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Synergies of Lean, BIM, and Extended Reality (LBX) for Project Delivery Management

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Abstract: The architecture, engineering, and construction (AEC) industry stands to benefit tremendously from the integration of lean construction (LC), building information modeling (BIM), and extended reality (XR) technologies at all stages of a project. These technologies enable multidimensional content viewing and collaboration through cloud-based systems and in real-scale environments, resulting in higher levels of efficiency. The aim of this research is to offer an integrative approach that combines project management philosophies, systems, technologies, and tools. The sections containing the results of this study are as follows. (1) A concise review of the benefits of LC, BIM, and XR technologies in the AEC industry, including BIM-based visualization support for LC (Lean-BIM) and BIM visualization in XR (BIM-XR). This section also presents an overview of the most commonly used wearable XRs on the market. (2) The presentation of an LBX process flow diagram and an IDEF0 diagram for the LBX project delivery management system at each stage of AEC projects, including design, construction, and operation. (3) Two possible scenarios for integrated lean, BIM, and XR implementation are suggested, referred to as "in the office" and "online or semi-online LBX meetings". (4) An analysis of the strengths and weaknesses of the LBX management system, practical implications, and open challenges of applying LBX to project management tasks. Overall, this study presents an enormous opportunity to increase the quality of construction project planning, understanding, and performance, and provides a roadmap for future efforts to implement the integration of LC, BIM, and XR technologies in the AEC industry.

Keywords: AEC industry; building information modeling (BIM); extended reality (XR); lean construction (LC)

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1. Introduction

The architecture, engineering, and construction, (AEC) industry is demanding changes at an exponential pace. Although the building industry has been slow in technology adoption and data awareness, this sector has been very active in the acceptance of information, communication, and technology in the last few years, and it is trying to elevate the importance of technology and, crucially, data [1]. These changes are essential to develop innovative approaches to collaboration, create ways of integrating technology into work, lead the way in establishing environments that encourage diverse perspectives, plan, design, construct, and monitor with a higher degree of accuracy, and design the built environment in a way that promotes environmental growth rather than just economic growth [2]. Poor data capture and management processes, insufficient knowledge transfer from project to project, a lack of visualization processes, low levels of research and development (R&D) activities, and cultural and mindset issues are some of the challenges that the AEC industry faces, as identified in previous studies [3–7]. These challenges need an industry-wide transformation, and Industry 4.0 may offer a broad foundation for such a transition [8]. Rafael Sacks (2020) [9] presented a visual representation of the framework for successful technological advancements, which culminates in "adoption" (Figure 1). Technological advancements must be underpinned by three critical theories of design, information, and production theories; they must then rely on advances in technology, processes, and people through building information modeling (BIM); and finally, they must be supported by technology, business processes (needs), and entrepreneurship, ultimately leading to the final success metric, adoption [9].

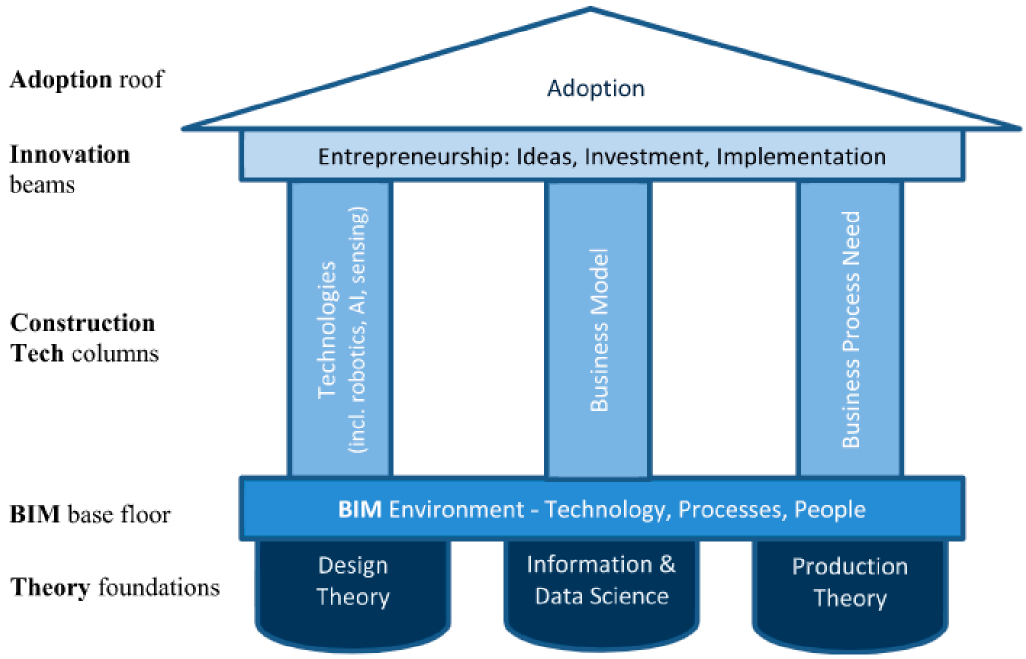

Figure 1. The house of construction tech. Reprinted from Ref. [9].

Lean construction (LC) is an approach for organizing projects to minimize waste and maximize performance at every stage from initiation to completion, based on mutual relationships and respect [10]. It is a paradigm-shifting approach to planning, designing, and constructing capital infrastructure [11–13]. LC's purpose is to increase predictability in construction projects by identifying and eliminating waste (time, materials, and effort), increasing productivity, lowering costs and timelines, improving collaboration between stakeholders, and maximizing the client's value, resulting in safer and more efficient projects [14,15]. All participants in LC must concur on the process's goals, milestones, and objectives. The lean construction concept model (LCCM) sums up seven LC principles and concepts: identify and map the value stream, perfection/continuous improvement, specify value, process variability, transparency, flow, and pull. BIM is defined by Autodesk as the whole process for the formation, creation, storage, and management of all data and information through intelligent nD digital model-based procedures for the entire lifecycle of a built asset [16].

The adoption of BIM as a process that culminates in a "Building Information Model" is rapidly becoming a critical component of total project improvement. What sets BIM apart from other design technologies is that BIM's data is properly structured, specified, and exchangeable, as well as its capacity to adapt to technology, business, and organizational structures [17]. The latest research on BIM and LC shows a positive and strong synergy of interactions between them, which includes increased visualization of products and processes, decreased process variation and cycle times, increased collaborative working, automation of some non-value-added activities, advanced prefabrication options, and improved value capture and rapid generation of alternatives via the use of BIM [10,18–20]. This synergy is evident during the planning, design, and construction phases of the project life cycle. While LC and BIM are used in conjunction, efficiency gains are much greater than when they are used alone. The result of the Lean-BIM collaboration is a virtual model that is very detailed, efficient, and accurate [21,22].

Additionally, advancements in XR, which encompasses virtual reality (VR), augmented reality (AR), and mixed reality (MR), have enabled researchers and industry professionals to elevate the AEC industry to the next level by enabling the viewing and collaboration of multidimensional (n-D) BIM content via cloud-based systems and in a real-scale environment [16,23]. When it comes to VR, it is used to replace surroundings with digital content, allowing users to fully immerse themselves in a digital world that is wholly unconnected to the real world. AR is used to improve the physical environment with digital content by overlaying digital content on top of real-world content to create an immersive experience [24]. Finally, MR is a hybrid of digital and physical environments that enables high interactivity between digital and real-world content [6].

The AEC industry is facing several challenges such as cost overruns, schedule delays, and quality issues due to the lack of efficient collaboration and communication among project stakeholders. The traditional project delivery approach, which relies on paper-based documentation, 2D drawings, and physical models, has limitations in terms of visualization and communication of complex design and construction processes. LC principles, BIM, and XR technologies have the potential to overcome these limitations by providing digital nD models that can be shared and visualized in real time, promoting continuous improvement, reducing waste, and enhancing productivity. However, the effective integration of these technologies with lean principles requires a comprehensive understanding of their interrelationships and potential benefits. Therefore, there is an urgent need to investigate how the integration of LC, BIM, and XR can enhance the AEC industry's project delivery performance.

