Hey Google. Call the Instructor*” or variations of this phrase. These keywords are two consecutive phrases that activate two processes in the Google Actions platform within VIVA. The “*Hey Google*” phrase, called the Google Actions Platform, and the “*Call the Assistant*” or the “*Call the instructor*” phrases, depending on the assembly, called the developed app.
- The conversation scenes are the central conversation layout for the Google Actions platform. It expects questions from the user and provides responses. For example, the main scene used in VIVA is when the smart speaker asks the participant “*How can I help?*”, and then the voice app is expecting a question that, completely or partly, matches the phrases in the database.

The second component of the communication hub, i.e., System Support Responses (SSR), embeds the following processes:

- The communication hub connects to the information hub to retrieve the instructions developed for each step.
- The SSR looks for and provides contextual information related to the assembly steps in no particular order. Therefore, participants are not constrained to a specific order of steps, and they could go back and forth between steps if they provided the proper context in their questions.
- It provides additional assembly tips as needed to facilitate user understanding through including other relevant information that makes the assembly completion process more efficient.

The third system layer is the interaction hub. This layer establishes direct communication between the user and the smart speaker and serves as the gate to the voice-based support system.

3.4.3 Usability Study

A quantitative usability study was designed and conducted to evaluate the effectiveness of VIVA in improving worker productivity as compared to the baseline method used traditionally in construction sites. The experiment has a within-subject experiment design where the participants conducted both methods to enable them to provide a comparison of both methods. The baseline method used 2D paper drawings with multiple assembly views. The experiment aimed to identify the potential productivity gains when using VIVA compared to the baseline. The productivity gains were evaluated in terms of performance changes and cognitive workload. Achieved performance was quantified using task completion times, number of errors made while completing assembly tasks, and number of required interventions during the assembly tasks. The NASA-TLX questionnaire was conducted after each assembly to evaluate changes in the participants' perceived workload after completing each assembly task.

3.4.3.1 Participants

A total of twenty students participated in the experiment (16 males, 4 females). Fourteen participants were between the ages of 18 and 24, and the remaining six participants were between 25 and 34 years old. Nine of the participants were current undergraduate students, five had completed their bachelor's degree, four had their master's degree, and two had either a professional degree or doctorate. Seven of the participants had experience in construction, and six of those seven had between one and five years of experience. The remaining thirteen participants either declared that they had no construction experience or did not clarify their experience level. The experiments were conducted over the course of a month in the BuildLAB at Virginia Tech in order to simulate a construction environment. Each participant spent 1.5 hours on average in a single session and was compensated \$10 US Dollars for their time.

3.4.3.2 Experiment Tasks

The experiment tasks were designed to simulate steel connection activities. The conditions and constraints of actual construction sites were embedded in the task parameters by including the following characteristics:

- Two assemblies corresponding to steel connection work were used during the experiment;
- Tools, as used in the construction field, were used;
- Participants were asked to use Personal Protection Equipment (PPE);
- The study was also conducted at a construction lab environment, the BuildLab, that involved noise from lab machinery. This helped replicate noisy construction environments.

3.4.3.3 Assemblies

In order to enable comparisons of the two scenarios, i.e., paper-based vs. voice-based instructions, two different assemblies were designed and built using 3D printed pieces and real bolts, washers, and nuts as shown in Figure 3.2. 3D printed parts were used to accommodate the experimental limitations on safety, development, and users' weightlifting. The assemblies were developed to make them comparable, with similar complexity and number of assembly parts. As shown in Figure 3.2 assembly 1 was a column assembly involving a standard beam-column connection with a main column section and two beams connecting to the column as used in building construction. The beams have different W sections and connections are made with clipped angles at both sides, fastened with bolts, washers, and nuts. The characteristics of the angles that form the structural connection differ on size, number of bolts, bolts sizes, and distribution. Bolts of 5/8 inches and 1/2 inches were used.

Assembly 2 was a roof assembly as shown in Figure 3.2. This roof assembly is a standard slanted beam-column side connection with purlin and stiffeners as found in warehouse construction. The beam-column connection was directly connected using holes within the assembly members. The beam-column connection also included a bolt plate as often used to strengthen steel members for bolt tension. Over the beam, there was a purlin made with a C-section that connects to the beam

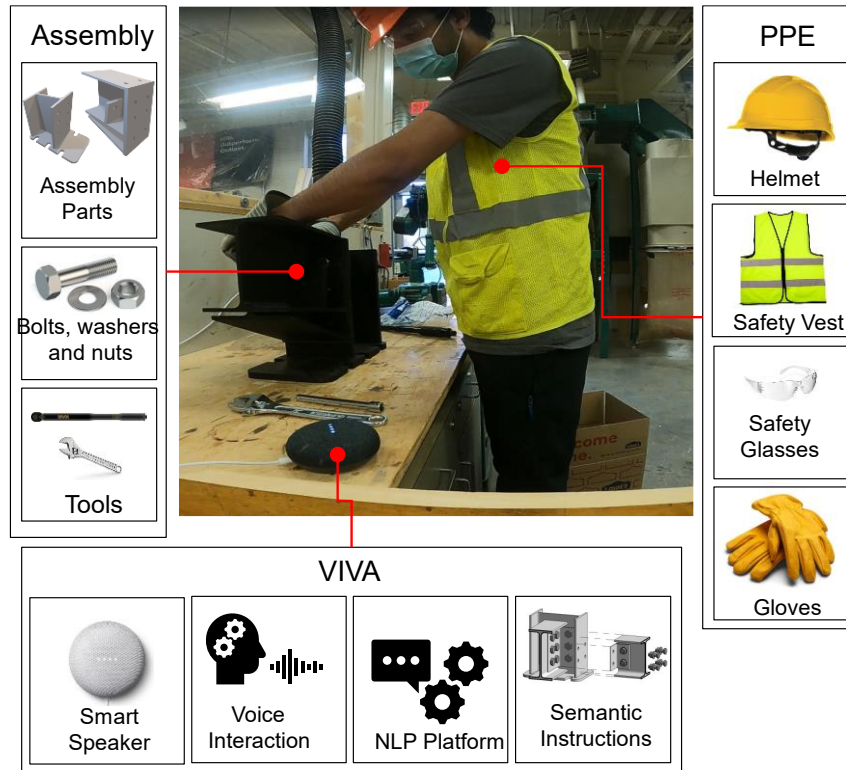


Figure 3.4. VIVA (Voice-Based) Experimental Setup

through a connector with middle stiffener. Lateral support to the purlin was provided with a diagonal angle bolted to the purlin and to an embedded plate in the column member. Bolts of 5/8 inches and 1/2 inches were used accordingly.

3.4.3.4 Experiment Setup, Scenarios, and Tasks

A different experimental setup was designed for each assembly as shown in Figure 3.4 and Figure 3.5. The VIVA experimental setup is presented in Figure 3.4. In this scenario, the participant had to complete an assembly using the voice-based support system, VIVA. In this scenario, participants asked the smart speaker questions about the assembly completion steps, assembly details, and parts/tools' locations. As shown in Figure 3.4, VIVA allowed participants to work in a single location without the need to go back to check details in the blueprints, as information was promptly provided to them. The baseline, i.e., the paper-based, experiment setup is presented in Figure 3.5. In this scenario, the participants completed an assembly using blueprints as a support method. In this scenario, participants had all the information they needed in the blueprints,

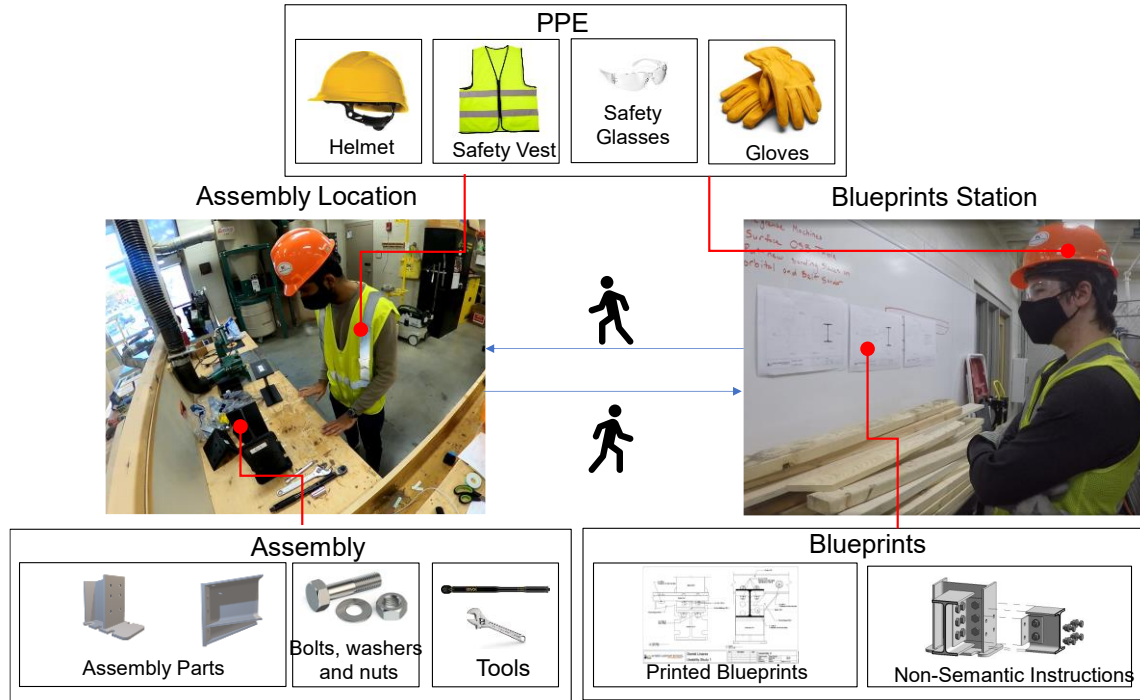


Figure 3.5. Baseline (Paper-Based) Experimental Setup

including views of the finished assembly and additional information about the location of material and specifications.

Both experimental setups have the following similarities:

- Both experimental setups were done in the same lab, i.e., the BuildLab. This lab immersed participants in an imitated construction environment with strong similarities to the construction field.
- Both experiment setups used similar assembly sets, although the order of assemblies was arbitrarily changed among the participants to investigate the impact of learning curve.
- Both experimental setups made use of the same PPE.
- In both scenarios, interventions were allowed to the participants. See section 3.5.1.3.

Differences among the scenarios are the following:

- Both locations in the paper scenario were inside the Build Lab at Virginia Tech. The blueprint station was located 15 ft apart from the work station, and would take around 5 seconds for the user to reach in one way and a total of 10 seconds round trip. The 15 ft distance between the work station and the blueprints station was carefully calculated to be equivalent to the time required for calling the voice app, including saying the key phrase and receiving system

confirmation. This corresponds to the time the user takes to say VIVA's key phrase and get VIVA's ready notification. This does not include the user inquiring about assembly steps and VIVA responding.

- The scenarios differ on the user's mobility and work locations. The participant worked only in a single workspace for the VIVA scenario, as shown in Figure 3.4. While in the baseline scenario, participants roamed between two locations in the lab, i.e., the workspace where the assembly completion task was conducted, and the blueprint station where the paper drawings were located (see Figure 3.5).

Each participant completed both assemblies, one with VIVA and the other one using paper-based support. The order of assembly completion among participants was selected randomly. In total, four different experiment scenarios are possible based on the random ordering, as shown in Table 3.1.

Table 3.1. Summary of experiment scenarios by support method, order, and assembly

Scenario	First Part of the Experiment	Second Part of the Experiment
1 (n=5)	Column with Voice	Roof with Paper
2 (n=5)	Roof with Paper	Column with Voice
3 (n=5)	Column with Paper	Roof with Voice
4 (n=5)	Roof with Voice	Column with Paper

3.4.3.5 Interventions

To handle the situations where provided spoken or paper-based instructions were not adequate or understandable for the participant, interventions were included in the experiment. In both cases, participants were encouraged to complete the assembly on their own as much as it was possible. For the VIVA scenario, the interventions occurred when VIVA failed to provide the correct instruction to the user up to three times, when the voice-based support system failed to understand the user requests up to three times, or when the participants requested for an intervention. Such interventions for the baseline scenario only occurred upon participant request.

3.4.3.6 Perceived Workload

The workload perceived by participants during the experiment was measured based on the NASA-TLX workload evaluation method. Each participant was asked to complete workload parameter assessment and pair-wise comparisons among perceived workload parameters as suggested in the method instructions. An online version of the survey was used to record participants' feedback (Hart and Staveland 1988).

3.4.3.7 Semi-Structured Interviews

After participants completed the assemblies and the NASA-TLX survey, a semi-structured interview was conducted to collect additional feedback from participants. The participants were asked to provide their subjective feedback regarding effectiveness and ease of use of each scenario, their experiences using voice-based assistance, and the benefits and drawbacks of each support method. Their responses were audio-recorded and analyzed.

3.4.3.8 Procedures

Voice-based Procedures

Before a participant completed the assembly with VIVA, the experiment supervisor gave specific instructions on using the system. The first element of these instructions included the system's wakeup call phrase for the assembly. Each participant was aware that they must use this phrase every time they prompted the system or would not respond appropriately. The second element to these instructions was describing how to formulate a question for the system. Since the system is unaware of the sequence of tasks, it was crucial to have participants provide context before asking any questions. To ask the system a question successfully, it was necessary first to refer to the previous step. All questions were directed to the voice assistant before any intervention was considered. If three consecutive errors occurred with the voice assistant, the experiment supervisor would intervene with the correct prompt that the voice assistant understands.

Paper-Based Procedures

For each assembly, there were paper-based blueprints that provided the participants with multiple views of the assembly. The blueprints had all of the necessary information to complete the assemblies. These blueprints were mounted on a wall about 15 feet from the workspace, called

blueprint station, and were placed around a corner so that they were not visible from the workspace. The blueprints also consisted of instructions on where to find tools and materials and helpful tips to ensure that rework was not needed. Each time a participant needed to look at the blueprints, they had to walk to the blueprint station. They were not allowed to move blueprints from their location. Therefore, they were required to go back and forth between the workspace and the blueprint station to acquire the needed instruction.

3.5 Results

For each participant, data were obtained from three sources: performance data from video recordings and research annotations, NASA-TLX workload survey and post-completion semi-structured interviews. Video recordings were reviewed to obtain timings for steps and total completion time of assemblies for each participant, as well as errors made during tasks completion. NASA-TLX workload survey was conducted after completing each assembly to receive participants' assessment on workload parameters. Post-completion semi-structured interviews were conducted at the end of the experiment to collect participants' feedback about both support methods and were manually transcribed by the authors. All the data were collected in spreadsheets and processed for analysis in Excel and SPSS software. The results were analyzed statistically

Table 3.2. Summary of Statistical Data for Performance Measures

Dependent Variables	VIVA		Baseline		p-value	Effect Size
	Mean	Std	Mean	Std		
Assembly Completion Time	26.07	1.36	31.90	2.01	0.0218*	-0.755
Assembly Errors	3.4	1.03	4.05	0.78	0.619	ns
Interventions	1.65	0.3015	2.95	0.52	0.0387*	-0.280

* Shows significance at $p \leq 0.05$. ns denotes no significance; therefore, effect size was not calculated

using paired samples t-tests, and normality was verified based on the Shapiro-Wilk test. An α level

of 0.05 in all significance tests was used. In the results figures, significantly different pairs (when $p \leq 0.05$) are marked with *. The summary of the statistical results is shown in Table 3.2.

3.5.1 Support Method Effect

The effect of the support method was analyzed based on three quantifiable metrics: completion time, the number of interventions, and the number of errors. The support method was also analyzed based on workload perceptions and subjective assessments based on the interview feedback.

3.5.1.1 Completion Time

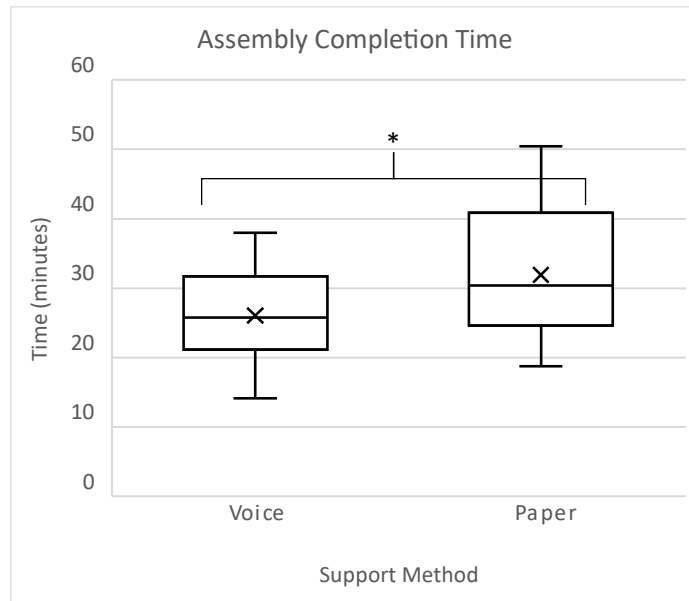


Figure 3.6. Comparison of completion time among participants based on support method. * shows significance at $p=0.0218 \leq 0.05$ and Effect Size of -0.755.

Statistical analysis based on t-tests was conducted to compare the times to complete both assemblies. It was found that the assembly completion time using VIVA ($M=26.07$, $SD=1.36$, $n=20$) was overall lower than the baseline ($M=31.90$, $SD=2.01$, $n=20$) with a normal distribution. This difference was found to be statistically significant $t(38) = 2.06$, $p = 0.0218$ (2-tails) with a medium-to-large effect size based on Cohen D efficient = 0.755 (see Figure 3.6). It can be concluded that participants who used the baseline were around 18% slower than the participants who used VIVA.

3.5.1.2 Assembly Errors

After the participants completed each assembly, the number of assembly errors was identified based on missing assembly parts or incorrect placement of assembly pieces. The recorded videos of each experiment were also used to detect all errors during the assembly completion process. Statistical analysis based on t-tests was done to compare the number of assembly errors made by participants during assembly tasks. However, for both scenarios, the distribution of the data was skewed. T-test also showed no significant difference among the number of errors made for participants using voice ($M=3.4$, $SD=1.03$, $n=20$) and paper ($M=4.05$, $SD=0.78$, $n=20$) instructions.