In light of the fact that the interactive relationships and integrative applications of Lean-BIM and BIM-XR are expected to be effective, the purpose of this study is to critically assess the shortfalls and incoherence in the pertinent literature to conceptualize the integration of lean, BIM, and XR, as well as to propose new research directions in the field. LC, BIM, and XR are increasingly being used in AEC projects, but the integration of these three is often neglected to increase design and construction efficiency. This research strongly suggests using a Lean-BIM-XR project delivery management system to optimize the advantages of AEC project performance. As shown in Figure 2, this paper starts out with a literature review of the previous work on the concepts of LC-based AEC performance, BIM-based visualization support for LC (Lean-BIM), and BIM visualization in XR (BIM-XR) in the AEC industry in Section 2. This section also presents an overview of the most commonly used wearable XRs on the market. In Section 3, this paper presents an LBX process flow diagram and an IDEF0 diagram for the LBX project delivery management system in each stage of AEC projects, which consists of the design, construction, and operation stages. Section 4 suggests two possible scenarios for integrated lean, BIM, and XR implementation, which are referred to as "in the office" and "online/semi-online LBX meetings". Section 5 presented the LBX management system's strengths and weaknesses. In Sections 5 and 6, this paper concludes with the practical implications and open challenges of applying LBX to project management tasks.

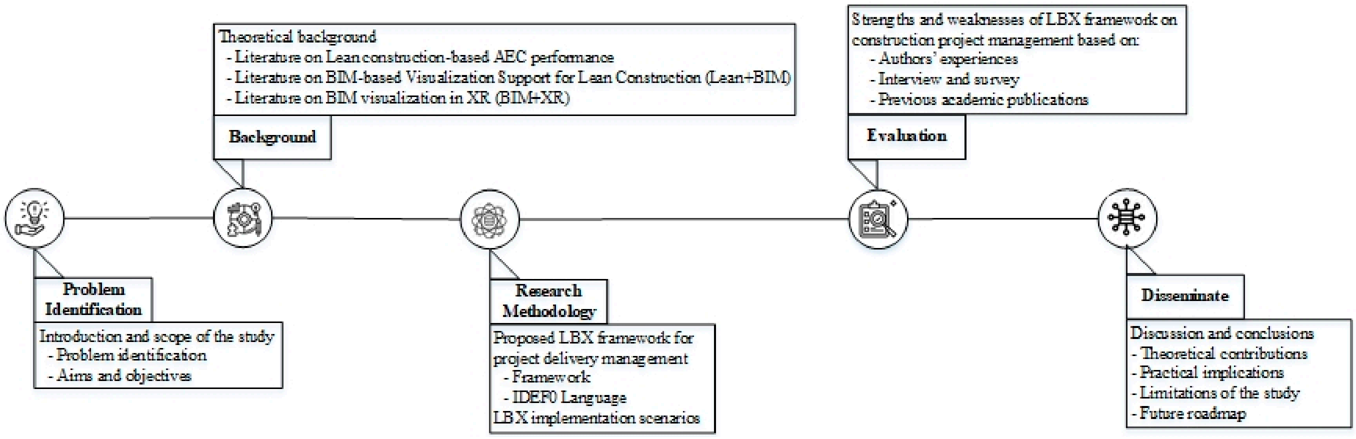

Figure 2. Research framework.

2. Theoretical Framework

This section sums up important studies in three main areas: (1) lean construction-based AEC performance; (2) BIM-based visualization support for lean construction (Lean-BIM); and (3) BIM visualization in XR (BIM-XR).

2.1. Lean Construction-Based AEC Performance

Recent years have seen rapid advancements in the integration of various technologies into AEC. While developing countries are committed to delivering infrastructure to support their growing populations, industrialized nations are concerned with the repair and maintenance of aging infrastructure. AEC industry solutions assist architects, engineers, contractors, owners, and many end-users in the development of large and complex commercial, residential, and industrial projects [25]. AEC industry solutions assist individuals in planning large and complex commercial, residential, and industrial projects, thus lowering capital costs and accelerating construction. Traditionally, the construction industry has been one of the largest in the United States, but its productivity has been lower than other industries [26]. Any construction project practitioner's favorite word is "success". Thus, defining success is a critical first step in achieving the desired outcome [27]. Individuals, stakeholders, and researchers often characterize project success differently and use a variety of metrics or key performance indicators (KPIs), such as cost, time, quality, client satisfaction, safety, sustainability, and profitability [28]. COVID-19 has caused delays in the AEC industry over the last two years; however, it also provided the potential to alter the thought processes and workflow. This demonstrates the critical significance of using novel techniques and technology.

LC is one of these approaches and processes that can assist AEC projects and their stakeholders in increasing productivity and achieving success [11,29]. The Toyota Production System (TPS) manufacturing philosophy was the first to establish the notion of lean manufacturing processes, and it is now extensively adopted across the globe [18]. This philosophy encourages businesses to increase the efficiency of their production processes. Numerous research methods have identified various lean manufacturing techniques, including efficient productivity and continuous improvement, employee motivation and organizational commitment, customer complaint mechanisms and customer satisfaction, green waste management and recycling practices, green human resource management (HRM), inventory management systems, production planning and control, resource utilization and exploitation, process and equipment, total preventative maintenance (TPM), sustainable waste reduction practices, stakeholder engagement, and wastewater treatment practices [30–33]. Some of the principles and sub-principles of LC are shown in Figure 3 [34].

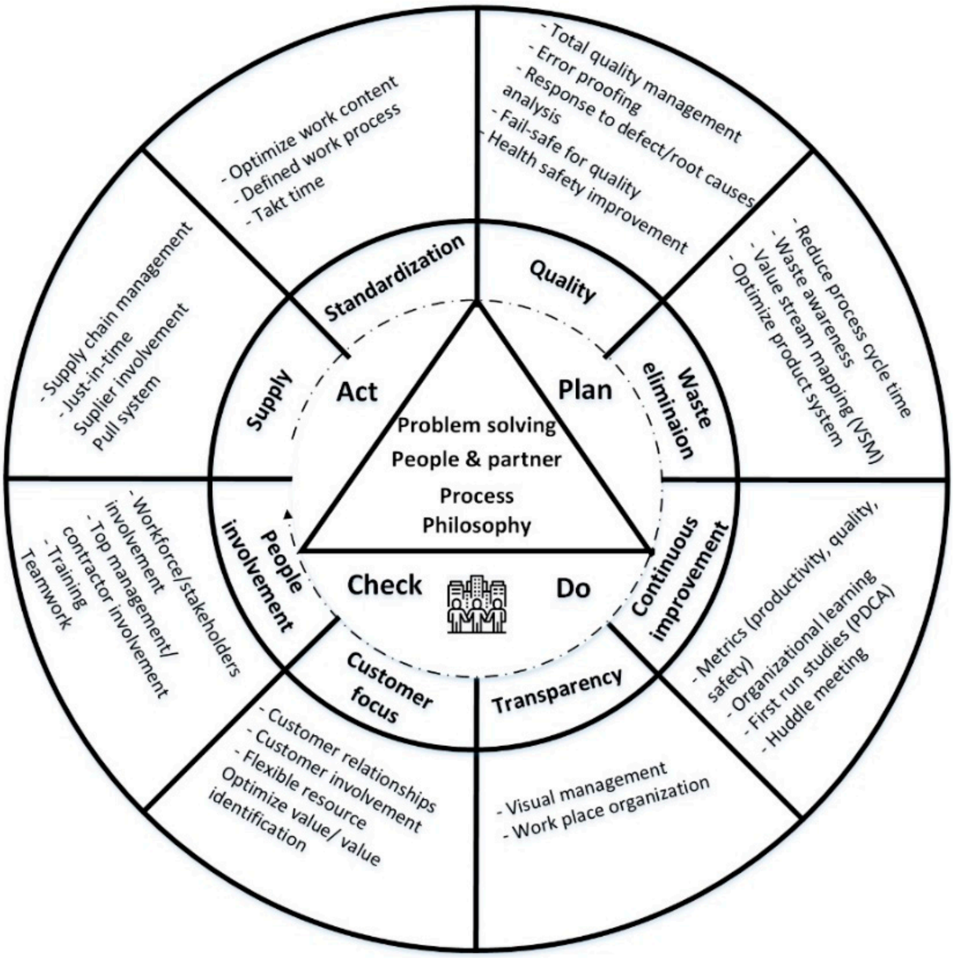

Figure 3. Lean construction framework.

LC aims to ensure that all aspects of the built environment function together and develop simultaneously everything from design to demolition [35]. This approach aims to manage and enhance construction processes through value-adding activities, such as the use of tools and techniques, as well as the perception of the production process as a continuous flow of materials, information, equipment, and labor, all while keeping costs low and maximizing value by taking into account customer needs. In accordance with numerous publications [36–40], some of the activities of lean thinking in the construction industry are summarized below:

(1) Respect for others is a tenet of lean thinking. Individuals transform concepts and materials into ultimate user value. In this paradigm, everyone's contribution is important, and tasks are performed right the first time;
(2) Lean thinking encourages continuous value evaluation and determines whether each resource is being used to its full potential;
(3) Lean thinking is a process-oriented approach that emphasizes flow and consistency through defined processes that produce repeatable results;
(4) Lean thinking drives people to continually seek to eliminate waste while also directly empowering individuals to fix their own challenges;
(5) To produce game-changing improvements, leaders must establish an environment where innovation is encouraged and small incremental failures are acceptable;
(6) Lean thinking aims to optimize the whole value chain, resulting in a safer and more satisfying work environment for employers, employees, and customers.

Despite all of the advantages of LC, there are significant obstacles to its widespread use in AEC projects that must be overcome before it can be widely adopted. Organizational acceptance, poor understanding and focus on the needs of the client, slow or partially visible and unverified outcomes by management, inaccuracies and incomplete designs, as well as a failure to apply the concept of design constructability, a lack of a long-term philosophy and planning, a failure to plan for quality, and insufficient management of the information necessary to begin a learning cycle and take corrective action are the main barriers for implementation.

2.2. BIM-Based Visualization Support for Lean Construction (Lean-BIM)

Building information modeling (BIM) solutions clearly meet many lean criteria when examined in the wide systematic viewpoint of construction planning and production control that LC thinking affords [41]. In a variety of ways, BIM contributes to meeting this need in a variety of ways, such as by automating some non-value-added activities, improving value capturing and rapid generation of alternatives, effectively communicating the intended sequence of processes to designers, ensuring that the space demand is met reliably, increasing visualization of products and processes, increasing collaborative working and advanced prefabrication options, and decreasing process variation and cycle times [42,43]. When used in combination with a fully specified manufacturing level, BIM simulations displaying specific work sequences are a powerful tool for developing and communicating standardized work practices [44]. BIM is effective in detecting and, in some situations, correcting design and construction issues and conflicts and generating accurate quantity take-offs, all of which minimize design and construction process variances [45]. It also facilitates the production of design drawings, design alternatives, quantity take-offs, construction schedules, and tasks, as well as substantial prefabrication support, resulting in shorter cycle times. Rapidly visualizing multiple design scenarios and their potential cost and schedule consequences can help improve efficiency [16].

The Lean-BIM synergy is no longer limited to the design phase, but can now be extended throughout the whole life cycle due to the fast development of multidimensional BIM capabilities and LC-based software [46]. This synergy is most visible during the design phase of the construction life cycle [47]. Target value design, set-based design, client-defined value, and collaborative design, as well as other LC-related design goals and concepts, make extensive use of BIM's multi-trade coordination and fast production of design solutions with fewer errors. Greater visualization of the design intent, efficient modeling for constructability, and sophisticated simulation options (e.g., lighting, heating, seismic resistance, and advanced pre-construction assessments) are among the BIM features that have been used. Visualization is currently supported by BIM in last planner pull sessions, design briefs, and stakeholder interaction. There are also initiatives to develop cutting-edge BIM-based systems for visualizing construction processes and facilitating visual controls on-site.

A variety of work activities have benefited from the use of 4D/5D simulations, such as resource allocation, time management, safety management, constructability, shorter cycle times, fewer requests for information (RFIs), reduced waste, and clash detection [48]. Additionally, since BIM models are highly compatible with industrial computer numerical control systems, they enable just-in-time (JIT) information, project drawings, material and logistical flows, and advanced, model-driven prefabrication. Although there are various benefits to connecting LC and BIM, some aspects must be taken into account to reap the full advantages of these integrations [49]. Neither BIM nor LC projects can be completed without strong organization and leadership in each phase and core processes of lean thinking, as well as BIM requirements, which must be taken into account. A strong collaborative culture between contractors and the supply chain should be implemented and a last planner schedule is necessary even on BIM projects to ensure stakeholders participation in short-term planning and improvement; and unclear roles and responsibilities should be defined. Based on previous research publications on the AEC industry, a summary of the advantages of the synergy of both lean and BIM paradigms and how they empower each other is shown in Table 1.

Table 1. Applications of synergies of lean and BIM (Lean-BIM), 2012–2022.

n	References	Year	Applications
1	[18]	2022	Applications of BIM-Lean-Sustainability synergy.
2	[50]	2022	Issues, implementation, utilization, and potential future application of LC-BIM.
3	[51]	2022	Assessing BIM's impact on LC performance.
4	[52]	2022	Investigation of BIM as a lean tool in the construction processes.
5	[53]	2022	BIM and LC for improving precast design workflow.
6	[54]	2022	Lean-BIM application in Malaysia's construction industry.
7	[55]	2022	Synergizing lean and BIM to enhance projects' productivity and performance.
8	[56]	2022	Identification of challenges and strategies for implementing BIM-LEAN in quantity surveying practices.
9	[57]	2021	Demonstrating the BIM-Lean-based synergy production management system to domain experts.
10	[58]	2021	Introduction and validation of LC principles and BIM functionality on mega-projects.
11	[59]	2021	Provide BIM and LC waste management exploratory research.
12	[60]	2021	Implementation of quantitative evaluation of BIM and lean on construction projects.
13	[61]	2021	Review published articles on lean, BIM, and the potential use of the IoT in the AEC industry.
14	[62]	2021	Applying BIM and lean practices to ensure early engagement of key stakeholders in decision-making.
15	[19]	2021	Examine the relationship between LDM and BIM in the planning and design stages of the infrastructure lifecycle.
16	[63]	2021	Development of a BIM-Lean framework for digitalization of pre-manufacturing stages in offsite construction.
17	[35]	2020	Review the adoption of LC and BIM in small- and medium-sized enterprises.
18	[64]	2020	Implementation of lean and BIM, and their impact on the value chain of a construction business.
19	[65]	2020	Examine critical success factors of BIM and LC integration for mega-projects.
20	[66]	2020	Utilizing BIM at look ahead meetings and in the last planner system.
21	[67]	2019	Lean-BIM-VR integration for heritage structure intervention planning.
22	[68]	2018	Lean-BIM integration in megaprojects.
23	[69]	2017	BIM-LC integration to enhance the quality of concrete bridge design.
24	[70]	2016	BIM and LC's impact on design management.
25	[71]	2015	Influence of lean in BIM adoption with two case studies.
26	[72]	2014	Lean-BIM integration approaches for Ireland's capital works management system.
27	[73]	2013	MEP collaboration using BIM and lean technologies.
28	[74]	2012	BIM maturity model interfaces with Lean-BIM interactions.