3.5.1.3 Interventions

Statistical analysis based on t-tests was done to compare the number of interventions participants needed when using each support method. The data's normality for the baseline interventions followed a Gaussian distribution. It was found that the distribution for the interventions with voice was skewed. However, t-test with unequal variance still shows significance in the difference in the number of interventions with $t(30) = -2.161$, $p = 0.0387$ (2-tails), indicating that the number of

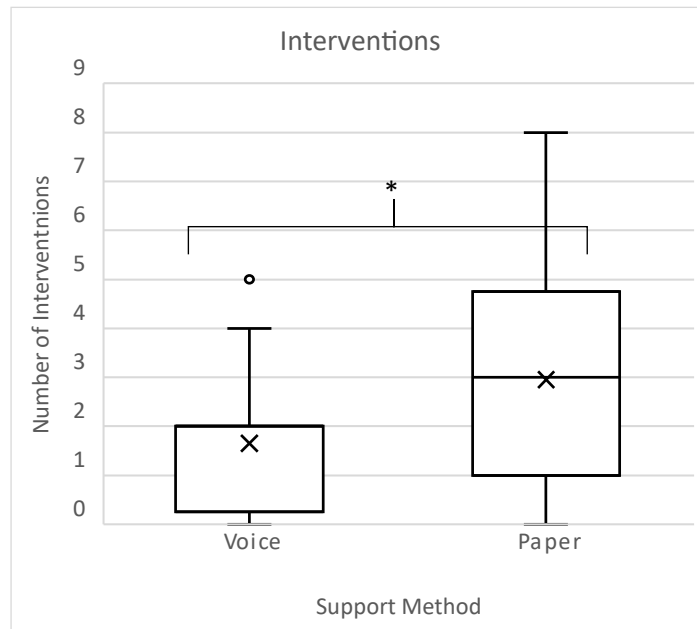


Figure 3.7 Comparison of # of required interventions among participants based on support method. * shows significance at $p=0.0266 \leq 0.05$ and Effect Size of -0.280

interventions with the voice support method ($M=1.65$, $SD=0.3015$, $n=20$) was significantly lower

than the interventions for participants using the paper-based support ($M=2.95$, $SD=0.52$, $n=20$). See Figure 3.7.

It can be concluded that participants who used paper as a support method needed around 44% more interventions than participants that used the voice support method.

3.5.1.4 Workload

The statistical analysis for the workload parameters was based on the individual unweighted assessment for each of the six workload parameters and the weighted overall workload. t-test analyses were conducted to compare the same parameters among VIVA and baseline participants. No statistically significant difference was found. See Figure 3.8. As a result, the voice-based intervention is not imposing more cognitive workload on the participants.

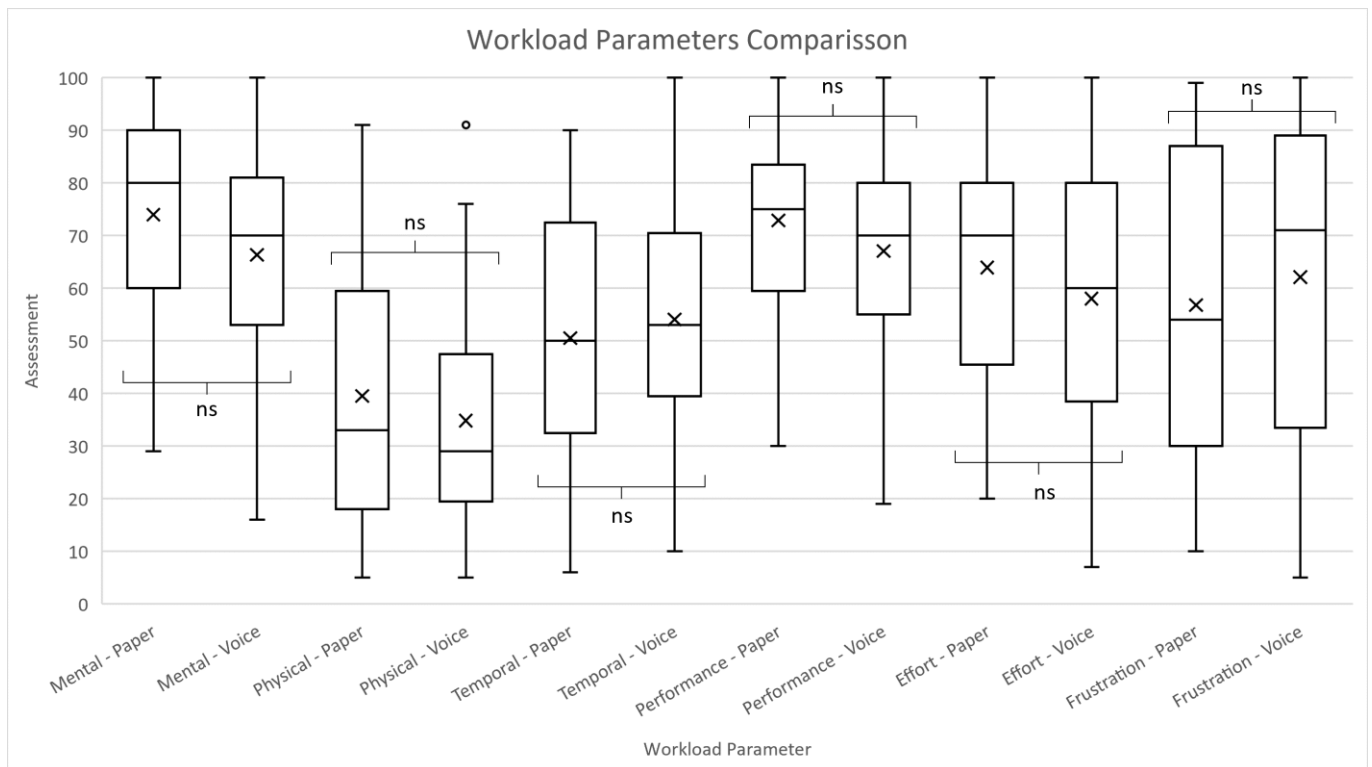


Figure 3.8. Comparison of Workload parameters among voice and paper support methods. ns shows no significance found

3.5.2 Order Effect

The completion order of the two different assembly tasks is expected to affect participants' performance. This is due to the fact that after completing the first assembly, the participant will be familiar with the process and may affect completing the second assembly. Because of this, random ordering was assigned, and a statistical analysis was performed to identify the effect of the order. We reviewed all data sources and found significance only in the duration of assembly completion. No other parameter either in the video data or workload was found significant. It was found that the completion time for the tasks completed first ($M=31.55$, $SD=2.05$, $n=20$) was longer than tasks completed second ($M=26.42$, $SD=1.39$, $n=20$). This difference was significant $t(38)=2.06$, $p=0.0454$ (2-tails) with a normal distribution. See Figure 3.9. Participants who performed the first assembly needed an average of 19% more time to complete it than participants who did the second assembly.

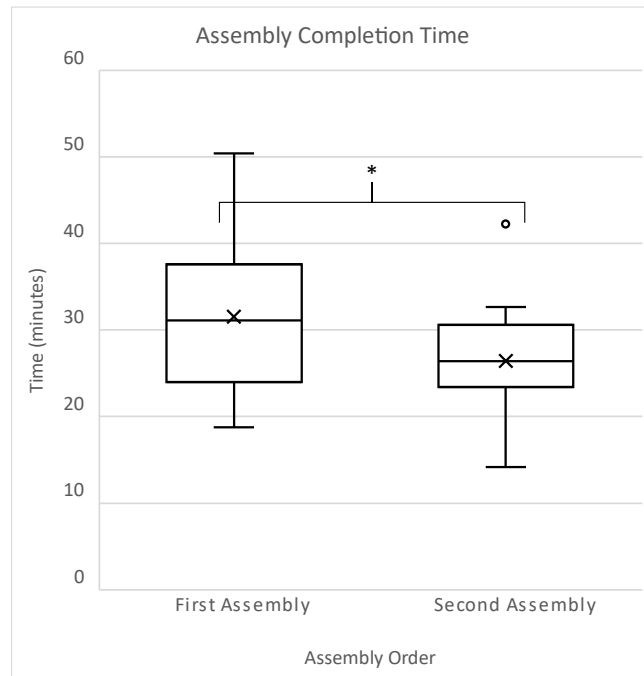


Figure 3.9. Comparison of time completion among participants based on assembly order. *

Shows significance at $p=0.0454 \leq 0.05$ and Effect Size of 0.654

3.5.3 Post-Experiment Feedback

Participants' feedback was collected through a semi-structured interview at the end of the experiment.

3.5.3.1 Support Method Assessments

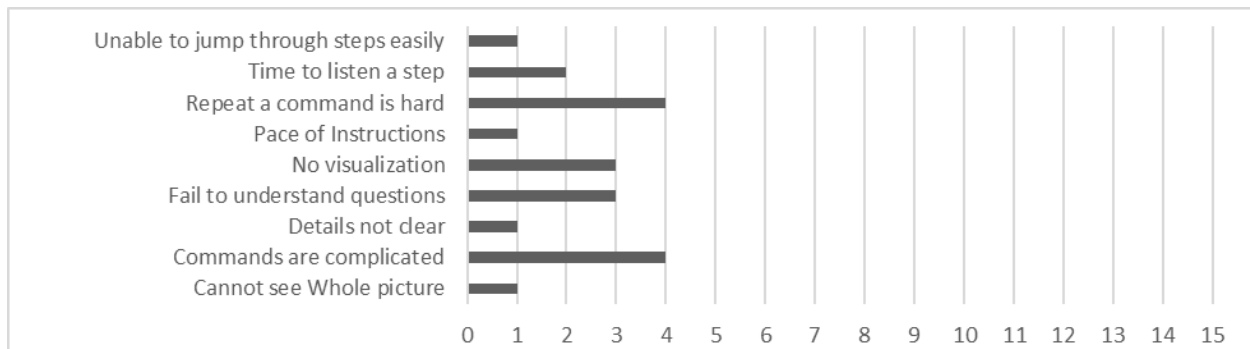
Participants were asked to assess each support method along with their benefits and shortcomings. The answers were collected and analyzed in terms of similarity and number of occurrences of responses across participants. The results are summarized in Figure 3.10.

Most of the participants ($n=15$) stated that the step-by-step instructions provided by VIVA were useful, see Figure 3.10a. Participants also highlighted how easier it was to interact with the system through voice verbal communication ($n=2$) and the convenience of using the system in place ($n=3$). Participants also highlighted multiple issues of VIVA, including difficulty related to having to repeat a question ($n=5$), complicated commands ($n=4$), no visualization ($n=3$), and system failing to understand questions due to accent ($n=3$). See Figure 3.10b.

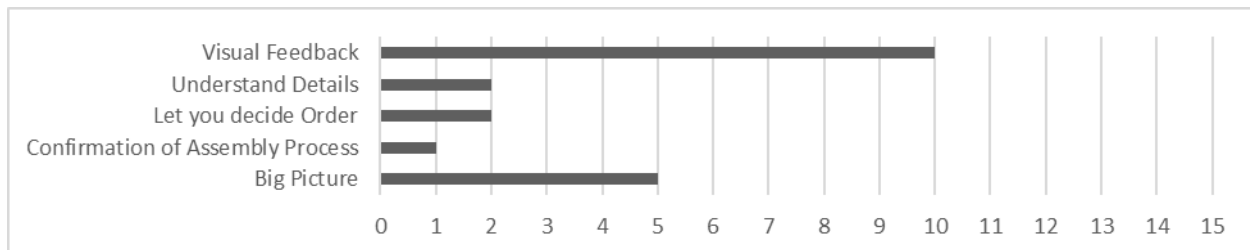
About the baseline, participants considered visual instruction provided by the drawings ($n=11$) and showing the big picture ($n=6$) about the assembly to be beneficial. See Figure 3.10c. In contrast, participants thought that paper instructions were not efficient as they did not provide steps ($n=7$), and instructions to figure out the assembly ($n=4$), and understanding drawings needed prior experience ($n=5$). See Figure 3.10d.



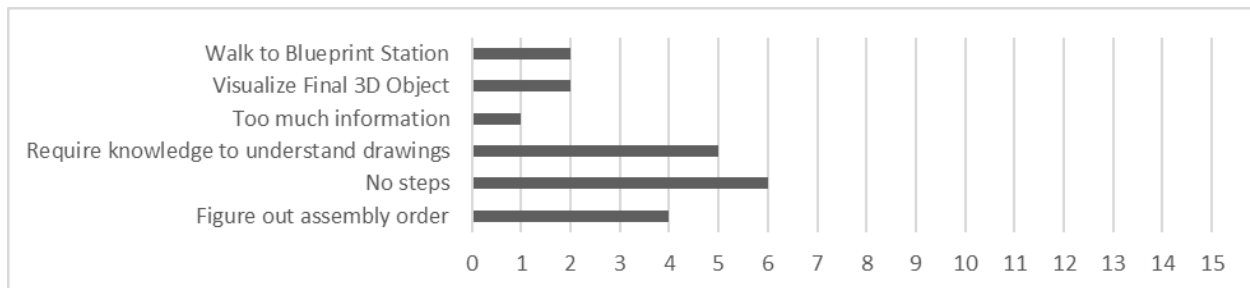
a) What was the Voice support method better at?



b) What was the Voice support method not good at?



c) What was the Paper support method better at?



d) What was the Paper support method not good at?

Figure 3.10. Results from Semi-Structured Interviews

3.5.3.2 Support Method Comparisons

During the post-experiment interview, participants were also asked to compare both support methods in terms of ease of use and support for efficiency. Their responses are summarized in Table 3.3. Participants' responses show that more participants (55%) thought VIVA was easier to use and 65% of participants felt that VIVA made them more efficient.

Table 3.3 Participants subjective feedback about support systems comparisons

Interview Questions	Voice	Paper
What Support Method was easier to use?	55% (n=11)	45% (n=9)
What Support Method made you the assembly more efficiently?	65% (n=13)	35% (n=7)

3.6 Discussion

In this article, a voice-based intelligent virtual agent (VIVA) was proposed to support and improve worker productivity. VIVA aims to support workers through in-time delivery of semantic knowledge to them in an intuitive way that is easy to understand and readily available in place where they do their work activities.

This study's outcomes provide valuable insights into the theories, developments, and assessment of voice-based support systems for the construction industry. Previous studies on voice-based worker support have identified the potential benefits of performance and workload improvements to workers in domain-specific worker applications [47,48]. However, no previous studies have focused explicitly on assessing using voice-based systems to support workers in the AEC industry. Therefore, the results of this study confirm the theoretical productivity performance gains achieved from voice-based systems such as VIVA in a different occupational setting. The results in this study also have implications in setting baselines for designing voice-based Human-Computer Interaction (HCI) interfaces for voice-based agents. In addition, VIVA's features, such as the step-by-step instructions, ease of invocation, and in-place use, were deemed more important than its command difficulties or not having visual feedback (see Fig. 10). Finally, users' feedback also highlighted how semantic knowledge, referred to as step-by-step instructions by the users, has proven to be a key benefit of VIVA, and results in significant productivity improvement.

Therefore, considering the performance improvements and their positive feedback about using implications for the theories of knowledge management and knowledge extraction from domain-specific knowledge sources.

Our research methodology first observed on-site activities for a specific construction trade, i.e., steelwork, to inform the system development. In this article, our worker support methods are a voice-based support system based on IoT. Using IoT platforms allows our system to be easier to develop and deploy, but it suffers from interoperability issues with construction platforms and information sources such as BIM. Therefore, this study focused on developing a prototype system for a specific construction trade: steelworkers. The effect of the voice-based support system was then analyzed from the performance and perceived workload perspectives through a usability study.

3.6.1 Performance Findings

The results of the usability study showed the effectiveness of the voice-based support through VIVA on improving the participants' performance. Specifically, the significant improvements were achieved in completion time of assemblies when using VIVA compared to the baseline, with a medium-to-large effect size (see Figure 3.6 and Figure 3.7). However, the other participants' performance measure, the assembly errors, were not significant. The number of interventions needed while doing the assembly tasks was defined not to measure participants' performance but to review support methods' performance. Based on our findings of interventions, we can observe that fewer number interventions were required when using VIVA in comparison with the baseline. The results were significant with a low-to-medium effect size. This means that VIVA is dependable as it is able to provide consistent and understandable instructions to the user.

3.6.2 Perceived Workload Findings

For measuring participants' workload after each assembly participation, the NASA-TLX workload survey methodology was used. After the data were analyzed, the data showed no significance among any pair of subscales when comparing VIVA and the baseline. This, however, indicates that providing technological intervention through VIVA does not have a negative impact on workers' cognitive workload. This is important as it supported the general conception about

technological interventions that are considered to be distractive and have negative impact on the workers to be incorrect.

3.6.3 Participants' Feedback

As a prototype system, VIVA was not flawless. It sometimes provided inconsistent responses or a complicated interaction process. The context had to be properly provided by the user to receive the correct answer. Despite these drawbacks, VIVA was perceived as easier to use and more efficient by the participants, as shown in Table 3.3. Participants highlighted that semantic knowledge or step-by-step instructions were beneficial features of VIVA. However, participants complained about how difficult it was to repeat a command, given that there was no “repeat” function in VIVA (i.e., just saying “Repeat” to elicit the last command), and the commands themselves could be complicated. We will address these drawbacks in future research.

3.6.4 Impact of environmental noise and face coverings on worker activities

It can be hypothesized that workers might have difficulty using VIVA at work while using the interaction device and wearing face coverings and working in noisy environments. To test this hypothesis, in our experiment, we included both conditions by asking participants to use face coverings due to Covid-19 restrictions and conducting the experiments at the construction lab that involved multiple running machinery working at the same time as the experiment, creating a noisy environment similar to the one experience on construction sites. Under these conditions, VIVA and users had no trouble understanding questions/instructions and the communication was effectively conducted. This is made possible through the noise-cancelling feature available in common voice interaction devices, including the one used in this study. In addition, most commercial voice interaction devices possess noise-canceling capabilities, another strength of using these devices for construction environments. However, noisy environment did make it a bit more difficult for participants to listen to VIVA's instructions. When this happened, participants had to get closer to the smart speaker to better listen to the instructions. In the future research, we plan to use personal devices with access to voice interaction platforms and noise-canceling capabilities, such as headphones, which can help overcome this issue.