Note: n = reference number; BIM = building information modeling; MEP = mechanical, engineering, and plumbing; LC = lean construction; VR = virtual reality; IoT = Internet of things; LDM = lean design management; AEC = architectural, engineering, and construction.

2.3. BIM Visualization in XR (BIM-XR)

Extended reality (XR) refers to any physical and digital mixed environments, as well as human–machine interactions, that are formed by computer technology and wearables. The letter "X" represents any spatial computing technology, whether existing or future, that might be used [16]. Computer technology and wearables create all kinds of real and virtual integrated worlds and human–machine interactions, which are referred to as XR. XR may be characterized as an umbrella term that encompasses all three realities of AR, VR, and MR [6]. More and more people are using the term "XR" to put VR, AR, and MR experiences into real projects in the AEC industry, even though the term's meaning is sometimes unclear and defined in different ways. Figure 4 shows the differences between VR, AR, and MR.

There are a variety of XR-enabled wearables available on the market currently. Table 2 lists the most prevalent forms of wearable headsets, including three main categories of VR, AR, and MR. This table is useful for comparing different goggles based on their type and manufacturer so that users can see what the most common area of use is.

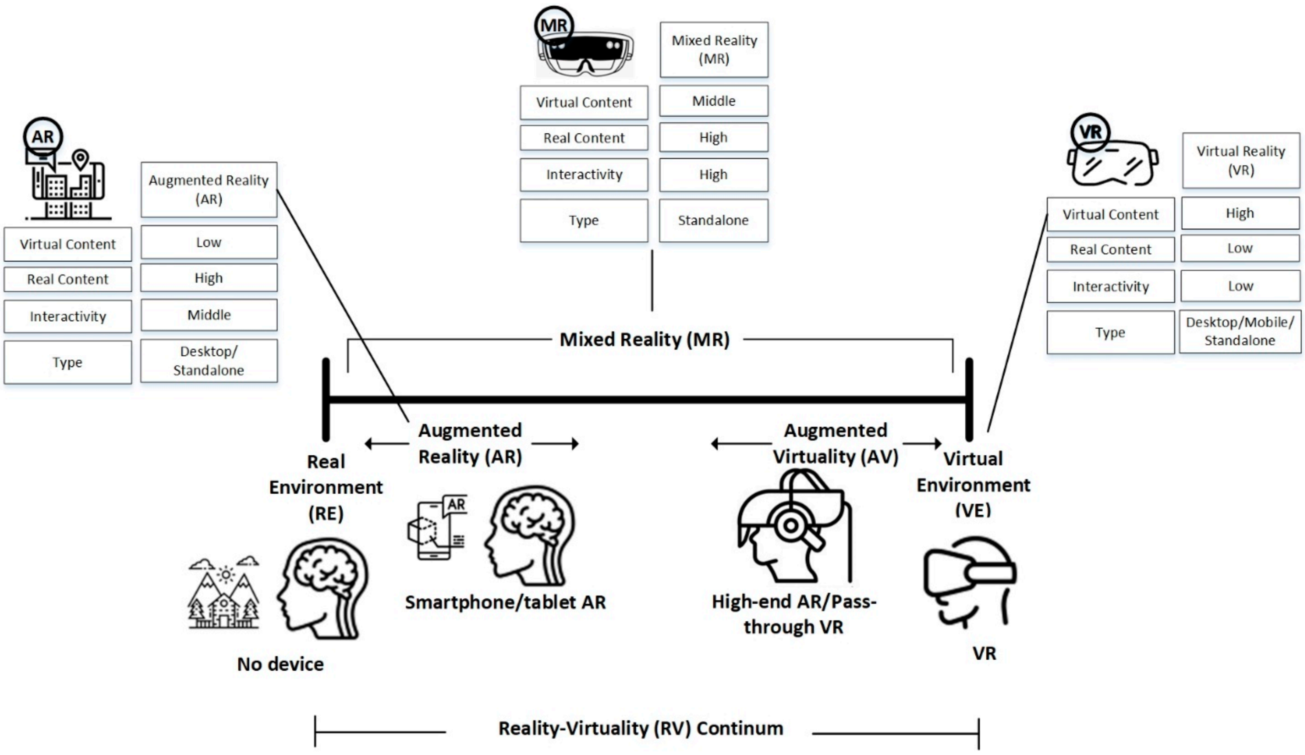

Figure 4. Wearable VR, AR, and MR technologies comparison (adopted from Ref. [16]).

BIM is about embedding information and data integration across the project life cycle; however, when this level is increased to the BIM-to-XR methodology, it allows for interactive design visualization with human scale and immersive experience. This workflow integration enables users to superimpose numerous design possibilities over actual worksite conditions or access additional information that is unavailable in reality. Aside from that, the BIM-to-XR conversion opens up a new path for design innovation that goes beyond 2D drawing. It is possible to add exceptional value to BIM processes by integrating holographic technologies, such as Microsoft Hololens 2, with them and integrate the design phase through the construction phase and the operations and maintenance phases.

An information-sharing platform or system is required for the BIM-to-XR process to facilitate the sharing of data and collaborative information while also enabling real-time communication between various stakeholders and users. There are several technologies available on the market for sharing BIM-XR data, but according to Banfi et al. (2019) [75], cloud-based platforms, such as Autodesk BIM Collaborate Pro, are the most popular and easiest to use. These systems integrate data in a BIM model into categories such as model, schedule, sheets, and text, among others, and in a variety of interchange formats such as rvt, nwc, txt, and dwg. Files can be communicated and shared through these main databases. According to the previous research in the AEC industry, Table 3 summarizes the advantages of the synergy between BIM and various XR technologies and how they complement one another.

Table 2. Most common wearable devices within extended reality, 2010–2023.

Type		Company	2013	2014	2015	2016	2017	2018	2019	2020–2023
Desktop	VR	Meta	*Oculus Rift DK1*		*Oculus Rift DK2*	*Oculus Rift*		*Oculus Santa Cruz*	*Oculus S*	
		HTC		*HTC Vive Dev Kit*	*HTC Vive Pre*	*HTC Vive*		*HTC Vive Pro (Wireless)*	*HTC Vive Pro Eye*	*HTC Vive Pro 2, HTC Vive Pro 3*
		Samsung					*Samsung HMD Odyssey*			
		Acer					*Acer Headset*			
		Dell					*Dell Visor*			
		HP					*HP Headset*		*HP Revereb*	*HP Reverb G2, HP Reverb G2 Omnicept*
		Lenovo					*Lenovo Headset*			
		Steam							*Valve Index*	
		Sony								*Sony PlayStation, Sony PlayStation VR2*
		Varjo								*Varjo VR-3, Aero*
	AR	Meta						*Meta 2*		
Phone-based	VR	Google		*Google Cardboard*		*Google Daydream*				
		Samsung			*Gear VR Innovator Edition*	*Gear VR*	*Gear VR with Controller*			
		Microsoft			*Microsoft HoloLens DK1*			*Microsoft HoloLens DK3*	*Microsoft HoloLens 2*	
Standalone	MR	Magic Leap		*The Beast*		*WD3*		*MagicLeap One*		*MagicLeap Two*
		DAQRI					*DARQI*	*DARQI Smart Glasses*	*Discontinued*	
		ODG					*ODG R7*	*ODG R9*		
		Nreal								*Nreal*
		Varjo								*Varjo XR-3*
	VR	Meta						*Oculus Go*	*Oculus Quest*	*Oculus Quest 2, Oculus for Business*
		Lenovo						*Lenovo Mirage Solo*		*Lenovo Think Reality VRX*
		HTC						*HTC Vive Focus*	*HTC Vive Cosmos*	*HTC Vive Pro 2*
	AR	Google	*Google Glass*				*Google Glass Enterprise Edition*			
		Apple								*Apple AR Headset*

Note: VR = virtual reality; AR = augmented reality; MR = mixed reality.