3.6.5 Targeted Workers' Experience

The developments in this study target workers who are developing their skills on the task at hand and have not reached productivity maturity yet, e.g., novice and low-experienced workers. According to Ha et al. [17] the baseline productivity maturity of construction workers has been identified to be 7 years for some trades. Therefore, VIVA is expected to help this group of workers bridge the experiences gap and increase their productivity in their early work years. The usability study participants were also selected to reflect a sample with little to no experience in construction. Supporting early-career workers with a support system like VIVA, also supports the skilled labor shortage issue in construction by addressing these workers' lack of experience and helping them reach better productivity outcomes earlier.

However, expanded features of VIVA are also expected to support more experienced workers, through providing on-demand information about their tasks to them from construction digital sources. Future research will study the particular effect of voice-based support systems on workers with different work experiences.

3.6.6 Radio Communication during Assembly Tasks

During the contextual inquiry phase, it was noticed that steelworkers relied on their experience and familiarity with the construction drawings to complete their work. Radio communication was predominantly used for coordination, less for knowledge retrieval and understanding. Given that our article focuses on novice and low-experienced workers, having a radio-only option would not encourage understanding and retrieving required knowledge. Also, if used for this purpose, it can add a burden to the instruction provider, e.g., the site superintendent or project manager. As a result, we focus on providing the ability to retrieve knowledge from construction blueprints.

Additionally, radio communication is used for person-to-person communication, while we envision our system enabling workers to be directly connected to data sources. Future research work will be conducted to embed radio-like communication to enable authentication of data by supervisors, as needed. As such, the developments in this article aim to embed the required characteristic of radio communication in the intervention parameter.

3.6.7 Contributions

The contributions of this research have implications for both the theory and practice of implementing voice-based information systems in the AEC industry. Previous research assessed using voice-based systems to support workers in industrial settings that have more structured and less noisy environments (Serras et al. 2020). However, such a setup does not properly fit construction activities. Our proposed solution provides a novel use of voice-based agents, in a dynamic and noisy work setting, compared to the conventional use of voice assistants in stationary or structured settings. In addition, the intuitive use of voice-based support eliminates the need for extensive training to prepare workers, therefore increasing its feasibility for implementation.

The first value of using voice assistants in construction is their expected safe interaction with the user, providing information in a non-disruptive way. Secondly, due to the familiarity of the user, i.e. workers, with interacting with voice assistants such as Alexa, Siri, etc. in their daily life, the proposed approach is envisioned to require less training compared to other interventions, thus broadening its future use. However, we acknowledge that implementation of voice assistants for construction can have varying degrees of complexity depending on the purpose defined for the system.

This study aimed to evaluate the extent of the benefits of using voice-based information retrieval in construction for a specific purpose and target user. The developed voice app in this study is simple in functionality. The development process is simple, and the amount of time for developing an app like the one developed in this article can be estimated at 20 to 30 hours of work. Once developed, more functionalities can be easily added to broaden the functionality, as the targeted application requires. In our ongoing work, we plan to explore more complex developments of voice apps for construction.

3.7 Limitations

The usability study was conducted involving engineering students as participants to evaluate the developed prototype system in a lab setting. The lab was selected in a way to represent construction dynamics. The authors plan to evaluate the system in a real construction environment in future work. VIVA as a support system, at its current state, has some limitations. First, it does not have additional sensors to perceive the context of a user's status or task. Therefore, the interaction developed asked participants to add the necessary context to the questions to help VIVA provide

a more accurate response. The limitation of VIVA's Google Actions backend platform in terms of efficiency of using wake phrases and repeating commands is also another area of future work.

3.8 Conclusions and Future Work

The AEC industry productivity is dissatisfactory. Construction worker productivity has a direct impact on project productivity and has great potential for improvements to address the productivity demands of the industry. Therefore, methodologies that support their productivity significantly contribute to the AEC industry improvements. Multiple methods have been researched for supporting construction workers. In this study, a voice-based worker support system, VIVA, was developed and evaluated for its effectiveness in supporting worker productivity.

A prototype of VIVA was developed for a specialty construction trade, steelwork, and was evaluated through a usability study. Participants of the user study completed a set of assembly tasks pertaining to the activities performed by steel workers in construction projects. The research methodology results found significant performance improvements in terms of reducing the amount of time needed to complete the assembly tasks, without causing more errors. VIVA was also able to provide consistent and understandable instructions to the user, minimizing the need to ask for supervisor intervention. No significant impact on perceived workload was found when comparing VIVA and the baseline, which indicates the technological intervention is not imposing more workload on the workers. Overall, the findings in this study contribute to paving the way for using voice-based systems in the AEC industry. Voice-based support is particularly effective as it is intuitive and is inherently embedded in everyday life, and thus, minimizes the amount of training needed for its proper use.

Importantly, this study explores the development of voice-based support systems based on IoT platforms. Highlights include interoperability challenges that exist to coordinate AEC sources and IoT platforms. Future work will continue developing a system prototype that automatically retrieves semantic knowledge from AEC sources, e.g., BIM, to provide support to construction workers. Future work will also take a more comprehensive look at workload and other workload assessment approaches, e.g., objective measures such as electroencephalogram (EEG) sensors, or Eye Tracking, will be explored.

Construction workers are expected to be the most benefited stakeholders of VIVA, given the provided potential improvements in knowledge transfer and understanding, safety, and task

support. Other stakeholders that benefited from a system such as VIVA include supervisors and foremen who can have the opportunity to manage a larger number of workers and use VIVA as a primary supervision system instead of being the direct contact with the workers.

CHAPTER 4. DEVELOPMENT OF A REAL-TIME VOICE-BASED INTELLIGENT VIRTUAL AGENTS (VIVA) BASED ON SYSTEMS INTEGRATION TO SUPPORT CONSTRUCTION WORKER PRODUCTIVITY

4.1 Abstract

The Architecture, Engineering, and Construction (AEC) industry in the United States faces increasing labor shortages while accumulating downward productivity trends. Previous research efforts have identified that prompt Information Extraction (IE) from BIM sources could support construction workers and increase their productivity. As a result, IE methodologies have been proposed and developed using Natural Language Understanding (NLU) methodologies that enable conversational solutions. However, research in IE has focused developing NLU algorithms for IE from the construction domain but not enable voice conversation linked to BIM sources. This study aims to develop a Voice-Based Intelligent Virtual Agent (VIVA) system to provide workers with prompt information on-demand, using voice-based communication. VIVA integrates construction sources with web platforms to enable real-time connection between the users, workers in this case, and BIM platforms. The scope of VIVA is presented through two example application case studies. Results indicate that the BIM-VIVA link and underlying NLU algorithms in the Google Actions platform provided good understanding of phrases understanding. With a performance of 97.50% of correct responses in the Interoperability and NLU test, VIVA is superior to previous research works based on NLU algorithms with text-based queries. Results also shows that similar to other voice agents, VIVA's Spoken Instructions Recognition and Matching test results vary for native and non-native English speakers. In sum, VIVA provides a novel alternative support system for construction workers while also providing an innovative seamless integration between BIM and web platforms for conversational IE from BIM databases.

4.2 Introduction

The Architectural, Engineering, and Construction (AEC) industry faces a continuous downward trend in productivity in the last decades compared to other industries (Neve et al. 2020). Additionally, Covid-19 pandemic's impact on labor shortages and difficulties in the supply chain of materials and components, exacerbated the industry's productivity challenge (King et al. 2022). In light of identifying factors that impact, and can significantly improve industry productivity, construction worker productivity was identified in the previous works to be of critical importance

(Neve et al. 2020). Because of this, methodologies that positively affects the productivity of construction workers are of great benefit to the AEC industry productivity improvements.

As a solution to this issue, enabling access to knowledge from Building Information Modeling (BIM) sources for construction workers to support their productivity is an area of interest (Wang and Meng 2019; Yeh et al. 2012). As a result, multiple methodologies to better use the knowledge contained in BIM sources have been presented previously, e.g. (Fan et al. 2015; Pan and Zhang 2021; Wang et al. 2022). However, due to the dynamic and hazardous nature of construction work, the means to provide knowledge from BIM sources should be carefully designed to ensure they are supportive and not disruptive (Ahmed and Kassem 2018; Calvetti et al. 2020). Because of this, different studies explore means to access BIM information for multiple circumstances and stakeholders to what is referred to as Information Extraction (IE) from BIM. IE from BIM to construction stakeholders has been done based on text queries and responses (Fan et al. 2015; Lin et al. 2016), visualizations obtained by IE from BIM (Alsafouri and Ayer 2019; Linares-Garcia et al. 2022; Yeh et al. 2012), and voice interaction (Anumba et al. 2020; Li et al. 2018; Shin and Issa Raja 2021). However, addressing conversational systems towards construction applications is challenged by the dynamicity of construction environments and the physical limitations of construction worker during their activities, e.g., visual distractions, workers using both of their hands. Nevertheless, the nascent stage of research developments on conversational systems, either text-based or voice-based, shed light on challenges on algorithm development (Fan et al. 2015; Wang et al. 2021), human factors involved (Rahimi Movassagh et al. 2021), and interoperability with construction systems (Park et al. 2013).

Voice interaction, is a nascent area of research for Information Extraction (IE) in the AEC industry, and seems to have great potential for IE from BIM through Natural Language Understanding (NLU). Most of the solutions developed have sought to enable the conversational capabilities of proposed systems through Natural Language Processing (NLP) developed from algorithms or interoperable NLP platforms. In this area, researchers focus not only on IE from BIM data sources but also on matching IE queries from users to provide a specific and concise answer to their questions, enabling conversational interaction based on IE, e.g., (Alexakis et al. 2019; Lin et al. 2016; Shin and Issa Raja 2021; Wang et al. 2022; Wang et al. 2022; Zhou et al. 2018). An approach used to link cyber and physical elements is named Cyber-Physical Systems (CPS). Previous research developments in conversational agents are considered to use a CPS approach to link cyber

elements, such as BIM, and physical elements, such as workers, to improve workers' productivity outcomes and overall construction projects. However, developing a real-time link between BIM and workers in the AEC Industry is challenging.

Therefore, this study identifies two main research gaps to consider: first, the development of voice conversational BIM IE systems for construction applications, and second, the development of real-time systems to address a CPS link between BIM and construction workers. Therefore, this study addresses these gaps by developing a Voice-based Intelligent Virtual Agent (VIVA) system that enables real-time BIM IE and provides bi-directional conversational interaction with the user, i.e., workers. In other words, VIVA enables workers to retrieve updated information from BIM databases in real-time through voice-based interaction, making the information extraction process on-demand and safe for workers, thus improving their productivity. These characteristics included in VIVA allows it to be friendly to use by users and data managers on the field. Furthermore, VIVA is based on BIM-web interoperability and uses conventionally available devices, such as smart speakers and web platforms, for rapid deployment and scalability. From the multiple BIM sources, the interoperability with the most popular software solution, Autodesk Revit, was selected to be connected in real-time with VIVA to provide geometric information for construction worker support. Web interoperability in VIVA is enabled through the Google Actions web platform for conversational systems for general purposes. Finally, potential use cases of VIVA are presented through two case studies of varying degrees of complexity and set the basis for future applications of VIVA.

4.3 Background

4.3.1 Cyber-Physical Systems (CPS) in the AEC Industry

Cyber-Physical Systems (CPS) is a promising approach that aims to holistically integrate technological advances with current standard practices (Rüßmann et al. 2015) to support efforts that improve productivity actively, given their smartness, bi-directionality, and connectedness (Klötzer et al. 2017). CPS bidirectionally connects physical and digital assets to achieve automated processes such as optimization, monitoring, and Knowledge Management (KM). Multiple efforts have been undertaken to solve the AEC industry challenges through a CPS-based approach, including monitoring equipment operations (Kan et al. 2017; Kan et al. 2018), object recognition of construction project elements (Srewil and Scherer 2017), progress monitoring (Omar et al.

2018), safety (Li and Leung 2020; Wang and Razavi 2019), and worker ergonomics (Akanmu and Olayiwola 2019). However, overall industry productivity has not improved significantly, suggesting that monitoring is insufficient to improve productivity, and more proactive means are needed.

Research also suggests that establishing an interoperability link between cyber and physical resources within CPS, and web platforms, has been more emphasized in developing the physical-to-cyber direction (Puri and Turkan 2018; Son et al. 2017; Turkan et al. 2013). However, previous research works have neglected the cyber-to-physical direction of CPS systems. Industry solutions are on the same page and focus on monitoring the physical-to-cyber direction of CPS (Ozturk and Yitmen 2019; Wang and Meng 2019). Such examples include monitoring solutions such as Reconstruct® and Knowledge Management Systems such as Autodesk® solutions. These solutions help define productivity boundaries, thresholds, issues, and gains; however, they neglect the cyber-to-physical direction (i.e., conveying knowledge from digital sources to the respective physical resources), creating a gap in digital construction management practices and leaving incomplete automated solutions. Therefore, providing solutions that also address the cyber-to-physical direction in CPS can enable important feedback to physical stakeholders, potentially enhancing productivity outcomes.

Based on the literature, a unified cyber-to-physical development solution within the context of CPS is not well established in the current research efforts in academia and industry. However, there are a few examples of complete approaches, including the work by Kan et al. (2018), which aims to support the productivity of crane operations actively; Teizer et al. (2017), that developed a localization and planning bi-directional system for construction workers; and Moreira et al. (2021) that developed a prototype for workers to navigate the field and be warned about health and safety hazards on the field. As a result, fully automated CPS-based solutions with special consideration of the cyber-to-physical aspects of CPS are needed to benefit from the full potential and benefits of CPS. On the other hand, the CPS-based approach introduces challenges associated with the interoperability among different components, platforms, and subsystems that already exist (Muñoz-La Rivera et al. 2020).

Therefore, this study explores and develops VIVA, as a solution that emphasizes a holistic CPS approach, including the cyber-to-physical aspect, to address the specific application of worker

productivity support. Figure 4.1 presents VIVA’s information flow and the bidirectionality of the proposed CPS-based approach. The remainder of the article provides an in-depth review of the interoperability challenges of connecting cyber and physical resources and implementing the proposed BIM-Web Voice-Based system, VIVA.

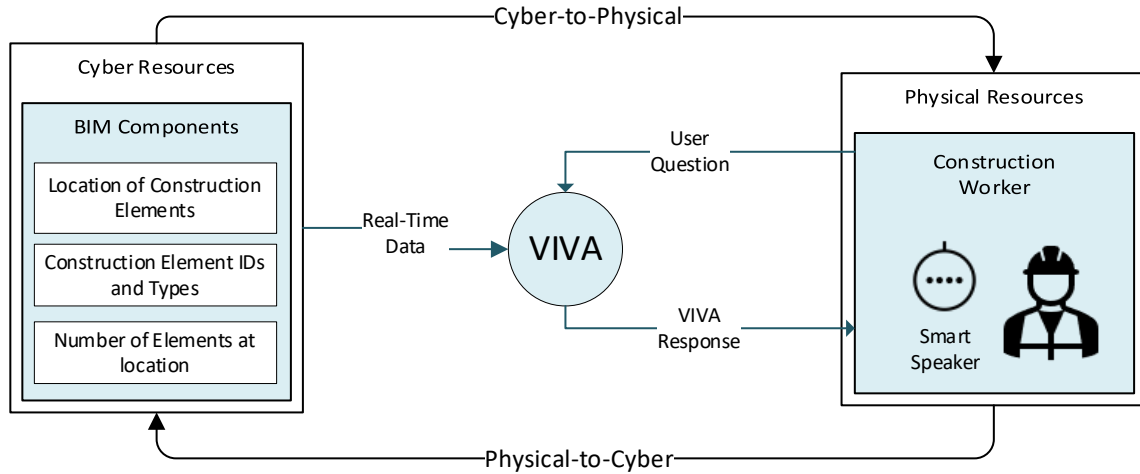


Figure 4.1. Context of Application of VIVA within CPS in the AEC Industry

4.3.2 BIM-Web Interoperability

BIM has become an important tool for digitalizing information about construction projects. However, BIM interoperability with other systems has been a second thought. To address that, interoperability solutions have been developed in academia and industry alike to integrate BIM with other platforms and systems towards addressing industry challenges. System interoperability is about identifying the tools to connect different systems and make these systems work together to accomplish a specific goal. In the era of web-connected apps and devices, interoperability with the web is in greater demand. Therefore, methodologies have been explored and developed to connect systems, devices, and platforms. In this direction, web services have provided the missing link between domain-specific construction systems and devices that do not natively possess web access. In the AEC industry, interoperability between BIM as the leading digitalization platform and web-based platforms, as the enabler for web access, has been thoroughly explored to propose solutions to industry problems. As such, BIM-Web interoperability is an enabler for CPS’s bi-directional information exchange for a wide range of applications.

Researchers proposed multiple BIM-Web interoperability solutions for specific applications. Shahinmoghdam and Motamedi (2021) provided a method to connect sensors to monitor occupants' comfort using web ontologies to connect local data sensors and web data to update BIM databases. Li et al. (2019) used a similar approach to connecting sensors for geospatial information through web services. Moreira et al. (2021) used web services and BIM to warn workers about environmental hazards on site, while Valinejadshoubi et al. (2021) used BIM-web service system interoperability to warn users about ambient conditions based on temperature sensors. Others connected IFC 3D models and added real-time sensor data with relational databases to feed into a web front-end and APIs (Chen et al. 2021; Dave et al. 2018; Han et al. 2022; Li et al. 2018). Park and Cho (2018) developed an asset tracking system for safety inspections based on mobile apps, while Li et al. (2018) developed a tracking system for prefabricated elements and operations. For facility management, multiple researchers have explored BIM-web interoperability for building automation, monitoring, and occupants' comfort (Dave et al. 2018; Shahinmoghdam and Motamedi 2021; Valinejadshoubi et al. 2021). And even for training support during emergencies, such as fires (Chen et al. 2021). This variety of methodologies highlights the lack of a unified interoperability approach for BIM-Web connection, leading to application-based tools that work for specific solutions.