Table 3. Synergies of BIM and XR technologies in design and construction stages, 2012–2022.

n	References	Year	VR	AR	MR	Applications
1	[76]	2022	√	√	–	BIM and VR/AR data management and visualization techniques for structural health monitoring
2	[77]	2022	√	√	–	Meta-analysis of articles on AR/VR usage in AEC
3	[78]	2022	√	–	–	Use immersive VR to extend the potential of BIM in the AEC sector
4	[79]	2022	√	√	√	VR, AR, and MR with BIM integration review
5	[80]	2022	–	–	√	MR applications for on-site building renovation assessment
6	[81]	2022	√	√	√	XR applications, requirements, and development software in the lifecycle of a construction project
7	[82]	2022	–	√	–	Development of an on-site BIM-based AR defect management system for construction inspections
8	[83]	2021	–	–	√	Application of BIM-based MR for bridge inspection and maintenance
9	[84]	2021	√	–	–	BIM-Enabled VR for sustainability life cycle and cost assessment
10	[85]	2021	–	–	√	MR-based dataset generation for learning-based scan-to-BIM
11	[6]	2021	√	√	√	Digital twin-based construction progress monitoring management through reality capture to XR
12	[16]	2020	√	√	√	BIM-based XR process to support AEC project management
13	[86]	2020	√	–	–	Monitoring of construction projects
14	[87]	2020	–	–	√	Applications of MR in the AEC industry
15	[10]	2019	–	–	√	Integration of BIM, LC, and MR
16	[88]	2019	√	–	–	Design and construction education
17	[89]	2018	√	√	–	Construction safety
18	[90]	2018	√	–	–	Collaborative decision making
19	[91]	2018	√	–	–	Construction safety training
20	[92]	2018	–	–	√	Prefabrication
21	[93]	2018	–	–	√	Site survey
22	[94]	2018	–	√	–	Evaluate the effectiveness of BIM and AR
23	[95]	2017	√	√	–	Review and comparison of VR and AR
24	[96]	2017	√	–	–	Collaborative decision making
25	[97]	2017	√	–	–	Construction safety
26	[98]	2017	√	–	–	Construction safety
27	[99]	2017	√	–	–	Benefits and challenges for VR in the construction industry
28	[100]	2016	√	–	–	Construction safety training/jobsite management
29	[101]	2016	√	–	–	Building energy performance gap
30	[102]	2015	√	√	√	Architecture and environmental planning education
31	[103]	2014	–	√	–	Real-time communication and problem solving
32	[104]	2014	√	–	–	VR-based cloud BIM platform for integrated AEC projects
33	[105]	2012	–	√	–	Real-time communication and integration of BIM into the site and task conditions, and the interaction of BIM with the field crew

Note: n = reference number; √ = mentioned; – = not mentioned; BIM = building information modeling; VR = virtual reality; AEC = architectural, engineering, and construction; AR = augmented reality; XR = extended reality; LC = lean construction.

3. Research Methodology

3.1. Scope of Research

As shown in Figure 5, this research aims to optimize the performance of the AEC industry by exploring the integration of LC, BIM, and XR, referred to as LBX. The proposed application framework consists of three interconnected components that provide a comprehensive and effective project management approach. By utilizing the strengths of these three methodologies, stakeholders can design, collect, and manage real-time and accurate data, visualize the data, make informed decisions, and have the most comprehensive project management available. The research methodology involves identifying common areas among these three methodologies and technologies and exploring their integration to maximize the benefits of AEC projects. The ultimate goal of this study is to enhance construction project performance, efficiency, and quality by incorporating and utilizing these methodologies and technologies into projects.

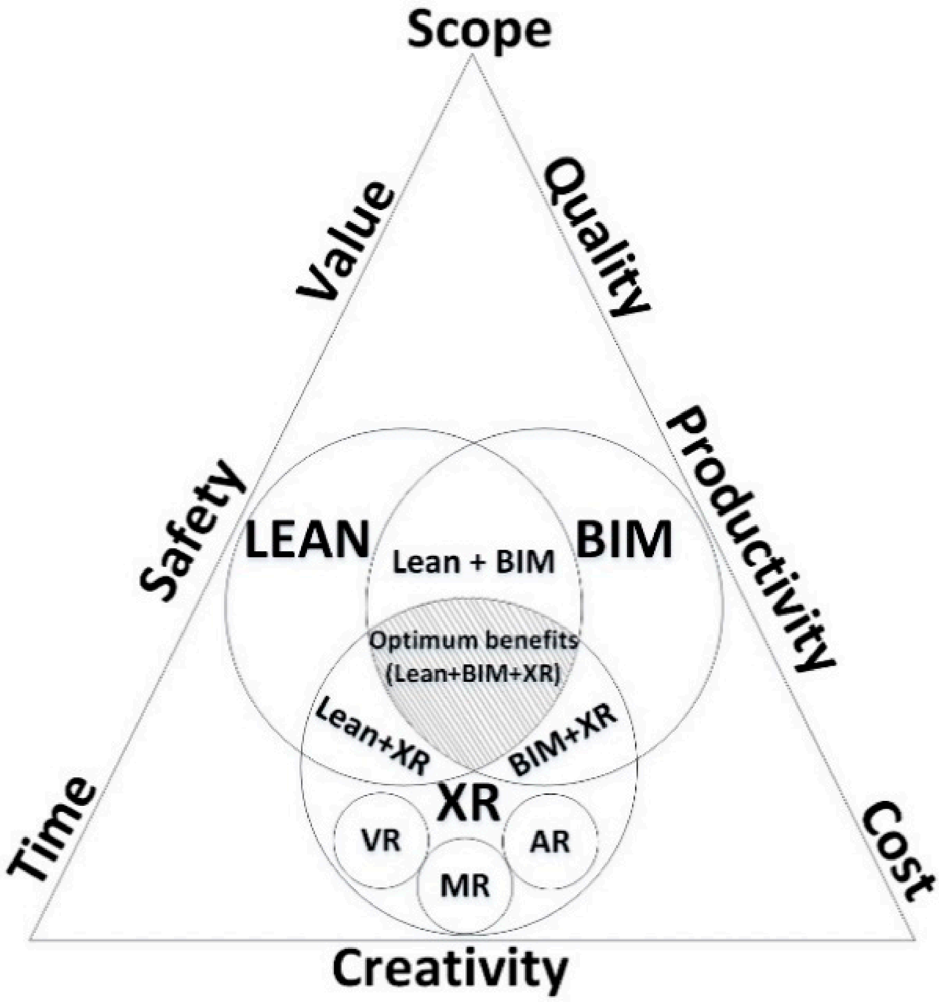

Figure 5. Model for implementing LBX project delivery management system.

The proposed LBX integration has the potential to revolutionize the construction industry by facilitating the adoption of a more comprehensive and effective project management approach. This approach is expected to result in a more effective delivery management system that addresses all relevant domains and implementation challenges and presents key project management issues in a systematic and cohesive manner. The integration of these methodologies will enable stakeholders to manage projects more effectively, make better decisions, and ultimately improve project outcomes.

3.2. Proposed nD-LBX Framework for Project Delivery Management (Lean-BIM-XR)

The key focus of this research is to conduct a review of existing BIM, XR, and lean approaches and techniques in the design and construction sectors to establish a conceptual model for integrating these principles and technologies as a unified process. This paper examines previous work on lean, BIM, MR, Lean-BIM, and BIM-XR, and provides a conceptual framework for enhancing construction project performance termed the "LBX project delivery management system". The procedures of the framework are described by the flowchart in Figure 6 and the IDEF0 model in Figure 7.