In light of these challenges associated with interoperability, Tang et al. (2019) reviewed and summarized the approaches for interconnected BIM and sensors methodologies from the literature. They focused on the interoperability between sensors and BIM databases while summarizing their findings on five interoperability alternatives for BIM-IoT. The approaches proposed in their article include using BIM APIs, relational databases, custom-built API tools, Structural Query Languages (SQL), using current data schemas, creating new data schemas, web, open standards (e.g., IFC), and others. However, this work is limited to communications with sensors and does not consider web interoperability between platforms for human-computer interaction such as web front ends or mobile apps.

Other researchers have suggested that BIM formats that respond to web-connected APIs need to be established to ease the process of connecting BIM and Web platforms. In this direction, Afsari et al. (2017) reviewed methodologies for collaboration with BIM data and cloud services. They proposed an ifcJSON schema to serialize data (i.e., data conversion for making transmission to other systems more straightforward) from BIM to web sources more seamlessly with cloud-based

applications. These efforts suggest that web-connected systems for the AEC industry are an area of current research interest, and interoperability is an issue.

The previous works show how BIM-Web interoperability is an obstacle and study this latent problem by proposing different levels of interoperability solutions. This article aims to add to the current approaches by providing an innovative BIM-web interoperability solution that connects data from BIM data sources to web-connected devices in real-time and enables on-demand human-system interaction. The proposed approach differentiates from previous works given the specific modality for exchange to be voice-based and add humans to the interoperable problem loop. By using web platforms to understand users' questions and provide spoken instructions to the user, VIVA can fulfill this objective of connecting BIM and workers in real-time through a voice modality.

4.3.3 BIM and Natural Language Processing (NLP) Systems

The research literature about CPS, BIM and Natural Language Processing (NLP) systems suggests two primary approaches for developing voice-based systems, such as VIVA. These approaches are domain-specific NLP algorithmic approaches and domain-specific NLP interoperable systems.

The first approach develops algorithms from the ground up based on Information Extraction (IE), and NLP applied to domain-specific knowledge. Figure 4.2 presents a schematic diagram of this approach. This approach is being explored by previous research to develop systems for IE from BIM sources through developing conversational solutions (Lin et al. 2016; Wang et al. 2022; Wang et al. 2021; Wang et al. 2022). These previous works focused on developing the underlying algorithms that recognize knowledge intents from user's queries and matching that with information in BIM databases to extract the detected knowledge and respond to the queries as shown for the custom-made processing algorithm in Figure 4.2. These algorithm have been usually is a single system element with multiple processes that needs to be custom-made by the developer. The validation of research work in this direction has provided consistent results for information queries at varying levels of complexity. However, research outcomes in this area have mostly provided text-based agent solutions for users' interaction without providing a voice-based interaction. These applications primarily focused on extracting information from construction project documents and BIM databases (Lin et al. 2016; Wang et al. 2022).

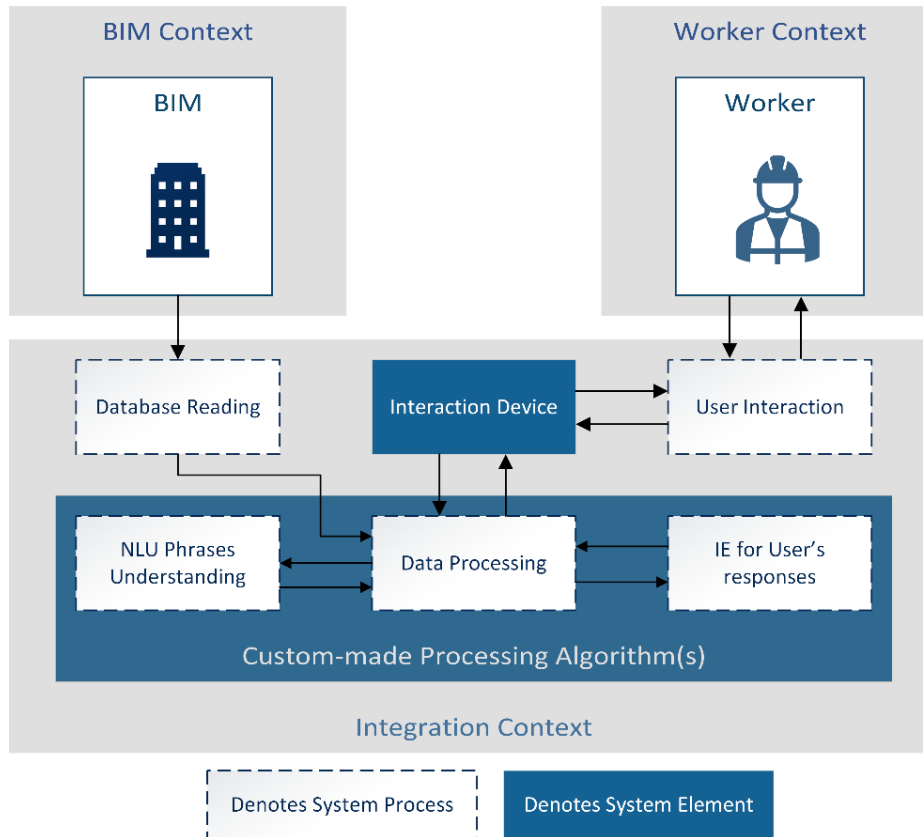


Figure 4.2. BIM IE based on NLP algorithm development

The other approach for BIM-IE systems is based on systems interoperability as presented in Figure 4.3. Research works with this approach used various interoperable tools and processes between different systems to enable solutions that provide conversational interaction with the user. In this approach, the interoperable processes integrate multiple system elements that shared data as needed to ultimately provide an interaction outcome, see Figure 4.3. Research works in this area mainly focus on home automation and energy management in buildings (Alexakis et al. 2019; He and Jazizadeh). Other few research works explored the use of BIM to extract information (IE) from construction projects data sources. For example, research by Shin and Issa Raja (2021) used user queries to make changes to a BIM project. This study uses a combination of visual scripting, text-to-speech APIs, SQL databases, and relational databases to extract information from users' queries and change parameters in a BIM project. The result of this project is not a conversational interaction but enables the user to command actions to the system to change BIM parameters.

VIVA follows the second BIM-IE approach, i.e., systems based on the interoperability of a BIM project and the Google Actions platform to enable Information Extraction for conversational

interaction with the user. VIVA interoperability is enabled based on a web-based platform that uses the embedded NLP algorithms in the Google Actions API and provides access to interact with the users through devices, such as smart speakers or headphones, that have access to this platform. This allows VIVA web-based system to be deployable broadly on a variety of devices that can use this platform, such as smart speakers, smart screens, headphones, smartphones, tablets, and web applications.

The literature review suggests that there is a need for solutions that better support worker productivity through providing ad-hoc knowledge to them while at work. This study developed a voice-based conversational system, VIVA, as a solution to support workers in accessing knowledge from BIM sources while doing their work activities. Its development is based on integrating different tools, including BIM software, intermediate web databases, and processing and interactions through a web platform. This integration approach is simpler than developing specific NLU algorithms for phrase understanding in other voice-based system approaches. VIVA takes a user-centric approach to provide users with access to project information they need, when needed, using safe voice interactions. The functionality of the proposed system and developed app are presented and then evaluated through two case studies.

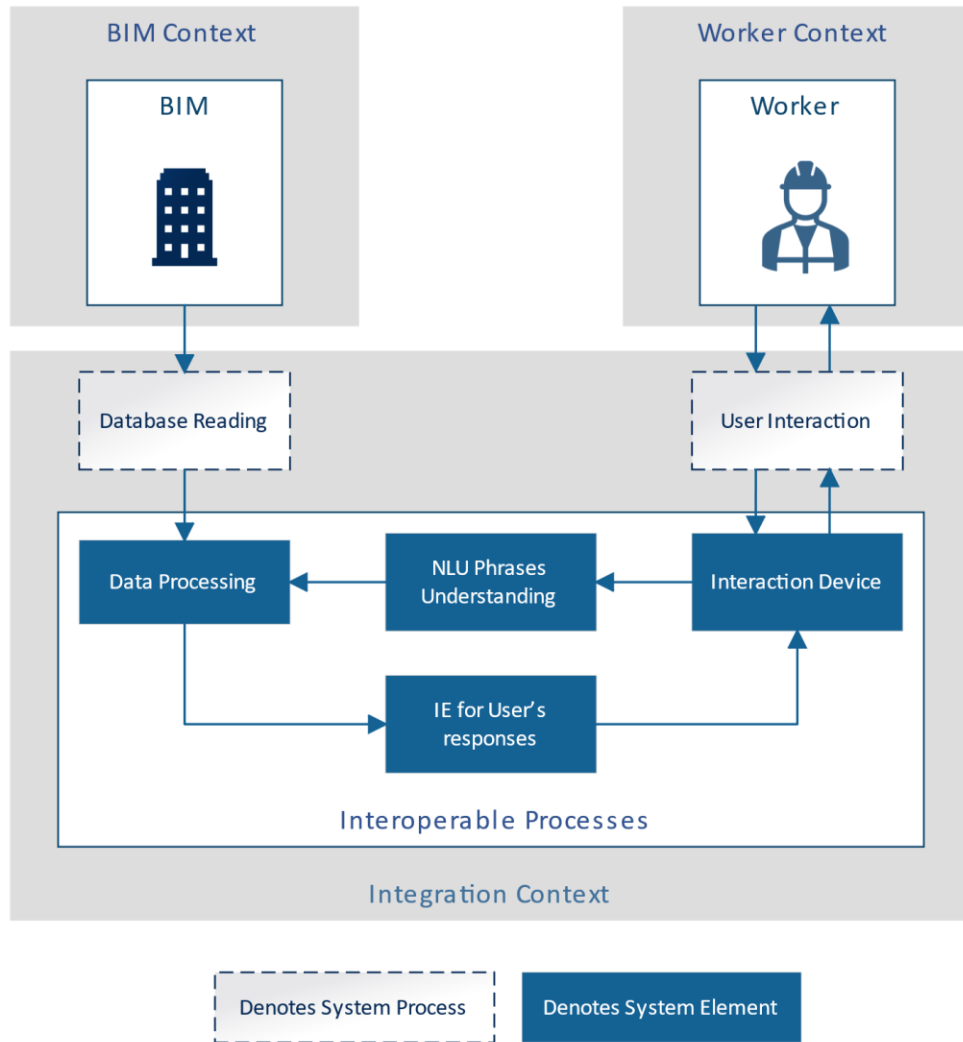


Figure 4.3. BIM IE based on Systems Interoperability

4.4 Research Methodology

This section presents the research steps taken to develop VIVA. First, two specific case studies are identified. Then, this study provides the details of the development of VIVA's interoperability framework, elaborating on the specifics of implementation processes. Data flows through the system components and details the different stages of the data analysis during the interoperability processes are then explained and the details of system interactions with the targeted two groups of users defined for each case study are elaborated. Finally, evaluation, conclusions, and future work are provided.

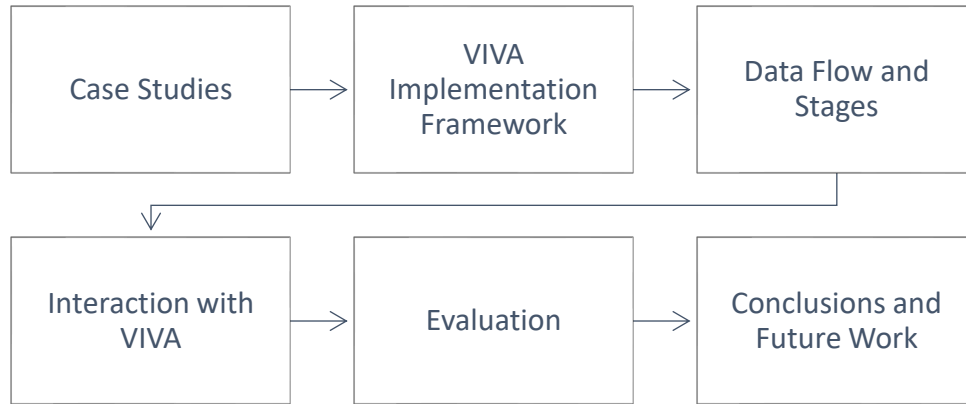


Figure 4.4. Research Methodology Diagram

4.5 Case Studies

Two case studies are presented to focus on the development of VIVA and present its possible applications. These case studies illustrate using VIVA within a specific context to support the targeted users' productivity by providing assistive tips in completing their activities.

4.5.1 Case Study 1: *Specify the installation location of objects during crane operations*

During crane operations, crane operator needs to know where construction elements will be needed for transportation with the crane. Crane operations are a team effort, and crane operators work in tandem with the on-site crew to move construction elements needed from the site storage. VIVA, in this context, helps the crane operations team by providing instructions on where a specific construction element needs to be transported on the site. Typically, construction elements have unique IDs assigned in the shop drawings, written in some parts of the element. Considering that these unique IDs are linked to unique IDs in the BIM model, VIVA helps retrieve the installation location of each element from the BIM model, upon request from the operation team. The voice-based information retrieval provided from BIM models through VIVA is more efficient than checking the blueprints to retrieve this information, and can significantly reduce the operation time.

4.5.2 Case Study 2: *Identifying the number of construction elements at a specific location*

Installation of building elements such as windows, doors, furniture, or equipment involves procuring, transporting to the site, and installing the elements at specific locations in the project. It is also known that these elements may have shared types. For example, two different doors may

have the exact dimensions, materials, and finishes for what a specific door type is defined that is common to both of them. In these scenarios, workers need to know how many elements of a specific type are needed at a specific place in the project for transportation logistics. Within this context, VIVA can help the workers with providing the number of project elements of a specific type that are needed at a specific building location based on the BIM model.

4.6 VIVA Implementation Framework

The VIVA system's implementation aims to provide an expandable productivity support framework that facilitate the development of voice-based systems for construction stakeholders, thus, enabling widespread use of voice-based systems in the AEC industry. Figure 4.5 presents the diagram for the implementation of VIVA's real-time interoperability schema. VIVA is focused on connecting BIM data sources to the Google Actions' web platform, to enable real-time user voice interaction. The most significant benefit of a real-time feature of VIVA is users always have access and can interact with the most updated data in BIM sources. Creating the real-time link between BIM data sources and the system voice interaction was implemented through developing system hubs in the proposed VIVA system, as shown in Figure 4.5 and further explained in this section.

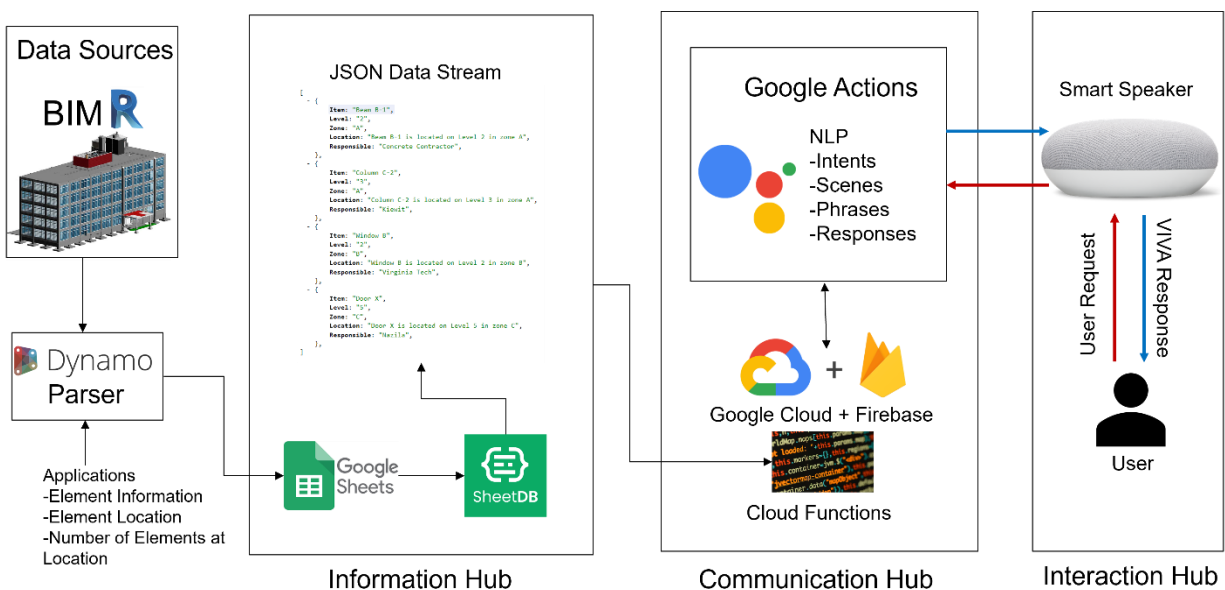


Figure 4.5. System Implementation Diagram

4.6.1 Development Setup

The development of VIVA was conducted through visual scripting, web interfaces, and web programming. Visual Scripts were developed in Dynamo v2.12 for Revit 2022. Web development was done in the Google Actions Console platform in a Google Chrome Browser in Windows 11. Web programming was done for the Cloud functions within the Google Actions Console. Google Cloud functions were written in JavaScript libraries. JavaScript code was written and debugged in IntelliJ WebStorm v2022.1. A single developer account was used to access the Google services and platforms.



Figure 4.6. 3D Model used to develop and evaluate VIVA

4.6.2 Data Sources

Construction workers have information needs from multiple BIM data sources, including 3D models, schedule, supply chain, etc. The development of the links between the information received by construction workers and each of these data sources require individual developments that is beyond the scope of this article. This article focuses on the implementation of a real-time link between 3D models and users through voice-based conversational interaction. As a result, a BIM data source driven from Revit model of a construction project was used to develop the real-time VIVA prototype. 3D models were considered here as the main BIM data source due to their priority when accessing project information required for conducting tasks by workers and management personnel. A single Revit Model was used for the development and evaluation of VIVA. The model used was the 3D Model of Bishop-Favrao Hall, the main building of the Myers-

Lawson School of Construction at Virginia Tech (27.2 MB). This model is a 4-story building, with total area of approximately 29,000 square feet. See Figure 4.7.

4.6.3 BIM Parser

A parser is a tool that transfers data from one format to another. The parser in VIVA was developed using Dynamo script that reads data from the 3D Model and sends it directly to an online Google Spreadsheet. The parser in VIVA takes all the information contained in a specific Revit schedule and transfers it to the Google Spreadsheet as a table. Information in this source schedule are general and include all the possible information that will be needed for the application's features. For example, for the specific case studies in this article, VIVA parses the following information:

- For case study 1: The developed user application is to identify the location of the construction element to be installed in the project. The parser for this application included information about the site zone and level of the element's installation location. The level was taken from the default Element Level parameter, while the zone was manually added to the 3D model element parameters. See the zone diagram in Figure 4.7. The zone parameter was added manually in the 3D model.
- For case study 2: The developed user application is to identify the number of construction elements to be installed in a specific project location. The parser for the application includes Element type, level, and zone.

A single schedule was created that had the mentioned parameters and other more general parameters for both VIVA applications used in this study. The script then parsed all these parameters for each case study.

4.6.4 Information Hub

The information hub in VIVA serves as the repository for BIM data storage. It consists of two primary intermediate databases: first, the Google Sheet is used to output data from the Dynamo parser, and the second, data from the Google Sheet is streamed to a JSON data stream updated in real-time. SheetDB is the service used in VIVA for the streaming of JSON data. The outcome of the JSON data stream is a web stream of information as contained in the Google Spreadsheet in JSON web format. The streamed data is available in real-time through a specific web address

publicly available. This data is shown in Table 4.1d in a web browser that has a JSON visualizer to show JSON data in a more organized format.

4.6.5 Communication Hub

VIVA's communication hub is based on multiple Google cloud services to read the data stream, process the NLP speech recognition, and enable spoken responses through a web-connected device. Google Actions platform is used as the central platform. It is a web platform that processes users' responses and identifies users' intents while processing responses to the user and enabling user interaction. To access the data stream and identify multiple parameters from user's responses for answers development, Google Cloud functions were used through the Google Actions webhook. A webhook in the Google Actions is an added functionality enabled through cloud functions that run through web services. Webhooks are the front-end of google cloud functions that allow the development of functions to enable data manipulation and establishing logical and methodological relationships between users' responses and provided answers. Responses from VIVA are provided in conversational mode to provide an easy-to-understand answer to the user.

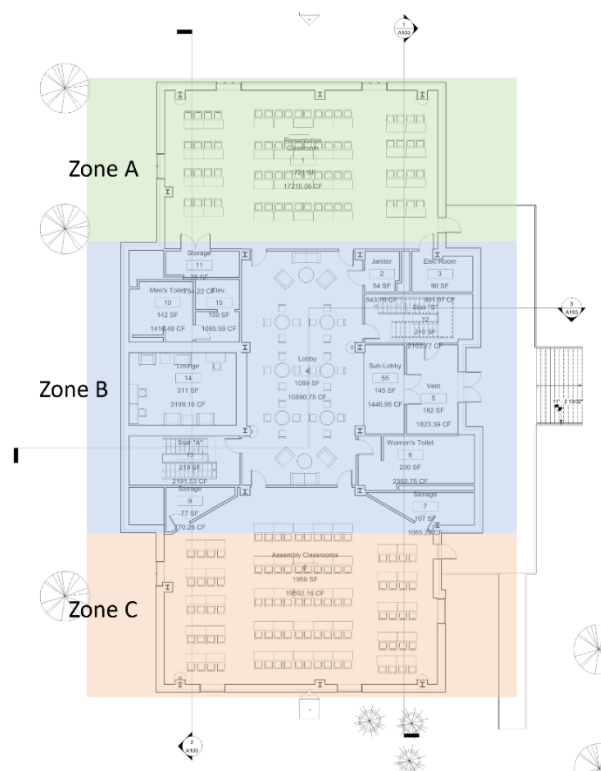


Figure 4.7. BIM Model Zones Diagram

4.6.6 Interaction Hub

Finally, the interaction hub is the physical interaction device between the user and the system. The developed prototype of VIVA uses a Smart Speaker for user interaction. A Google Nest Mini device was used in this study for VIVA interaction with users. However, the interaction hub can be enabled with any device that can access the Google Actions platform, including headphones, Smart Screens, Smartphones, Tablets, and PCs. The device for interaction in VIVA is an internet-connected device that listens to the users' queries. These queries are then sent to the communication hub for processing in the Google Actions platform. The response is created using the NLP algorithm and is transferred back to the interaction device and spoken to the user.

4.7 Data Flow and Stages

The interoperability of VIVA is enabled through the transformation of the source data to the spoken responses through VIVA's processing hubs. As a result, data is transformed and analyzed in multiple stages, as shown in Table 4.1, which shows the data flow for two example elements in VIVA, i.e., a door and a structural steel column, as follows:

- First, project data is aggregated into a Revit model. In this first data stage, the data from all the elements in the project is aggregated into a single model file and interactive through the Revit software. Table 4.1a shows the example elements at this data stage, showing their properties in the Revit interface as selected as 3D objects.
- In this data stage, data can also be visualized as schedules in the Revit interface. Table 4.1b shows the example elements as shown in the Revit schedules.
- Any changes made to the project should be completed in the Revit interface to continue to the following data transformation steps. Then, the following data exchange has been facilitated by VIVA as an Addin has been created for Revit to send the current state of the Revit database to VIVA. This Revit Addin update button is shown in Figure 4.8.
- When the VIVA update button is clicked in the interface, the BIM parser runs in the background and converts the Revit data to a schedule that is then transferred to an online google spreadsheet, an intermediate database. More details about the BIM parser are further detailed in section 4.6.3. Our examples elements, door and column, are shown in this data stage in Table 4.1c as selected. However, the database used for testing contained thousands of objects, so Table 4.1c only shows a small portion of the intermediate database

to increase the reader's understanding. At this point, data is now in the information hub. See section 4.6.4.

- Still, in the information hub, a separate data streaming service (SheetDB) was configured to read the google spreadsheet content automatically and then stream this information to a web JSON data stream. This specific data stream has a unique web address that is publicly accessible (read-only) by any human or machine. Data at this stage can be seen in Table 4.1d for the two example elements.
- Then, the communication hub takes control of the JSON data stream. The Google Actions platform entirely enables the communication hub. Reading the JSON data stream was done using the Axios JavaScript API to read the specific JSON stream based on its unique URL of it.
- In the communication hub, and using the Google Actions platform, a cloud function in JavaScript was developed to read the JSON data stream and save the data stream in a single variable for processing. The data stage at this point can be seen in Table 4.1e for the example elements as shown in the Google Actions console log.
- The Google Actions app was set with variables to match expected user keywords in the communication hub. Variables included element IDs, name, level, and zone for case 1. More variables were added for case 2, such as Element Type. For example, for the level variable, the Google Actions app had a variable for level that included variants such as floor or story.
- Still in the communication hub, cloud functions in JavaScript were created to retrieve the user's keywords and match them to items in the data variable that contains the data streams at this point. Additional cloud functions do the matching of data items in the Google Actions app.
- The cloud functions enable data matching and responses depending on the case enabled in the app. In other words, the cloud function for case study 1 does the matching as needed for that case study but also provides the syntax for the responses to be provided to the user. Table 4.1f shows VIVA's responses for the example elements for case 1, while Table 4.1g shows VIVA's response for the example element for case 2. These responses are presented in Table 4.1 as text, but this will be spoken to the user in the last data stage. Also important to mention is that there is no response for case study 2 for the column because there is no

shared type for the columns. This is due to steel elements usually only have unique IDs instead of element types in construction projects.

- As the last step, now in the interaction hub, a smart speaker will read aloud VIVA's responses, as shown in Table 4.1f and Table 4.1g.

4.8 Interaction with VIVA

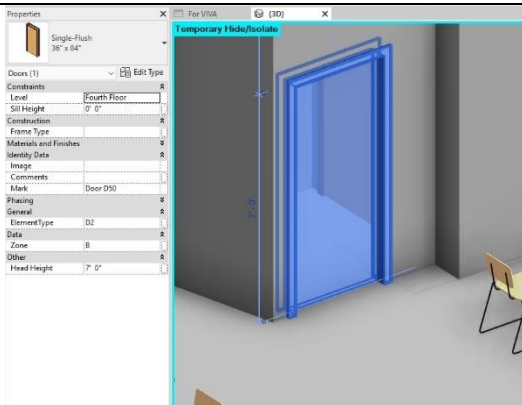
VIVA aims to support construction stakeholders' operations through voice interaction that gives them access to information available in the construction project digital sources. VIVA will interact with two types of users: The main user of VIVA is the on-site user who interacts directly with VIVA through the smart speaker or other device connected to the VIVA app. the second group are expected to be the office users that interacts with the BIM database and make changes to the project. As such, VIVA is designed to provide a unified middleware for both on-site and office crew to connect to and send and receive information.

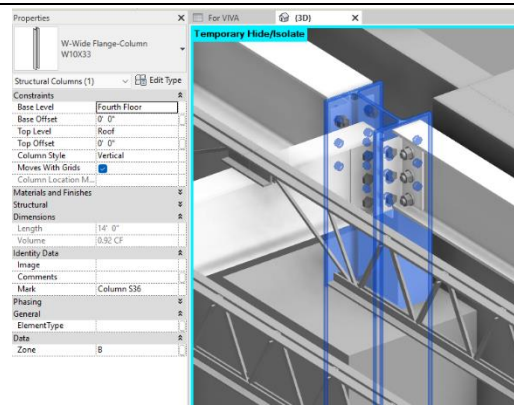
4.8.1 On-site User Interaction

VIVA provides a dynamic bidirectional interactions on-site user and BIM sources through voice conversation. The user accesses the VIVA app in the Google Actions platform by talking to the VIVA device, e.g. cellphone or in-ear headsets, and saying the following key phrase: "*Hey Google, talk to Connector.*" The "Hey Google" phrase activates the device and gives the user access to the Google Action platform. The second phrase, "*Talk to Connector*" is to call the VIVA app within the Google Actions platform. VIVA's welcome message was: "*This app helps you get information about elements in the construction project. What do you want to know about project elements?*". The user can then ask a question through the app, VIVA seeks for an answer in the updated information hub repository and provides an appropriate response. Examples of responses are shown in parts Table 4.1f and Table 4.1g.

Table 4.1. Example of Data Flow and Stages for two BIM Objects

a) Data Element in BIM Model



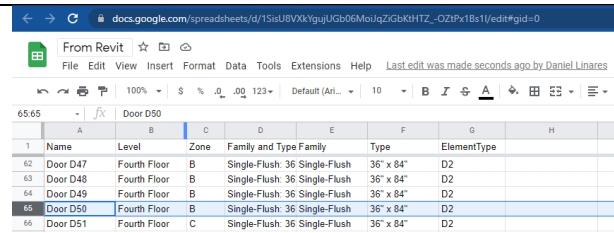


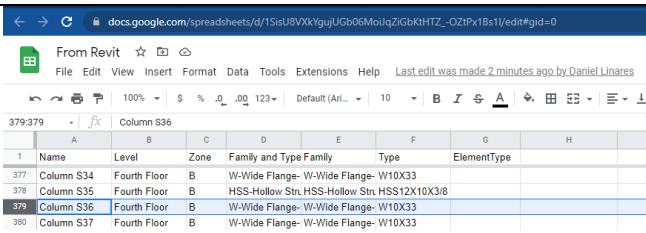
b) Data Element in BIM Schedule

Name	Level	Zone	Family and Type	Family	Type	ElementType
Door D48	Fourth Floor	B	Single-Flush: 36" x 84"	Single-Flush	36" x 84"	D2
Door D49	Fourth Floor	B	Single-Flush: 36" x 84"	Single-Flush	36" x 84"	D2
Door D50	Fourth Floor	B	Single-Flush: 36" x 84"	Single-Flush	36" x 84"	D2
Door D51	Fourth Floor	C	Single-Flush: 36" x 84"	Single-Flush	36" x 84"	D2

Name	Level	Zone	Family and Type	Family	Type	ElementType
Column S34	Fourth Floor	B	W-Wide Flange-Column	W-Wide Flange-Col	W10X33	
Column S35	Fourth Floor	B	HSS-Hollow Structural	HSS-Hollow Struct	HSS12X10X3/8	
Column S36	Fourth Floor	B	W-Wide Flange-Column	W-Wide Flange-Col	W10X33	
Column S37	Fourth Floor	B	W-Wide Flange-Column	W-Wide Flange-Col	W10X33	

c) Data Element in Online Google Spreadsheet





d) Data Element in JSON Data Stream

```
563 {
564   "Name": "Door D50",
565   "Level": "Fourth Floor",
566   "Zone": "B",
567   "Family and Type": "Single-Flush: 36\" x 84\"",
568   "Family": "Single-Flush",
569   "Type": "36\" x 84\"",
570   "ElementType": "D2"
571 },
```

```
3389 {
3390   "Name": "Column S36",
3391   "Level": "Fourth Floor",
3392   "Zone": "B",
3393   "Family and Type": "W-Wide Flange-Column: W10X33",
3394   "Family": "W-Wide Flange-Column",
3395   "Type": "W10X33",
3396   "ElementType": ""
3397 },
```

e) Data Element in Google Cloud Function

```
11:24:16.834 PM cf-Cfoc5NyDifwgPXZFNyq1zA-name
{
  Name: 'Door D50',
  Level: 'Fourth Floor',
  Zone: 'B',
  'Family and Type': 'Single-Flush: 36\" x 84\"',
  Family: 'Single-Flush',
  Type: '36\" x 84\"',
  ElementType: 'D2' }
```

```
11:28:20.441 PM cf-A8bfSnx6368bwp1zHG3W9w-name
{
  Name: 'Column S36',
  Level: 'Fourth Floor',
  Zone: 'B',
  'Family and Type': 'W-Wide Flange-Column: W10X33',
  Family: 'W-Wide Flange-Column',
  Type: 'W10X33',
  ElementType: '' }
```

f) Data Element as Response from the Google Actions to the User for Case Study 1. User question: Where [Element] will be installed?

Spoken phrase: "These are the details for Door D50 of type D2. It will be installed in zone B, at Fourth Floor."

Spoken phrase: "These are the details for Column S36. It will be installed in zone B, at Fourth Floor."

g) Data Element as Response from the Google Actions to the User for Case Study 2. User question: How many [Element Type] of [Element Type ID] will be installed in the [Fourth Floor]?	
Spoken phrase: <i>"There are 13 Doors of type D2 in the Fourth Floor."</i>	Not Applicable because there is no shared types for columns in the model used.

4.8.2 Office User Interaction

Because VIVA is designed to help workers-on-foot with their tasks and support their productivity, the interaction between VIVA and office users, e.g. BIM manager, is minimal. This interaction is mainly designed to ensure any changes made to BIM models are reflected in the answers provided through VIVA and on-site user always have access to the most updated information. To this end, after making any changes to the model, the office user, e.g. BIM manager, can update the data flowing through VIVA hubs by using the designed Revit Add-In plugin. See Figure 4.8. By clicking “update VIVA” plugin, any changes made to the model will be sent to VIVA for processing, and used in the answers provided on-site.

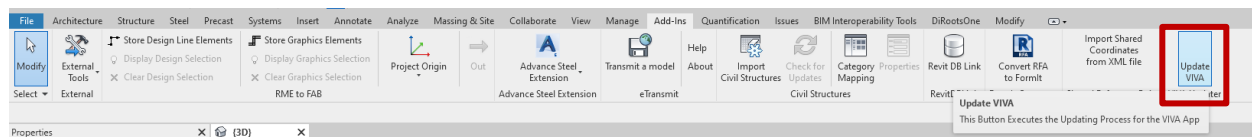


Figure 4.8. Designed Revit Add-in to automatically update the VIVA database

4.9 Evaluation

The performance of VIVA was evaluated using two case studies. The performance was evaluated based on (1) measuring VIVA's Natural Language Understanding performance in providing the correct information from BIM model; and (2) measuring VIVA's performance in understanding spoken instructions and providing accurate responses.

4.9.1 Interoperability and Natural Language Understanding Test

The interoperability and Natural Language Understanding performance of VIVA were evaluated on its ability to provide accurate responses based on the information retrieved from the BIM databases. The methodology for evaluating VIVA was based on repetitive tests calling on VIVA and asking questions for each case study. For this evaluation, VIVA was called from the developer testing platform, using written commands to elicit VIVA responses and not its availability to recognize spoken instructions, which will be done in the second evaluation test. By using text,

VIVA's responses were evaluated based on its interoperability and Natural Language Understanding and correct matching to the database.

To evaluate the first performance metrics, users asked VIVA multiple questions aiming at retrieving information for each case study. In other words, for the evaluation of VIVA for the first case study, the user asked VIVA questions about the installation location of different building elements, and for the second case study, the user made queries about the number of elements of specific element type located at specific locations in the project. For each case study, the user was asked to repeat his query multiple times and developed questions that varied in syntax and vocabulary but rendered the same expected results.