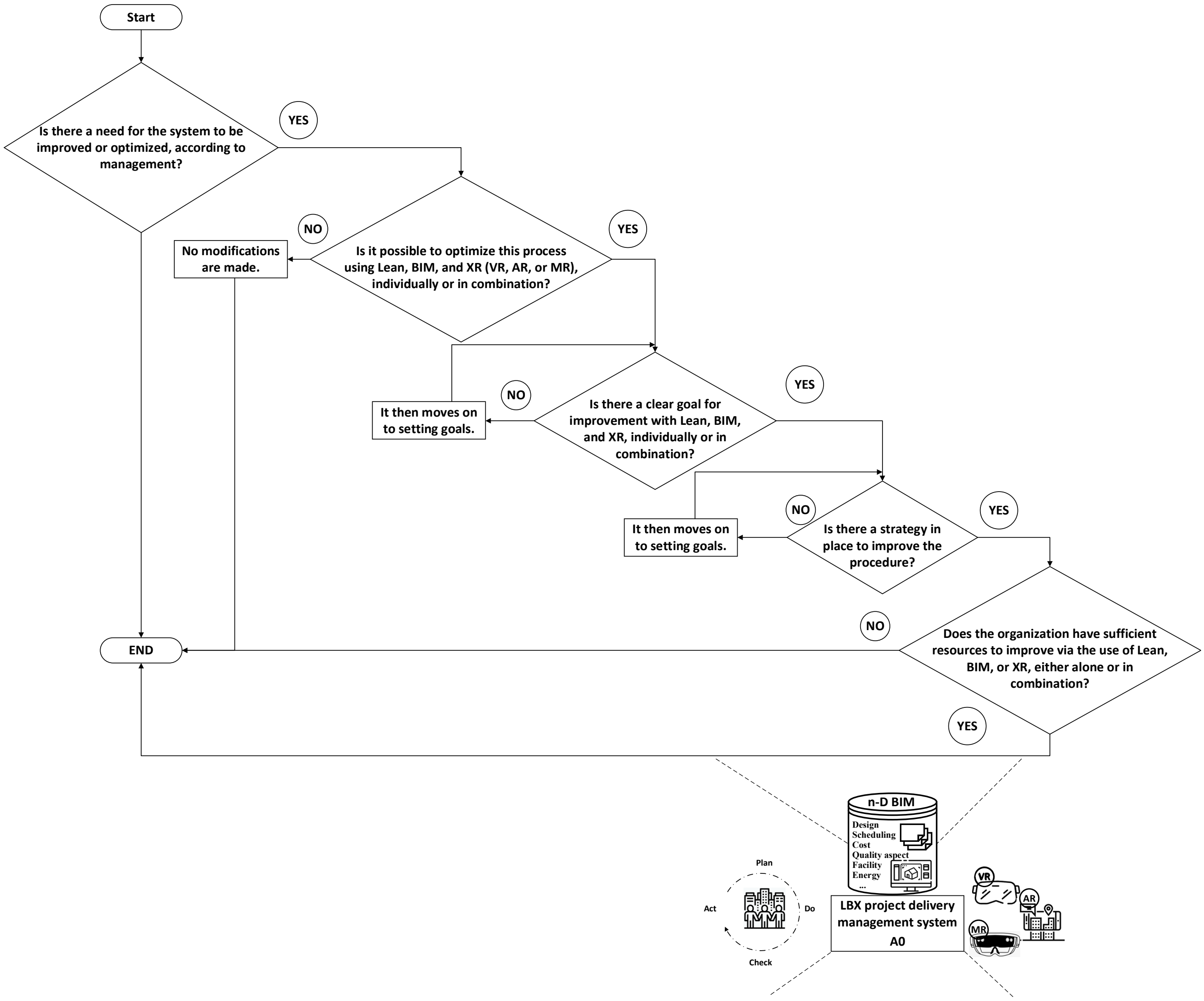

Figure 6. LBX process flow diagram.

The first step for each organization is to form an analytical team to examine the processes and identify what sort of optimization may be implemented, as well as whether the company wants or is capable of doing this optimization. The enhancements must be founded on LC principles, their interaction with BIM, and the use of various forms of XR, such as VR, AR, or MR, at different phases of the project. The process flow shown in Figure 6 should be followed to conduct an analysis of the processes. Many goals can be achieved by using formal procedures to manage changes that occur within the organization. These include continuous improvement, the minimization of variability, and engaging multiple management voices.

To conduct an appropriate process analysis, it is vital to determine if it is feasible or necessary to enhance the process by improving the methods, technologies, and processes applied. Whether the response is yes, the process moves on to ask the stakeholders if the improvement's goals are clear to them. It is critical to inquire if there has been an upsurge in value from the owner's standpoint, as the primary tenet of LC is to define value from the client's perspective. This inquiry is critical because it is in the process of making this inquiry that the organization will establish a strategy. Later, a strategy for improving each process will be established. To adapt this strategy to the realities of the organization, collaborative workshops are needed in which everyone engaged in each step participates.

Thus, it is feasible to acquire the diverse perspectives of everyone and thus verify that the Lean-BIM-XR enhancements contribute value to the company's value chain.

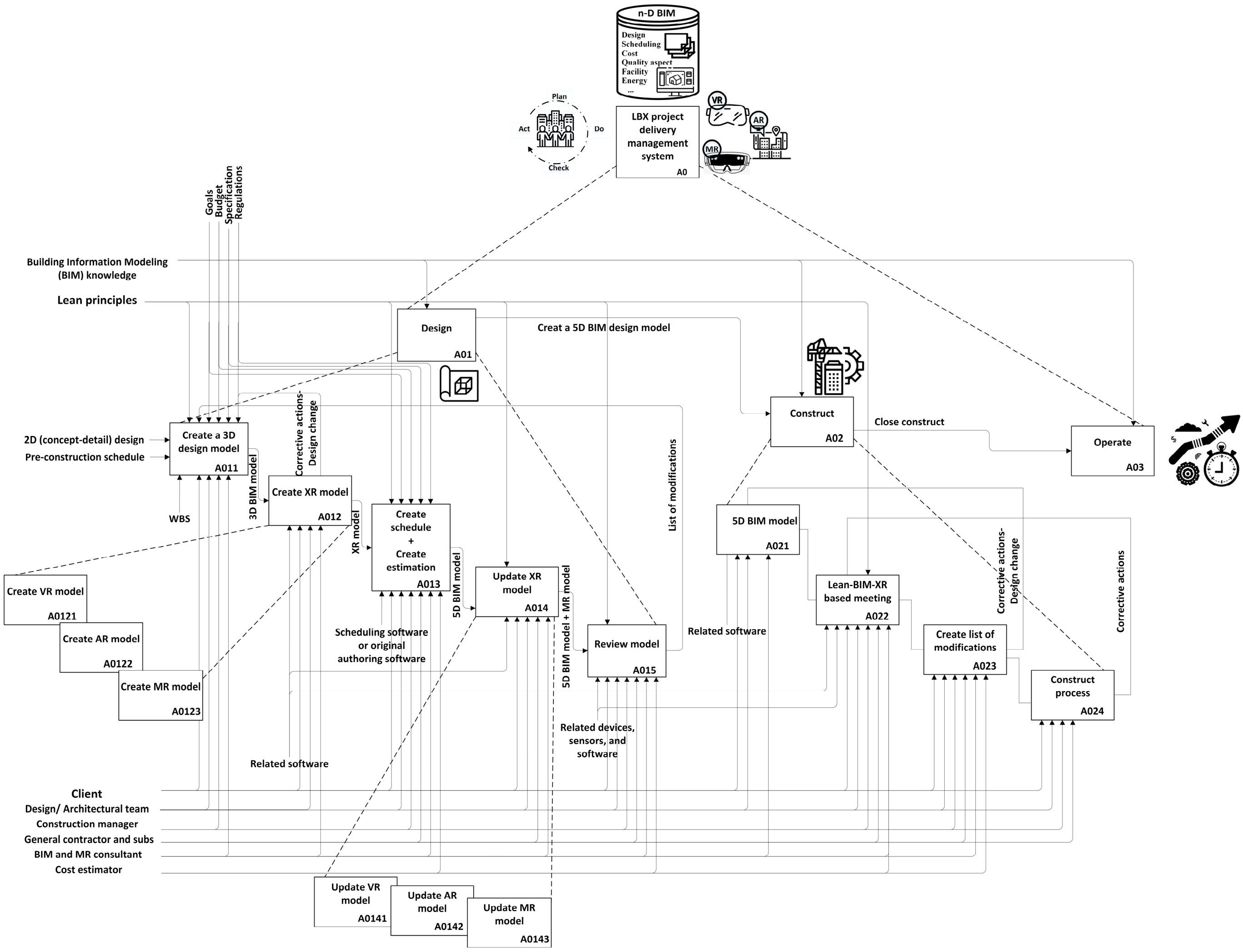

Figure 7. IDEF0 diagram for LBX project delivery management system.