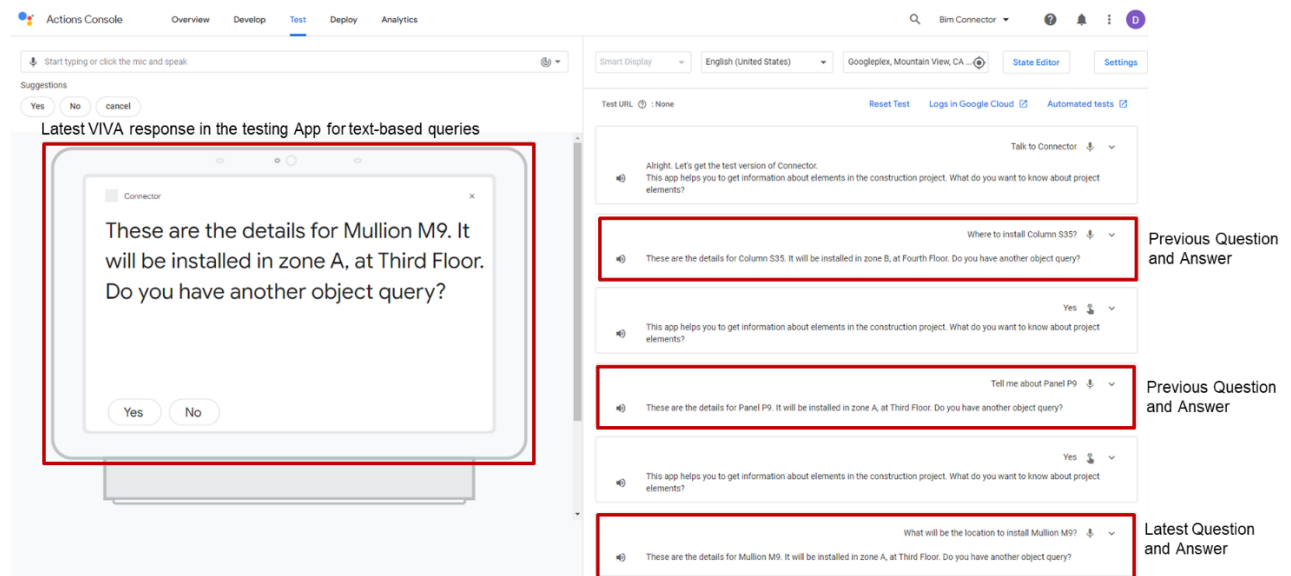


Figure 4.9. Interoperability Test Platform and Execution Example on Case 1

4.9.2 Spoken Instruction Recognition and Matching Test

The Spoken Instruction Recognition and Matching test seeks to evaluate the performance of VIVA in understanding spoken dialogs and providing correct responses. In other words, the Interoperability and Natural Language Understanding test seeks to measure the performance of VIVA in understanding semantic knowledge embedded in user's questions while the 4.9.2 Spoken Instruction Recognition and Matching Test focuses on the performance of VIVA in understanding spoken language and developing phrases based on the information retrieved from BIM databases. Similar to the Interoperability and Natural Language Understanding Test, the users asked about project elements relative to each case study, this time through the smart speaker. For this test, we

asked two different participants to make the tests for both case studies to include feedback from native English speakers and non-native English speakers.

4.9.3 Summary of Evaluation Results

The results of both evaluation tests are summarized in Table 4.2. In sum, the VIVA's interoperability between BIM-Web platforms achieved very high-performance results. However, the NLP performance varies depending on the English proficiency of the user showing better results for English speakers compared to non-English speakers.

Table 4.2. Summary of Evaluation Results for VIVA

Evaluation Test		Case Study 1		Case Study 2		Average Response Rate
		Correct Responses	Incorrect Responses	Correct Responses	Incorrect Responses	
4.9.1 Interoperability and Natural Language Understanding Test		20	0	19	1	97.50%
Spoken Instruction Recognition and Matching Test	Non-Native English Speaker	12	8	11	9	57.50%
	Native English Speaker	16	4	17	3	82.50%

4.10 Discussion

This study develops a voice-based intelligent virtual agent (VIVA) that aims to support on-site workers with their daily tasks through connecting them to BIM databases and enabling on-demand information retrieval. VIVA uses conversational interaction with users, making the provided information easier to understand, and reducing the potential distractions, thus enabling safe interactions. The main objective of VIVA is to provide a voice-based interaction, but the developed system also enables text-based interaction with BIM models. The study's outcomes provide valuable insight into the theories, developments, and assessment of voice-based systems for AEC industry. The previous research on Information Extraction (IE) has focused on developing text-based conversational systems to provide workers access to BIM data. VIVA goes further to provide a practical solution based on spoken interaction with BIM sources empowered by enabling interoperability between BIM models and web platform's NLU algorithms.

VIVA was first evaluated for its Natural Language Understanding (NLU) performance to assess its capability to understand users' questions based on text-based queries and to seek for, and provide accurate responses to the user. The results demonstrated that VIVA's accuracy of 97.50%

of correct answers. This evaluation test is comparable to previous research works by Wang et al. (2022) with an accuracy of 81.9% and by Wang et al. (2022) with an accuracy of 96.8%. Results like this shed light on the strength of the commercial NLU web platforms used for BIM-VIVA link compared to domain-specific algorithm developments in making a correct interpretation of phrases and user queries.

The main objective of this study was to develop voice-based interactions to enable on-demand onsite support for construction worker enabled by VIVA. When VIVA was evaluated based on its voice-based capabilities, the Spoken Instruction Recognition and Matching test, it was found that, similar to other voice assistants, VIVA's spoken language understanding performance varies depending on the VIVA user's English-language proficiency. The Spoken Instruction Recognition and Matching test demonstrates superior performance for VIVA in understanding native English speakers' queries compared to queries made by non-native English speakers. However, considering that the measured human performance on Questions-Answer tasks to be 86% (Rajpurkar et al. 2018), VIVA's performance for native English speakers is approximately only four percentage points lower. As such, further work would be needed to improve the performance of VIVA for non-native speakers. When performing the Spoken Instruction Recognition and Matching test, the NLU algorithms within the web platform used (Google Actions) encountered errors in recognizing elements' letter-number format or confusing words or letters with other words. For example, frequently when the user asked a question like *"doors D2 are on the Second Floor"*, the NLU algorithm in VIVA concatenated the *"are"* after the element type D2 and tried to get the number of types *"D2R"*. The NLU algorithm's other errors in VIVA include confusing numbers with definitive articles, e.g., *"the"* was confusing with the number 2. These errors happened to native and non-native English speakers, but to a more extent to non-native English speakers. The results of the Spoken Instruction Recognition and Matching performance test shed light on the need for improvement of Google Actions platform in recognizing users' spoken phrases which might indicate a training bias.

This article also contributes to the theories and developments of BIM-Web interoperability in the AEC industry. Our interoperability approach is based on BIM connection to Web platforms using automatic connection to Google Spreadsheets, streaming data, and accessing data through Google Cloud functions. Furthermore, enabling conversational interaction makes VIVA a safe intervention for supporting workers while working in hazardous construction environments. The

developed Revit add-In helps in facilitating real-time data updating and flow, guaranteeing access to the most updated project information for on-site workers, thus reducing need for changes and/or reworks.

The proof-of-concept version of VIVA presented in this article is developed to showcase the potential applications of such a system in providing on-demand support to construction workers. As such, the presented case studies are expected to set the basis for future developments where scalability can be enabled by developing more cloud functions that enable other functionality based on the needs of different projects. In addition, the context of an application evaluated in this study is based on its application of VIVA to the construction phase of project development; its usability in other development phases is an area of future work.

4.11 Conclusions and Future Work

The AEC industry needs productivity improvements, and the productivity of construction workers has good potential to significantly boost industry's productivity trend. Information Extraction (IE) from BIM data sources is a crucial component of construction worker support that has been explored in recent years to improve workers' access to information. This article contributes to the research on application of conversational agents in the AEC by developing VIVA, that enables users' voice conversations and provide on-demand information from BIM sources through an internet-connected smart speaker. This article also contributes to the CPS research area as VIVA closes the Cyber-to-Physical link and includes the human in the loop. Two potential use cases of VIVA are presented and evaluated through case studies. The case studies focus on retrieving information for two specific use cases: the installation location of project elements, and the number of elements of a specific type that should be placed at a specific location in the construction project. However, VIVA is scalable to account for other applications and functionalities through simply adding cloud functions that enable a more varied range of queries. Finally, evaluation results for VIVA show remarkable performance for text-based queries (Interoperability and Natural Language Understanding Test). As expected, the results for voice-based queries (Spoken Instruction Recognition and Matching Test) achieved better performance for native English speakers compared to non-native English Speakers. Further evaluation in this area will also be future research work to be completed. Potential future applications include but are not limited to

updating work progress through voice commands, retrieving updated information about supply chain, activity progress, and work orders, to name a few.

CHAPTER 5. CONCLUSIONS

This chapter concludes this dissertation with a summary and discussion of this study's contributions, its limitations, and future research work.

5.1 Summary

Construction workers' access to knowledge from cyber sources in the AEC industry has the potential to bring productivity improvements at the worker and project levels. Nevertheless, workers consuming this knowledge are challenged by their environment and physical limitations while performing their activities. BIM is spearheading the construction industry's digitalization; therefore, knowledge from BIM sources was prioritized in this study.

As a result, the first knowledge gap identified was (1) how to integrate BIM and construction workers to improve productivity. This gap summarizes the challenges to systems interoperability between BIM sources and the worker-systems interactions that positively affect the productivity of construction workers. Next, two related gaps were identified to be (2) identifying the most appropriate modality that supports construction workers while minimizing disruption of their activities and (3) assessing this modality's effects on performance and perceived workload. By addressing these gaps, a CPS approach was the response to develop systems that connect the knowledge the workers need and the devices that provide this knowledge in the field. Finally, systems that connect BIM and workers seamlessly and in real time need to be developed. Therefore, the next gap is (4) what would be an interoperable process that connects real-time cyber knowledge from the AEC industry to human workers for the modality selected.

Chapter 2 focused on investigating gap (1), the missing link between the most prominent AEC data sources, BIM, and human subjects in construction. An in-depth literature review was done of the research works that have developed a cyber-to-physical systematic link between BIM and humans. This review revealed two primary system types and five integration approaches that synthesized the related research works and developments. The first system type focused on knowledge retrieval CPS systems based on text, voice, and visual and multimodal modalities. In contrast, the second type of system is activity-monitoring and context-aware systems. These system types include two approaches: systems with data transfer and web-assisted tools to enable multimodal data interoperability. The results from this chapter highlighted the challenges and opportunities of BIM-humans integration systems.

Chapter 3 focused on gaps (2) and (3) by identifying the most appropriate modality to provide knowledge to workers in the field by conducting a contextual inquiry in a development construction project where steel work was in progress. Stakeholders' feedback and observations in the field led to choosing the voice as the most appropriate modality for workers with a limited visual modality and having to use both hands while completing their work. However, implementing a voice-based system that provides knowledge to workers brings multiple questions, including about performance and the cognitive workload effect on the workers' performance. Chapter 2 also focused on the investigation of these questions. For this purpose, a voice-based intelligent virtual agent (VIVA) system was developed to be used in a user study where participants completed simulated construction assembly activities. The results presented in this chapter favored the use of VIVA over the paper baseline for visually and manually constrained workers' activities. However, a limitation of the system developed in this chapter was that it was not dynamically linked to AEC data.

Chapter 4 built on the developments in Chapters 2 and 3, proposed a system architecture, and developed an upgraded prototype of a voice-based system for worker support. The version of VIVA developed in this chapter automatically retrieves BIM data from a construction project and makes this knowledge available to workers in the field through the voice modality enabled by a smart speaker, a solution to gap (4). While considering the integration methods approaches in Chapter 3, the version of VIVA in Chapter 4 is similar to the integration approach A2 but still differs from it; it is entirely based on web platforms for its implementation, enabling functions, and databases. This makes this version of VIVA more versatile from the development and deployment perspectives. Development is more versatile because the algorithms for knowledge extraction and natural language understanding (NLU) were not developed but taken from the used platforms. Using these tools already available, VIVA can use state-of-the-art NLU algorithms and web tools that otherwise would require more significant resources. Deployment is another benefit of using web platforms, as the interaction device can be any device with access to the Google Action web platform. Still, the challenge of this integration method was the interoperability of the processes to connect a BIM project and the web platform and devices. The resulting system was evaluated based on the accuracy of the information provided based on the interoperable processes with BIM and the user and the system's ability to recognize spoken queries from different target users. Overall, the performance of VIVA was satisfactory and provided better performance than

previous works that have used other integration approaches. Drawbacks in our system include NLU bias towards better performance for native English speakers and limitations to the information provided based on the case studies in this study.

In summary, voice-based systems have multiple benefits for knowledge access aimed at construction workers. These benefits have great potential for productivity improvements in the activities of construction workers, which can improve the productivity of construction projects. The performance evaluations done in Chapter 3 prove this. Developments in this direction also support broader research on CPS based on further research in the cyber-to-physical direction of systems development. This study also highlights the synergy between humans and CPS in the dynamic environment of the AEC industry. The following sections further discuss contributions, limitations, and future research work.

5.2 Contributions

This research studies the methodologies to support construction workers in the field by allowing them to access knowledge from BIM project sources. The voice modality was identified as the most appropriate means to provide knowledge support to workers with limited visual attention and constantly occupying both hands to do their work. Subsequently, the effect of using the voice modality in these scenarios was qualitatively and quantitatively measured through user studies. Two voice interaction virtual agents (VIVA) systems were first developed for the user study, and then a more advanced version connected in real time to BIM project sources. The research has filled the gap for methodologies to support construction workers' productivity, with three significant contributions described in the following subsections.

5.2.1 Productivity effect of voice-based support systems on construction workers

Previous research works have explored voice-based systems in the AEC industry. Most of these developments have sought to develop solutions for knowledge retrieval and project feedback. However, the effect of voice-based systems (e.g., VIVA) on construction stakeholders' productivity has not been fully understood. A gap exists between developing these systems and identifying the drawbacks and benefits of their implementation in construction environments. In particular, addressing voice-based systems to construction in the field, especially to laborers limited in their visual cues and using both hands, brings more pressing concerns. This study

identified such gaps and concerns and assessed these effects through a user study on the productivity effect on a visually and manually constrained construction worker. The results of this assessment, done in Chapter 2, confirmed these benefits and contributed to the body of knowledge regarding the effect of voice-based systems and the challenges of using these systems for construction laborers in the AEC industry. To the author's knowledge, this is the most comprehensive evaluation of the effectiveness of voice-based systems on workers' productivity in the AEC industry.

5.2.2 BIM-worker system integration approaches

Previous research works have developed multiple integration approaches to link project data sources and human subjects in the construction industry's cyber-physical systems (CPS). However, no previous research has identified the common elements, processes, and purposes for developing these systems. In other applications, such as linking BIM and sensor data, addressing this gap was of utmost importance to stimulate the development of systems in this research direction and to improve the outcomes of these systems. Therefore, Chapter 2 contributes to the body of knowledge by addressing this gap and identifying system types, integration approaches, and future research directions for developing BIM-worker CPS. Chapter 2's outcomes also set the baseline for research trends or integration methods approaches besides those identified in this review, as demonstrated in the developments made for VIVA in Chapter 4, which might be considered an integration approach A2 for voice knowledge retrieval based entirely on web platforms. Nevertheless, the identified system types and integration approaches allow research works to be positioned within a development context within the BIM-worker CPS's research area for construction workers' productivity support.

5.2.3 Voice-based systems based on web platforms for the AEC industry

Chapter 3 developed the first version of a voice intelligent virtual agent (VIVA) for workers' productivity support. However, although purposeful, this version had a limited link to the project BIM databases, and its update will require a completely new development cycle. However, this limitation was leveraged at this point because this app's purpose was to evaluate the benefits of voice-based systems for construction workers. Nevertheless, this limitation was addressed in the following version of VIVA developed in Chapter 4. This version of VIVA can then be updated in real time and automatically from a project database. There are still limitations to this version of

VIVA, as it can only provide specific knowledge retrieval for the case studies addressed in Chapter 4, including getting the installation location of objects and providing the number of construction elements from the BIM project. Still, given that the underlying link between BIM and the voice interaction device is present, adding more functionality to this version of VIVA is only a matter of adding more logical functions. This development of VIVA at its different stages contributes to the body of knowledge as it provides a tool and the systematic process to develop an application such as VIVA.

Previous researchers developed voice-based systems similar to VIVA, using integration methods relying on algorithms and, to some extent, combinations of multiple platforms. However, the degree of integration of VIVA through web platforms is not present in any previous research work. Therefore, the presented development framework and solution contribute to the knowledge on developing construction CPS linked to web platforms. Substantial efforts were made to detail each process and system characteristic to denote all the integration processes that allow VIVA to work finely. Finally, VIVA as an outcome also contributes to the body of knowledge, as it provides a solution for workers whose activities limit them visually and manually and who rely on straightforward pieces of knowledge to do their work.

5.3 Limitations and Future Research Work

Through the journey of completing this research work, multiple limitations were identified that are worthy of continued future research. These are discussed in this section.

5.3.1 Taxonomy of CPS for the AEC industry

While first investigating the topic of CPS in the AEC industry, a clear point of departure was not easily identified. In other words, the development of CPS concepts and applications within the AEC industry's research body disagreed on terminology and what constitutes CPS in the AEC industry and its processes and components. In other research areas, academia and industry have widely accepted taxonomies that define all aspects of a phenomenon. Therefore, a taxonomy of CPS for the AEC industry has great potential to support developments in the AEC industry ahead, and it will be an area of future research work. This taxonomy must consider all aspects of CPS in the AEC industry, including humans in the loop and integration with CPSs in other industries.

5.3.2 Further evaluation of voice-based systems in construction applications

Chapter 3 focused on assessing voice-based systems in specific construction applications for construction worker support. A user study was conducted to measure the performance effect on construction workers' activity performance, workload, and users' opinions. Objective performance measures were based on the activities' step completion times, the number of errors made while completing the user tasks, and interventions when the support system failed to provide support. Subjective performance measures were also used to measure perceived cognitive workload using standardized workload surveys, NASA-TLX. However, the results from this cognitive workload test did not provide enough evidence to support cognitive workload improvements with voice-based systems for construction workers. Therefore, future research in this direction can explore using objective cognitive workload measures such as an electrocardiogram (ECG) or eye-tracking to measure the mental stimuli of a voice-based system while performing construction worker tasks. This objective measure might provide evidence of voice-based systems' effect on workers' mental workload.

5.3.3 Performance of voice systems on multilingual target users

Chapter 4 validated the developed voice-based system, VIVA, through a user testing process with different target users. However, this evaluation identified differences in VIVA's performance depending on the target user's English proficiency. This was attributed to the Natural Language Understanding (NLU) algorithms used in VIVA, which come from the Google Actions web platform. Although this evaluation was limited to identifying such differences, future research can be done to measure the extent of such differences and make a deeper assessment of VIVA focused on users' language and proficiency. Further research in this area is especially important for the AEC industry, as it relies on workers from different backgrounds, including English speakers, non-native English speakers, and non-English speakers. Following this direction, research can be done to measure the performance of VIVA in other predominant languages among construction workers, such as Spanish, in similar settings to those in Chapter 3 or 4.