In order for the process to be continuously improved, the strategy must be specific and include quantifiable/measurable objectives. Finally, the firm should have the necessary resources it needs to put the improvement plan into action. If these resources are unavailable, the lessons learned are documented in an information system that stores the data and information to make them available in the future. Finally, if the process is approved and the required resources are available, the team needs to go through the LBX process in detail and execute it step-by-step, as shown in Figure 6. If they follow the flow diagram, the feedback cycles within the company are guaranteed.

To effectively develop a management system strategy for any practical applications, the first step should be to obtain a comprehensive knowledge of the process. IDEF0 is one of the approaches that may represent industrial operations and communicate complicated ideas using simple boxes and arrows [106]. It helps develop, analyze, and integrate systems such as lean, BIM, and XR. The presented model in this study, graphically shown as an IDEF0 diagram, depicts an AEC project delivery management system. This adaptable, comprehensive, and understandable model is ideal for illustrating the interconnections between the pre-construction (design) and construction phases. Key processes are outlined in the boxes in Figure 7.

The proposed model, called LBX, comprised three phases: design (A01), construction (A02), and operations (A03). As illustrated in the LBX model (A0), the 5D BIM-based model (3D + schedule + estimation), in conjunction with lean techniques and XR technologies, is generated and optimized to identify possible mistakes and fix them via the LBX system during the design/pre-construction phase in the design stage. Due to the lack of actual projects in the pre-construction stage, VR may become more prevalent during this stage.

After the client, design team, and construction crews, as well as other involved project stakeholders, have agreed on the best appropriate design model scenario and approved the 5D model for the construction phase, the construction teams can use the LBX system to execute the following three functions:

- Clarify the project's execution on a regular basis.
- Identify errors and potential mistakes.
- Enhance communication and collaboration among stakeholders.

In the operational phase—with up-to-date, high-quality data—the LBX model can be used by anyone who is involved in the building's life cycle to obtain access to digital data at any time to use them for model records, schedule maintenance, analyze buildings, manage assets, plan for disasters, and keep track of space.

3.2.1. Design Stage (A01)

The planning stage of the proposed LBX framework, as seen in Figure 7, consists of five activities: A011 is for developing a 3D BIM-based design model; A012 is for developing an XR model; A013 is for developing a schedule and estimate; A014 is for updating the XR model; and A015 is for reviewing the model. Step A01 is focused on a construction project's planning and design stages. BIM, being one of the most influential contemporary design tools available, allows participants engaged in the design stage of a project to visualize a virtual model of the project before construction. Following the creation of a series of conceptual early alternative models, the designers can establish and discuss the optimized nD plans and choose the ideal scenario utilizing LC principles and meetings. Later, using a lean-based BIM model, BIM-XR professionals produce an XR model that enables project teams to immerse and visualize the clients and teams in prospective projects through goggles, computers, and tablets. Visualizing the 3D model contents allows for the detection and elimination of non-value-added design processes.

Using the combination of Lean-BM-XR at the same time significantly increases value-added activities and reduces the number of design cycles and design defects, resulting in a quicker, smoother, and more cost-effective construction project process. Clients and users will be able to see and experience how a project will appear and feel when using it. A design team can assess the simulated model scenario and identify issues where changes can be made. If the project team uses an updated/modified version of the BIM (3D) model, as well as a work schedule (4D), and a project estimate, they can effectively develop and convey a BIM (5D) model. Projecting a BIM model into XR enables architects to rapidly validate the model using lean principles to produce a final 5D design model that they can then present to owners in an interactive and immersive manner. In all stages of design, this model can be used. It can be used to make design options, to make interior designs that can be applied to real-world places, and to see if there are any problems with construction.

3.2.2. Construction Stage (A02)

After finalizing the 5D BIM model by merging BIM, MR, and LC, the next step is to put it into practice. As presented in section A02 of Figure 7, the construction stage consists of four main sub-activities. A021 is utilizing 5D BIM modeling, A022 is for having an LBX-based meeting, A023 is for creating a required or requested list of modifications, and A024 is for execution and construction. The key benefits of utilizing LBX during the construction stage are reduced uncertainty and waste, improved collaboration and communication, and enhanced construction process visualization. This integration contributes to reducing overall time requirements and enhancing value and quality for all crews. Stakeholders meet and interact remotely (online hybrid) or in person in a big room (at the office) to utilize XR technologies to assist in identifying constraints associated with planned and upcoming activities. The teams discuss and mark work handoffs and criteria of pleasure for activities after identifying and flagging potential obstacles. Teams commit to accomplishing weekly tasks during this phase, which is based on practical and realistic estimates. They discuss how and when they will be ready for each other's activities at this point. The "Look-Ahead" meeting adds value to the whole process and minimizes waste by repeated reviews of what they "Plan, Do, Check, and Act". This approach visualizes the project workflow, identifies deliverables and inspections, uncovers and removes constraints that prevent operations from being completed on time, within budget, and with the expected level of quality, and ensures reliable handoffs of work, resulting in collaboration, communion, and responsibility for the success of a project.

3.2.3. Operation Stage (A03)

The utilization of lean, BIM, and XR in the AEC industry provides significant advantages for improving communication and coordination among construction teams and facilities managers. BIM models can be utilized to recognize maintenance requirements and plan maintenance activities, while XR technologies can provide virtual training and simulations for maintenance personnel. These technologies facilitate more efficient and effective maintenance planning by delivering real-time data on equipment performance and energy consumption. These data can be leveraged to optimize maintenance schedules and reduce downtime, enhancing the overall performance and longevity of the building. Furthermore, the adoption of LBX in the operation and maintenance phase of the building lifecycle provides an opportunity for increased sustainability. LC methodologies can decrease waste and enhance energy efficiency, while BIM models can provide data on energy consumption and carbon emissions. XR technologies can be utilized to visualize and analyze building performance data, enabling informed decision-making around energy management and sustainability initiatives. By leveraging this integration, AEC projects can decrease their environmental impact and contribute to a more sustainable future.

4. LBX Implementation Scenarios

In this section, based on the authors' experiences, as well as a comprehensive analysis of previous publications, two possible scenarios for integrated lean, BIM, and XR implementation are suggested, which are referred to as "In the Office" and "Online/semi-online LBX meetings".

4.1. Scenario 1: In the Office

In the office, LBX rooms are basically dedicated meeting spaces in the workplace or office that allow stakeholders to focus on a certain project comprehensively as a whole, with a broader picture of the project than the narrow specialized areas where they do their day-to-day tasks. Physical space distribution has a direct impact on how professionals develop their tasks, even more so when working in a collaborative context such as lean, BIM, or XR. To facilitate more effective interactions, it is necessary to remodel the company's workspaces. Figure 8 shows a sample of using the office LBX environment system for a collaborative planning session and a close-up view of the smart master plan, nD BIM model display boards, XR display boards, and how a similar room space should be organized. The use of an LBX room is useful to bring together the owner and the other disciplines, achieving an integrated collaborative process. Professionals can work from their computers, different boards containing various linked data, reports, models, and documents, and they can also walk through a real-scale environment through their VR, AR, or MR devices and even share what they see on the XR projection screen. Furthermore, the LBX collaboration environment acts as a meeting and decision-making space for all project stakeholders to uncover issues or come up with creative tactics to develop new and constructive ideas and options.