REFERENCES

- A-lHamouz, S. O., El-Omari, N. K. T., and Al-Naimat, A. M. "An ISO Compliant Safety System for Human Workers in Human-Robot Interaction Work Environment." *Proc., 2019 12th International Conference on Developments in eSystems Engineering (DeSE)*, 9-14.
- Abdel-Monem, M., and Hegazy, T. (2013). "Enhancing Construction As-Built Documentation Using Interactive Voice Response." *Journal of Construction Engineering and Management*, 139(7), 895-898.
- Afsari, K., Eastman, C., and Shelden, D. (2017). "Building Information Modeling data interoperability for Cloud-based collaboration: Limitations and opportunities." *International Journal of Architectural Computing*, 15(3), 187-202.
- Afsari, K., Eastman, C. M., and Castro-Lacouture, D. (2017). "JavaScript Object Notation (JSON) data serialization for IFC schema in web-based BIM data exchange." *Automation in Construction*, 77, 24-51.
- Ahmed, A. L., and Kassem, M. (2018). "A unified BIM adoption taxonomy: Conceptual development, empirical validation and application." *Automation in Construction*, 96, 103-127.
- Ahn Changbum, R., Lee, S., Sun, C., Jebelli, H., Yang, K., and Choi, B. (2019). "Wearable Sensing Technology Applications in Construction Safety and Health." *Journal of Construction Engineering and Management*, 145(11), 03119007.
- Akanmu, A., and Anumba, C. J. (2015). "Cyber-physical systems integration of building information models and the physical construction." *Engineering, Construction and Architectural Management*, 22(5), 516-535.
- Akanmu, A., and Olayiwola, J. (2019). *Towards a Cyber-Physical Postural Training System for Construction Workers*.
- Akanmu, A. A., Olayiwola, J., Ogunseiju, O., and McFeeters, D. (2020). "Cyber-physical postural training system for construction workers." *Automation in Construction*, 117, 103272.
- Akhavian, R., and Behzadan, A. H. (2015). "Construction equipment activity recognition for simulation input modeling using mobile sensors and machine learning classifiers." *Advanced Engineering Informatics*, 29(4), 867-877.

- Al-Ali, A. R., Gupta, R., and Al Nabulsi, A. "Cyber physical systems role in manufacturing technologies." *Proc., 2018 6th International Conference on Nano and Materials Science: ICNMS 2018, 15-17 Jan. 2018*, AIP Publishing, 050007 (050007 pp.).
- Alexakis, G., Panagiotakis, S., Fragkakis, A., Markakis, E., and Vassilakis, K. (2019). "Control of Smart Home Operations Using Natural Language Processing, Voice Recognition and IoT Technologies in a Multi-Tier Architecture." *Designs*, 3(3), 32.
- Allmon, E., Haas, C. T., Borcharding, J. D., and Goodrum, P. M. (2000). "U.S. Construction Labor Productivity Trends, 1970-1998." *Journal of Construction Engineering and Management*, 126(2), 97-104.
- Alsafouri, S., and Ayer, S. K. (2019). "Mobile Augmented Reality to Influence Design and Constructability Review Sessions." *Journal of Architectural Engineering*, 25(3), 04019016.
- Anumba, C. J., Akanmu, A., Yuan, X., and Kan, C. (2020). "Cyber—physical systems development for construction applications." *Frontiers of Engineering Management*.
- Anumba, C. J., Issa, R. R. A., Pan, J., and Mutis, I. (2008). "Ontology-based information and knowledge management in construction." *Construction Innovation*, 8(3), 218-239.
- Ashuri, B., Yarmohammadi, S., and Shahandashti, M. (2014). *A Critical Review of Methods Used to Determine Productivity of Mechanical, Electrical, and Plumbing Systems Coordination*.
- ASTM International (2016). "Standard Practice for Job Productivity Measurement." 04.12.
- Azzam, A., Miranda, S., and Indrawati, S. (2019). "Information system design using labor productivity measurement for construction." *IOP Conference Series: Materials Science and Engineering*, 528, 012003.
- Barbosa, F., Woetzel, J., Mischke, J., Ribeirinho, M. J., Sridhar, M., Parsons, M., Bertram, N., and Brown, S. (2017). "Reinventing construction: a route to higher productivity." *McKinsey Global Institute*.
- Boechat, L. C., and Corrêa, F. R. "Augmented BIM Workflow for Structural Design Through Data Visualization." *Proc., Proceedings of the 18th International Conference on Computing in Civil and Building Engineering*, Springer International Publishing, 180-196.
- Brachten, F., Brünker, F., Frick, N. R. J., Ross, B., and Stieglitz, S. (2020). "On the ability of virtual agents to decrease cognitive load: an experimental study." *Information Systems and e-Business Management*, 18(2), 187-207.

- Brathen, K., and Moum, A. (2016). "Bridging the gap: Bringing BIM to construction workers." *Engineering, Construction and Architectural Management*, 23(6), 751-764.
- Calvetti, D., Magalhães, P. N. M., Suján Sujesh, F., Gonçalves, M. C., and Campos de Sousa, H. J. (2020). "Challenges of upgrading craft workforce into Construction 4.0: framework and agreements." *Proceedings of the Institution of Civil Engineers - Management, Procurement and Law*, 173(4), 158-165.
- Calvetti, D., Meda, P., Gonçalves, M. C., and Sousa, H. (2020). "Worker 4.0: The Future of Sensored Construction Sites." *Buildings*, 10(10), 169 (122 pp.).
- Chan, Z. Y., and Shum, P. (2018). "Smart Office: A Voice-controlled Workplace for Everyone." *Proceedings of the 2nd International Symposium on Computer Science and Intelligent Control*, Association for Computing Machinery, Stockholm, Sweden, Article 34.
- Chang, C.-K., Hanna, A. S., Lackney, J. A., and Sullivan, K. T. (2005). "Quantifying the Impact of Schedule Compression on Construction Labor Productivity." *Construction Research Congress 2005*, 1-10.
- Chen, H., Hou, L., Zhang, G., and Moon, S. (2021). "Development of BIM, IoT and AR/VR technologies for fire safety and upskilling." *Automation in Construction*, 125, 103631.
- Chuah, Y. D., Lee, J. V., Tan, S. S., and Ng, C. K. (2019). "Implementation of smart monitoring system in vertical farming." *IOP Conference Series: Earth and Environmental Science*, 268, 012083.
- Constantinescu, M. (2009). "Knowledge Management: Focus on Innovation and Labor Productivity in a Knowledge-Based Economy." *IUP Journal of Knowledge Management*, 7(1), 7-33.
- Correa, F. R. (2018). "Cyber-physical systems for construction industry." *2018 IEEE Industrial Cyber-Physical Systems (ICPS)*, 392-397.
- Dave, B., Buda, A., Nurminen, A., and Främling, K. (2018). "A framework for integrating BIM and IoT through open standards." *Automation in Construction*, 95, 35-45.
- Demian, P., Ruikar, K., and Morris, A. (2015). *3DIR: three-dimensional information retrieval from 3D building information modelling environments*.
- Eastman, C. M., and Sacks, R. (2008). "Relative Productivity in the AEC Industries in the United States for On-Site and Off-Site Activities." *Journal of Construction Engineering and Management*, 134(7), 517-526.

- EHS Today Staff (2021). "Construction Worker Shortage at 'Crisis Level'." *EHS Today*.
- Elghamrawy, T., and Boukamp, F. (2010). "Managing construction information using RFID-based semantic contexts." *Automation in Construction*, 19(8), 1056-1066.
- Ensafi, M., Thabet, W., Devito, S., and Lewis, A. (2021). "Field Testing of Mixed Reality (MR) Technologies for Quality Control of As-Built Models at Project Handover: A Case Study." *Proc., ASC 2021. 57th Annual Associated Schools of Construction International Conference*, EasyChair, 246-254.
- Eskandar, S., Wang, J., and Razavi, S. (2020). "Human-in-the-Loop Cyber-Physical Systems for Construction Safety." *Cyber-Physical Systems in the Built Environment*, C. J. Anumba, and N. Roofigari-Esfahan, eds., Springer International Publishing, Cham, 161-173.
- Fan, H., Xue, F., and Li, H. (2015). "Project-Based As-Needed Information Retrieval from Unstructured AEC Documents." *Journal of Management in Engineering*, 31(1), A4014012.
- Fang, Y., Roofigari-Esfahan, N., and Anumba, C. "A knowledge-based cyber-physical system (CPS) architecture for informed decision making in construction." *Proc., Construction Research Congress 2018: Construction Information Technology, CRC 2018, April 2, 2018 - April 4, 2018*, American Society of Civil Engineers (ASCE), 662-672.
- Ghosh, A., Edwards, D. J., and Hosseini, M. R. (2021). "Patterns and trends in Internet of Things (IoT) research: future applications in the construction industry." *Engineering, Construction and Architectural Management*, 28(2), 457-481.
- Golzarpoor, B., Haas, C. T., Rayside, D., Kang, S., and Weston, M. (2018). "Improving construction industry process interoperability with Industry Foundation Processes (IFP)." *Advanced Engineering Informatics*, 38, 555-568.
- Gomar, J. E., Haas, C. T., and Morton, D. P. (2002). "Assignment and Allocation Optimization of Partially Multiskilled Workforce." *Journal of Construction Engineering and Management*, 128(2), 103-109.
- Goodrum, P. M., and Haas, C. T. (2002). "Partial Factor Productivity and Equipment Technology Change at Activity Level in U.S. Construction Industry." *Journal of Construction Engineering and Management*, 128(6), 463-472.

- Goodrum, P. M., and Haas, C. T. (2004). "Long-Term Impact of Equipment Technology on Labor Productivity in the U.S. Construction Industry at the Activity Level." *Journal of Construction Engineering and Management*, 130(1), 124-133.
- Griffor, E., Greer, C., Wollman, D., and Burns, M. (2017). "Framework for Cyber-Physical Systems: Volume 1, Overview." National Institute of Standards and Technology.
- Guodong, N., Qingbin, C., Linhua, S., Wenshun, W., and Dongchun, X. (2018). "Knowledge-sharing culture, project-team interaction, and knowledge-sharing performance among project members." *Journal of Management in Engineering*, 34(2), 04017065 (04017012 pp.).
- Gürdür, D., Vulgarakis Feljan, A., El-khoury, J., Kumar Mohalik, S., Badrinath, R., Pradeep Mujumdar, A., and Fersman, E. (2018). "Knowledge Representation of Cyber-physical Systems for Monitoring Purpose." *Procedia CIRP*, 72, 468-473.
- Gurmu, A. T., and Ongkowijoyo, C. S. (2020). "Predicting Construction Labor Productivity Based on Implementation Levels of Human Resource Management Practices." *Journal of Construction Engineering and Management*, 146(3), 04019115.
- Ha, D. K., Kim, S. Y., and Nguyen, V. K. "An MCS-based Model to Qualify the Relationship between Worker's Experience and Construction Productivity." *Proc., 2020 5th International Conference on Green Technology and Sustainable Development (GTSD)*, 280-285.
- Ham, Y., Han, K. K., Lin, J. J., and Golparvar-Fard, M. (2016). "Visual monitoring of civil infrastructure systems via camera-equipped Unmanned Aerial Vehicles (UAVs): a review of related works." *Visualization in Engineering*, 4(1).
- Han, T., Ma, T., Fang, Z., Zhang, Y., and Han, C. (2022). "A BIM-IoT and intelligent compaction integrated framework for advanced road compaction quality monitoring and management." *Computers and Electrical Engineering*, 100, 107981.
- Hart, S. G., and Staveland, L. E. (1988). "Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research." *Advances in Psychology*, P. A. Hancock, and N. Meshkati, eds., North-Holland, 139-183.
- Hartson, R., and Pyla, P. S. (2012). "Chapter 3 - Contextual Inquiry: Eliciting Work Activity Data." *The UX Book*, R. Hartson, and P. S. Pyla, eds., Morgan Kaufmann, Boston, 87-127.

- Hasan, A., Elmualim, A., Raufdeen, R., Baroudi, B., and Marshall, A. (2018). "An exploratory study on the impact of mobile ICT on productivity in construction projects." *Built Environment Project and Asset Management*, 8(3), 320-332.
- Hasanzadeh, S., Polys, N. F., and de la Garza, J. M. (2020). "Presence, Mixed Reality, and Risk-Taking Behavior: A Study in Safety Interventions." *IEEE Transactions on Visualization and Computer Graphics*, 26, 2115-2125.
- Hashiguchi, N., Cao, J., Lim, Y., Kubota, Y., Kitahara, S., Ishida, S., and Kodama, K. (2020). "The Effects of Psychological Factors on Perceptions of Productivity in Construction Sites in Japan by Worker Age." *International Journal of Environmental Research and Public Health*, 17(10), 3517.
- He, T., and Jazizadeh, F. "Nudging Occupants for Energy-Saving through Voice-Based Proactive Virtual Assistants." *Proc., Construction Research Congress 2022*, 402-411.
- He, T., Jazizadeh, F., and Arpan, L. (2022). "AI-powered virtual assistants nudging occupants for energy saving: proactive smart speakers for HVAC control." *Building Research & Information*, 50(4), 394-409.
- Hewage, K. N., and Ruwanpura, J. Y. (2009). "A novel solution for construction on-site communication - the information booth." *Canadian Journal of Civil Engineering*, 36(4), 659-671.
- Huang, A. L., Chapman, R. E., and Butry, D. T. (2009). "Metrics and tools for measuring construction productivity: Technical and empirical considerations."
- Hwang, B.-G., and Soh, C. K. (2013). "Trade-Level Productivity Measurement: Critical Challenges and Solutions." *Journal of Construction Engineering and Management*, 139(11), 04013013.
- Jimenez, C., Saavedra, E., Campo, G. d., and Santamaria, A. (2021). "Alexa-Based Voice Assistant for Smart Home Applications." *IEEE Potentials*, 40(4), 31-38.
- Johari, S., and Jha Kumar, N. (2020). "Impact of Work Motivation on Construction Labor Productivity." *Journal of Management in Engineering*, 36(5), 04020052.
- Johari, S., and Neeraj Jha, K. (2020). "How the Aptitude of Workers Affects Construction Labor Productivity." *Journal of Management in Engineering*, 36(5), 04020055.

- Junbok, L., Young-Jin, P., Chang-Hoon, C., and Choong-Hee, H. (2017). "BIM-assisted labor productivity measurement method for structural formwork." *Automation in Construction*, 84, 121-132.
- Kan, C., Anumba, C. J., and Messner, J. I. "Potential Use of Cyber-Physical Systems (CPS) for Planning and Operation of Mobile Cranes on Construction Sites." *Proc., ASCE International Workshop on Computing in Civil Engineering 2017. Sensing, Simulation and Visualization, 25-27 June 2017*, ASCE - American Society of Civil Engineers, 139-146.
- Kan, C., Anumba, C. J., Yihai, F., and Messner, J. I. (2018). "A cyber-physical system (CPS) for planning and monitoring mobile cranes on construction sites." *Proceedings of the Institution of Civil Engineers - Management, Procurement and Law*, 171(6), 240-250.
- Kanan, R., Elhassan, O., and Bensalem, R. (2018). "An IoT-based autonomous system for workers' safety in construction sites with real-time alarming, monitoring, and positioning strategies." *Automation in Construction*, 88, 73-86.
- Karimi, H., Taylor Timothy, R. B., Dadi Gabriel, B., Goodrum Paul, M., and Srinivasan, C. (2018). "Impact of Skilled Labor Availability on Construction Project Cost Performance." *Journal of Construction Engineering and Management*, 144(7), 04018057.
- Kazerooni, M., Nguyen, P., and Fayek, A. R. (2021). "Prioritizing Construction Labor Productivity Improvement Strategies Using Fuzzy Multi-Criteria Decision Making and Fuzzy Cognitive Maps." *Algorithms*, 14(9).
- Kiani, A., Salman, A., and Riaz, Z. (2014). "Real-time environmental monitoring, visualization, and notification system for construction H&S management." *Journal of Information Technology in Construction*, 19, 72-91.
- Kim, J., Lorenz, M., Knopp, S., and Klimant, P. "Industrial Augmented Reality: Concepts and User Interface Designs for Augmented Reality Maintenance Worker Support Systems." *Proc., 2020 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*, 67-69.
- Kim, S.-A., Chin, S., Yoon, S.-W., Shin, T.-H., Kim, Y.-S., and Choi, C. "Automated building information modeling system for building interior to improve productivity of bim-based quantity take-off." *Proc., 2009 26th International Symposium on Automation and Robotics in Construction, ISARC 2009, June 24, 2009 - June 27, 2009*, International Association for Automation and Robotics in Construction I.A.A.R.C), 492-496.

- Kim, S., Chang, S., and Castro-Lacouture, D. (2020). "Dynamic Modeling for Analyzing Impacts of Skilled Labor Shortage on Construction Project Management." *Journal of Management in Engineering*, 36(1), 04019035.
- Kim, S., and Park, S. "CPS(Cyber Physical System) based Manufacturing System Optimization." *Proc., 5th International Conference on Information Technology and Quantitative Management, ITQM 2017, December 8, 2017 - December 10, 2017*, Elsevier B.V., 518-524.
- King, S. S., Rahman, R. A., Fauzi, M. A., and Haron, A. T. (2022). "Critical analysis of pandemic impact on AEC organizations: the COVID-19 case." *Journal of Engineering, Design and Technology*, 20(1), 358-383.
- Klötzer, C., Weißenborn, J., and Pflaum, A. "The Evolution of Cyber-Physical Systems as a Driving Force Behind Digital Transformation." *Proc., 2017 IEEE 19th Conference on Business Informatics (CBI)*, 5-14.
- Kondratova, I. (2003). "Voice and Multimodal Access to AEC Project Information."
- Koseoglu, O., and Nurtan-Gunes, E. T. (2018). "Mobile BIM implementation and lean interaction on construction site." *Engineering Construction & Architectural Management (09699988)*, 25(11), 1298-1321.
- Lee, S. C., and Jeon, M. (2022). "A systematic review of functions and design features of in-vehicle agents." *International Journal of Human-Computer Studies*, 165, 102864.
- Lee, W., Lin, K.-Y., Seto, E., and Migliaccio, G. C. (2017). "Wearable sensors for monitoring on-duty and off-duty worker physiological status and activities in construction." *Automation in Construction*, 83, 341-353.
- Li, C. Z., Xue, F., Li, X., Hong, J., and Shen, G. Q. (2018). "An Internet of Things-enabled BIM platform for on-site assembly services in prefabricated construction." *Automation in Construction*, 89, 146-161.
- Li, H., Chan, G., Wong, J. K. W., and Skitmore, M. (2016). "Real-time locating systems applications in construction." *Automation in Construction*, 63, 37-47.
- Li, J., Li, N., Afsari, K., Wu, Z., and Cui, H. (2019). "Integration of Building Information Modeling and Web Service Application Programming Interface for assessing building surroundings in early design stages." *Building and Environment*, 153.

- Li, R. Y. M., and Leung, T. H. (2020). "Computer Vision and Hybrid Reality for Construction Safety Risks: A Pilot Study." *Proc., Fourth International Congress on Information and Communication Technology*, Springer Singapore, 17-22.
- Li, X., Yi, W., Chi, H.-L., Wang, X., and Chan, A. P. C. (2018). "A critical review of virtual and augmented reality (VR/AR) applications in construction safety." *Automation in Construction*, 86, 150-162.
- Lin, J.-R., Hu, Z.-Z., Zhang, J.-P., and Yu, F.-Q. (2016). "A Natural-Language-Based Approach to Intelligent Data Retrieval and Representation for Cloud BIM." *Computer-Aided Civil and Infrastructure Engineering*, 31(1), 18-33.
- Lin, T.-H., Liu, C.-H., Tsai, M.-H., and Kang, S.-C. (2015). "Using Augmented Reality in a Multiscreen Environment for Construction Discussion." *Journal of Computing in Civil Engineering*, 29(6), 04014088.
- Linares-Garcia, D. A., Flores-Linares, G., and Roofigari-Esfahan, N. "Framework and Case Studies for Context-Aware AR System (CaARS) for Ubiquitous Applications in the AEC Industry." *Proc., Construction Research Congress 2022*, 1278-1288.
- Linares, D. A., Anumba, C., and Roofigari-Esfahan, N. "Overview of Supporting Technologies for Cyber-physical Systems Implementation in the AEC Industry." *Proc., ASCE International Conference on Computing in Civil Engineering 2019, 17-19 June 2019*, ASCE - American Society of Civil Engineers, 495-504.
- Linares Garcia, D. A., Dongre, P., Roofigari-Esfahan, N., and Bowman, D. A. "The Mobile Office: A Mobile AR Systems for Productivity Applications in Industrial Environments." *Proc., Virtual, Augmented and Mixed Reality*, Springer International Publishing, 511-532.
- Liu, H., and Wang, L. (2017). "An AR-based Worker Support System for Human-Robot Collaboration." *Procedia Manufacturing*, 11, 22-30.
- Liu, T., Hou, J., Xiong, G., Nyberg, T. R., and Li, X. (2016). "Smart cloud-based platform for construction sites." *IEEE*, 168.
- Maskuriy, R., Selamat, A., Ali, N. K., Maresova, P., and Krejcar, O. (2019). "Industry 4.0 for the Construction Industry—How Ready Is the Industry?" *Applied Sciences*, 9(14).
- Mirzaei, A., Nasirzadeh, F., Parchami Jalal, M., and Zamani, Y. (2018). "4D-BIM Dynamic Time–Space Conflict Detection and Quantification System for Building Construction Projects." *Journal of Construction Engineering and Management*, 144(7), 04018056.

- Monisha, K., and Rajasekhara Babu, M. (2019). "A novel framework for healthcare monitoring system through cyber-physical system." Springer Verlag, 21-36.
- Moreira, L. C. d. S., Mota, P. P., and Machado, F. A. "BIM, IoT and MR Integration Applied on Risk Maps for Construction." *Proc., Proceedings of the 18th International Conference on Computing in Civil and Building Engineering*, Springer International Publishing, 895-906.
- Muñoz-La Rivera, F., Mora-Serrano, J., Valero, I., and Oñate, E. (2020). "Methodological-Technological Framework for Construction 4.0." *Archives of Computational Methods in Engineering*.
- Murvold, V., Vestermo, A., Svalestuen, F., Lohne, J., and Lædre, O. (2016). *Experiences from the Use of BIM-Stations*.
- Nagorny, K., Scholze, S., Ruhl, M., and Colombo, A. W. "Semantical support for a CPS data marketplace to prepare Big Data analytics in smart manufacturing environments." *Proc., 2018 IEEE Industrial Cyber-Physical Systems (ICPS)*, 206-211.
- Nasirzadeh, F., and Nojedehe, P. (2013). "Dynamic modeling of labor productivity in construction projects." *International Journal of Project Management*, 31(6), 903-911.
- Neve, H. H., Wandahl, S., Lindhard, S., Teizer, J., and Lerche, J. (2020). "Determining the Relationship between Direct Work and Construction Labor Productivity in North America: Four Decades of Insights." *Journal of Construction Engineering and Management*, 146(9), 04020110.
- Nikolakis, N., Alexopoulos, K., Xanthakis, E., and Chryssolouris, G. (2019). "The digital twin implementation for linking the virtual representation of human-based production tasks to their physical counterpart in the factory-floor." *International Journal of Computer Integrated Manufacturing*, 32(1), 1-12.
- Niu, Y., Anumba, C., and Lu, W. (2019). "Taxonomy and Deployment Framework for Emerging Pervasive Technologies in Construction Projects." *Journal of Construction Engineering and Management*, 145(5), 04019028.
- Okpala, I., Nnaji, C., Ogunseiju, O., and Akanmu, A. (2022). "Assessing the Role of Wearable Robotics in the Construction Industry: Potential Safety Benefits, Opportunities, and Implementation Barriers." *Automation and Robotics in the Architecture, Engineering, and Construction Industry*, H. Jebelli, M. Habibnezhad, S. Shayesteh, S. Asadi, and S. Lee, eds., Springer International Publishing, Cham, 165-180.

- Omar, H., Mahdjoubi, L., and Kheder, G. (2018). "Towards an automated photogrammetry-based approach for monitoring and controlling construction site activities." *Computers in Industry*, 98, 172-182.
- Ozturk, G. B., and Yitmen, I. (2019). "Conceptual Model of Building Information Modelling Usage for Knowledge Management in Construction Projects." *IOP Conference Series: Materials Science and Engineering*, 471, 022043.
- Pamidimukkala, A., and Kermanshachi, S. (2021). "Impact of Covid-19 on field and office workforce in construction industry." *Project Leadership and Society*, 2, 100018.
- Pan, Y., and Zhang, L. (2021). "A BIM-data mining integrated digital twin framework for advanced project management." *Automation in Construction*, 124, 103564.
- Park, H.-S., Thomas, S. R., and Tucker, R. L. (2005). "Benchmarking of Construction Productivity." *Journal of Construction Engineering and Management*, 131(7), 772-778.
- Park, J., and Cho, Y. K. "Use of a Mobile BIM Application Integrated with Asset Tracking Technology Over a Cloud." *Proc., Proceedings of the 21st International Symposium on Advancement of Construction Management and Real Estate*, Springer Singapore, 1535-1545.
- Park, M., Lee, K.-w., Lee, H.-s., Jiayi, P., and Yu, J. (2013). "Ontology-based construction knowledge retrieval system." *KSCE Journal of Civil Engineering*, 17(7), 1654-1663.
- Pasini, D., Ventura, S. M., Rinaldi, S., Bellagente, P., Flammini, A., and Ciribini, A. L. C. "Exploiting Internet of Things and building information modeling framework for management of cognitive buildings." *Proc., 2016 IEEE International Smart Cities Conference (ISC2)*, 1-6.
- Prastianing Atas Kasih, R., and Joko Wahyu Adi, T. (2019). "Construction project productivity assesment model and its implementation in Indonesia construction industry." *MATEC Web Conf.*, 258, 02026.
- Puri, N., and Turkan, Y. "A Review of Technology Supplemented Progress Monitoring Techniques for Transportation Construction Projects."
- Rahimi Movassagh, M., Roofigari-Esfahan, N., Won Lee, S., Evia, C., Hicks, D., and Jeon, M. (2021). "Human Factors Considerations for Teaming between Construction Workers and Voice-based Intelligent Virtual Agent (VIVA)." *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 65(1), 72-76.

- Rajpurkar, P., Jia, R., and Liang, P. "Know What You Don't Know: Unanswerable Questions for SQuAD." *Association for Computational Linguistics*, 784-789.
- Rezgui, Y., Boddy, S., Wetherill, M., and Cooper, G. (2011). "Past, present and future of information and knowledge sharing in the construction industry: Towards semantic service-based e-construction?" *Computer Aided Design*, 43(5), 502-515.
- Rodriguez, F. S., Spilski, J., Hekele, F., Beese, N. O., and Lachmann, T. (2020). "Physical and cognitive demands of work in building construction." *Engineering, Construction and Architectural Management*, 27(3), 745-764.
- Rogers, Y. (2012). "HCI Theory: Classical, Modern, and Contemporary." *Synthesis Lectures on Human-Centered Informatics*, 5(2), 1-129.
- Romero, M., Guédria, W., Panetto, H., and Barafort, B. (2020). "Towards a Characterisation of Smart Systems: A Systematic Literature Review." *Computers in Industry*, 120, 103224.
- Roofigari-Esfahan, N., White, E., Mollenhauer, M., and Talledo Vilela, J. P. (2021). "Development of a Connected Smart Vest for Improved Roadside Work Zone Safety."
- Rouhanizadeh, B., and Kermanshachi, S. "Causes of the mental health challenges in construction workers and their impact on labor productivity." *Proc., Tran-SET Conference 2021, June 3, 2021 - June 4, 2021*, American Society of Civil Engineers (ASCE), 16-26.
- Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P., and Harnisch, M. (2015). "Industry 4.0: The future of productivity and growth in manufacturing industries." *Boston Consulting Group*, 9(1), 54-89.
- Ruwanpura, J. Y., Hewage, K. N., and Silva, L. P. (2012). "Evolution of the i-Booth© onsite information management kiosk." *Automation in Construction*, 21, 52-63.
- Salai, A.-M., Cook, G., and Holmquist, L. E. "IntraVox: A Personalized Human Voice to Support Users with Complex Needs in Smart Homes." Springer International Publishing, 223-244.
- Sangyun, S. (2020). "Framework for Automatic Speech Recognition-Based Building Information Retrieval from BIM Software." *Construction Research Congress 2020 - Computer Applications*, 992-1000.
- Sappelli, M. (2016). "Knowledge Work in Context: User Centered Knowledge Worker Support." *ACM SIGIR Forum*, 50(2), 107-108.
- Schweigkofler, A., Monizza, G. P., Domi, E., Popescu, A., Ratajczak, J., Marcher, C., Riedl, M., and Matt, D. (2018). "Development of a Digital Platform Based on the Integration of

- Augmented Reality and BIM for the Management of Information in Construction Processes." *Proc., Product Lifecycle Management to Support Industry 4.0*, Springer International Publishing, 46-55.
- Seo, J., Lee, H., Cassule, L. N., and Moon, S. "Machine guidance based site control technology (SCT) for earthwork equipment fleet." *Proc., 32nd International Symposium on Automation and Robotics in Construction and Mining: Connected to the Future, ISARC 2015, June 15, 2015 - June 18, 2015*, International Association for Automation and Robotics in Construction I.A.A.R.C).
- Serras, M., García-Sardiña, L., Simões, B., Hugoálvarez, and Arambarri, J. (2020). "AREVA: Augmented Reality Voice Assistant for Industrial Maintenance." *Procesamiento de Lenguaje Natural*, 65, 135-138.
- Shahinmoghadam, M., and Motamedi, A. "An Ontology-Based Mediation Framework for Integrating Federated Sources of BIM and IoT Data." *Proc., Proceedings of the 18th International Conference on Computing in Civil and Building Engineering*, Springer International Publishing, 907-923.
- Shalaby, W., Arantes, A., Diaz, T. G., and Gupta, C. "Building chatbots from large scale domain-specific knowledge bases: Challenges and opportunities." *Proc., 2020 IEEE International Conference on Prognostics and Health Management, ICPHM 2020, June 8, 2020 - June 10, 2020*, Prognostics and Health Management Society.
- Shan, Y., Goodrum, P., Haas, C., and Caldas, C. "Assessing productivity improvement of quick connection systems in the steel construction industry using building information modeling (BIM)." *Proc., Construction Research Congress 2012: Construction Challenges in a Flat World, May 21, 2012 - May 23, 2012*, American Society of Civil Engineers (ASCE), 1135-1144.
- Shin, S., and Issa Raja, R. A. (2021). "BIMASR: Framework for Voice-Based BIM Information Retrieval." *Journal of Construction Engineering and Management*, 147(10), 04021124.
- Solis, F. A. M., Howe, J., and O'Brien, W. J. (2015). "Integration of Information Technologies into Field Managers' Activities: A Cognitive Perspective." *Journal of Management in Engineering*, 31(1), A4014001.
- Son, H., Kim, C., and Cho, Y. (2017). *Automated Schedule Updates Using As-Built Data and a 4D Building Information Model*.

- Srewil, Y., Ismail, A., and Scherer, R. J. "A Method to Integrate Virtual-Physical Construction Environment in Framework of CPS Approach." *Proc., Smart SysTech 2016; European Conference on Smart Objects, Systems and Technologies*, 1-8.
- Srewil, Y., and Scherer, R. J. (2017). "Construction objects recognition in framework of CPS." *IEEE*, 2472.
- Tang, S., Shelden, D. R., Eastman, C. M., Pishdad-Bozorgi, P., and Gao, X. (2019). "A review of building information modeling (BIM) and the internet of things (IoT) devices integration: Present status and future trends." *Automation in Construction*, 101, 127-139.
- Teizer, J., Wolf, M., Golovina, O., Perschewski, M., Propach, M., Neges, M., and König, M. (2017). "Internet of Things (IoT) for Integrating Environmental and Localization Data in Building Information Modeling (BIM)." *Proceedings of the 34th International Symposium on Automation and Robotics in Construction (ISARC)*, Tribun EU, s.r.o., Brno, 603-609.
- Teo, E. A. L. (2016). "Briefing: Determining productivity and safety indices using BIM." *Proceedings of Institution of Civil Engineers: Management, Procurement and Law*, 169(4), 143-144.
- Thomas, H. R., and Yiakoumis, I. (1987). "Factor Model of Construction Productivity." *Journal of Construction Engineering and Management*, 113(4), 623-639.
- Turkan, Y., Bosché, F., Haas, C. T., and Haas, R. (2013). "Toward Automated Earned Value Tracking Using 3D Imaging Tools." *Journal of Construction Engineering & Management*, 139(4), 423-433.
- Valinejadshoubi, M., Moselhi, O., Bagchi, A., and Salem, A. (2021). "Development of an IoT and BIM-based automated alert system for thermal comfort monitoring in buildings." *Sustainable Cities and Society*, 66, 102602.
- Vivi, Q. L., Kumar, P. A., Philip, W., Don, R. G., and James, H. (2019). "Developing a Dynamic Digital Twin at a Building Level: using Cambridge Campus as Case Study." *International Conference on Smart Infrastructure and Construction 2019 (ICSIC)*, 67-75.
- Wang, H., and Meng, X. (2019). "Transformation from IT-based knowledge management into BIM-supported knowledge management: A literature review." *Expert Systems with Applications*, 121, 170-187.

- Wang, H., Meng, X., and Zhu, X. (2022). "Improving knowledge capture and retrieval in the BIM environment: Combining case-based reasoning and natural language processing." *Automation in Construction*, 139, 104317.
- Wang, J., and Razavi, S. (2019). "Integrated & Automated Systems for Safe Construction Sites." *Professional Safety*, 64(2), 41-45.
- Wang, N., Issa, R., and Anumba, C. (2021). *A Framework for Intelligent Building Information Spoken Dialogue System (iBISDS)*.
- Wang, N., Issa, R. R. A., and Anumba, C. J. (2022). "NLP-Based Query-Answering System for Information Extraction from Building Information Models." *Journal of Computing in Civil Engineering*, 36(3), 04022004.
- Wang, X., Truijens, M., Hou, L., Wang, Y., and Zhou, Y. (2014). "Integrating Augmented Reality with Building Information Modeling: Onsite construction process controlling for liquefied natural gas industry." *Automation in Construction*, 40, 96-105.
- World Economic Forum, and The Boston Consulting Group (2016). "Shaping the future of construction a breakthrough in mindset and technology."
- Yang, C.-C., Kamat, V. R., and Menassa, C. C. (2016). "BIMap: Plan Drawings as Tangible Interfaces for Building Information Models." *Construction Research Congress 2016*, 2239-2249.
- Yang, Z., Shi, J., Jiang, W., Sui, Y., Wu, Y., Ma, S., Kang, C., and Li, H. (2019). "Influences of Augmented Reality Assistance on Performance and Cognitive Loads in Different Stages of Assembly Task." *Frontiers in Psychology*, 10(1703).
- Yates, J. K. (2014). "Global Productivity Issues." *Productivity Improvement for Construction and Engineering*, 327-346.
- Yeh, K.-C., Tsai, M.-H., and Kang, S.-C. (2012). "On-Site Building Information Retrieval by Using Projection-Based Augmented Reality." *Journal of Computing in Civil Engineering*, 26(3), 342-355.
- You, Z., and Feng, L. (2020). "Integration of Industry 4.0 Related Technologies in Construction Industry: A Framework of Cyber-Physical System." *IEEE Access*, 8, 122908-122922.
- Yuan, X., Anumba, C. J., and Parfitt, M. K. (2016). "Cyber-physical systems for temporary structure monitoring." *Automation in Construction*, 66, 1-14.

- Zaher, M., Greenwood, D., and Marzouk, M. (2018). "Mobile augmented reality applications for construction projects." *Construction Innovation*, 18(2), 152-166.
- Zhou, C., Luo, H., Fang, W., Wei, R., and Ding, L. (2019). "Cyber-physical-system-based safety monitoring for blind hoisting with the internet of things: A case study." *Automation in Construction*, 97, 138-150.
- Zhou, H., Wong, M. O., Ying, H., and Lee, S. "A Framework of Multi-user Voice-driven BIM-based Navigation System for Fire Emergency Response." *Proc., EG-ICE*.
- Zuboff, S. (1988). *In the age of the smart machine : the future of work and power*, Basic Books, New York.