Figure 8. A sample of using the office LBX environment system for a collaborative planning session and a close-up view of the master plan and 5D model display boards.

4.2. Scenario 2: Online/Hybrid from Different Locations

Figure 9 demonstrates the second proposed scenario, which is an online or semi-online LBX-based environment. In this scenario, the project team members are not situated in an LBX room together, so they have to be connected through online systems. So far, they rely on online video and audio conferencing software/platforms such as Google Meet, Microsoft Teams, Zoom, Skype, WhatsApp, and others. Various challenges affect these types of meetings, and they are not really as accurate and effective as people just hearing or seeing each other or 2D or 3D files on the screens. In the LBX system, all stakeholders are connected to a central cloud-based system and obtain access to shared files in 2D, 3D, 4D, or even 5D. Additionally, each one of them needs to be connected to these files through their VR or MR to see the nD BIM models. Through this system, all stakeholders are able to communicate scheduling, cost, quality, and various scenarios in a real-scale environment. In this process, some stakeholders can be gathered in the office while the rest from other locations can attend the meeting online. This system allows streamlined collaboration for the AEC industry and allows architects, engineers, general contractors, on-site personnel, and other stakeholders to spin up inputs in real time. Implementation of LBX conferencing tools and features facilitates better training, project management, and real-time environment-based communication with site teams, clients, etc. These cloud-based systems enable AEC companies and users the potential to leverage powerful project collaboration all under one roof. In this scenario, the BIM software, 2D CAD, pictures, documents, time scheduling, and cost estimating can be seen through XR devices and collaborated on while they are walking through the real-scale project with high-quality BIM models. As they can during office LBX meetings, all stakeholders can obtain access to all data and documents while they are able to share their experiences and suggestions through smart lean software. This system facilitates the completion of several tasks and the sharing of ideas among participants in kick-off meetings, construction meetings, project team meetings, contractor and subcontractor meetings, and so on. Microsoft Mesh for Teams and Meta Horizon Workrooms are new platforms to achieve this scenario.

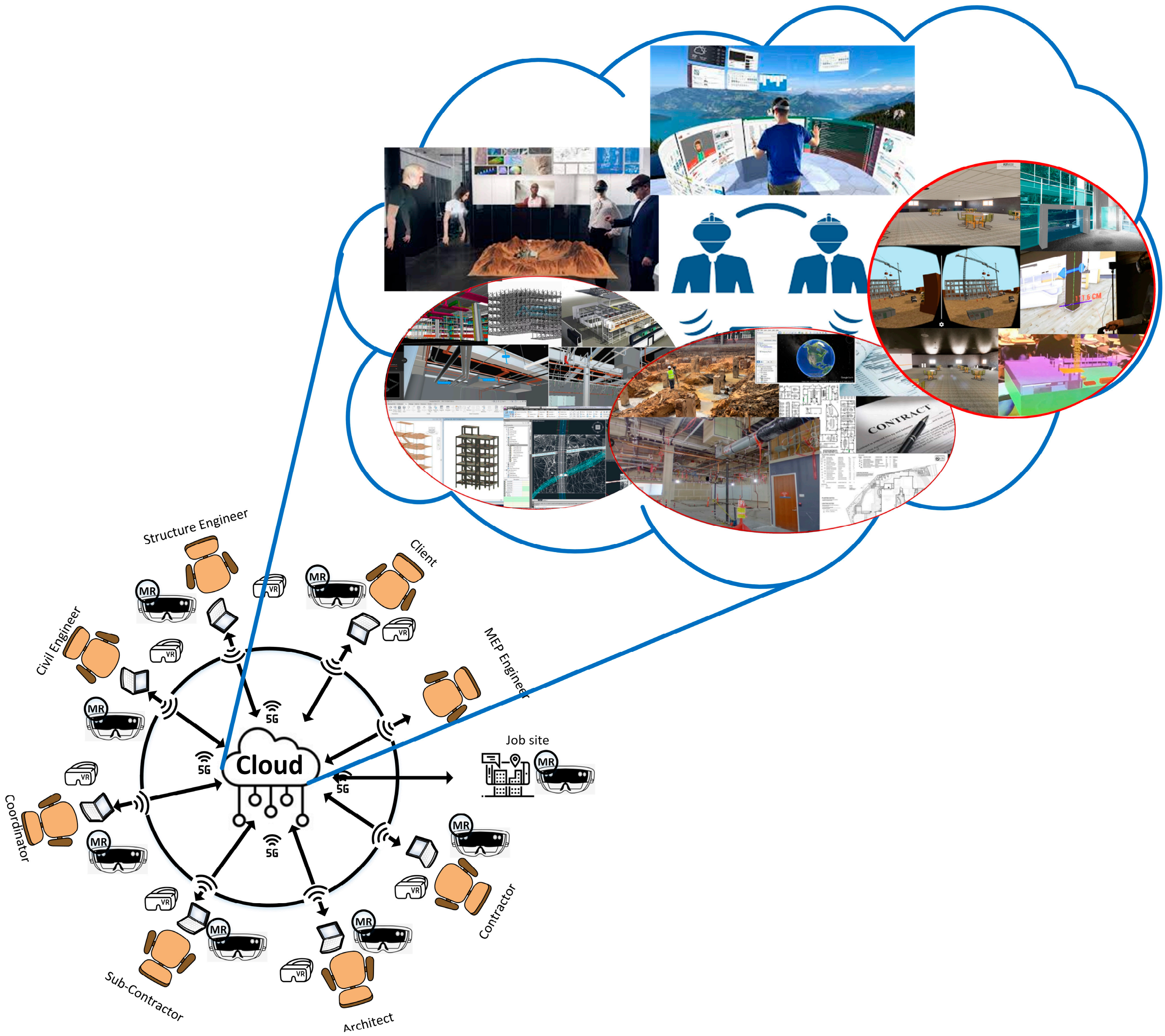

Figure 9. A close-up view of the sample of the master plan and 5D model display boards in the online/semi-online LBX environment system.

5. Evaluation and Lessons Learned: LBX on Construction Project Management

Through lean methodology, changes and improvements reduce the amount of time and resources that are wasted during the construction process. BIM is the foundation of digital transformation in the AEC industry, and immersive experiences are changing how we connect with people, information, and experiences in the AEC industry. Implementing XR helps bridge distance and address problems like never before. The cost of headsets, PC hardware, and software is still relatively high. While the software and plugins for lean, BIM, and XR have been rapidly improving in recent years, many BIM-authoring applications are still limited or missing support for material and texture definitions when exporting 3D data for visualization purposes. Additionally, the spread of data presents a new layer of vulnerability for cyberattacks, while the high cost of implementation is a barrier to entry for many firms. Table 4 summarizes the individual strengths and weaknesses of the LBX model of framework. The objective of evaluating the proposed model is to understand the effectiveness of the model if it is implemented in real-world practice, thereby validating the model. The strengths and weaknesses of the LBX system have been evaluated based on three sources:

- Authors' lessons learned (A): Based on the authors' knowledge and expertise, which includes more than 10 years of professional and academic practices in the fields of lean, BIM, and XR.
- Interview and survey (IS): The authors contacted a wide variety of professionals through LinkedIn and direct email in order to solicit feedback and conduct interviews with all those professionals. The authors conducted interviews with over sixty seasoned professionals who had a high level of information and were experienced with LC, BIM, and various types of XR technologies in order to evaluate the proposed framework. The authors provided enough information regarding the designed IDEF0 model, proposed LBX scenarios, and the main goal of the research projects. The questions were distributed via the LinkedIn platform and direct emails. The respondents were project management professionals such as BIM managers, 4D planners, VDC coordinators, construction managers, and project managers in consulting and contracting firms in the United States.
- Academic publications (P): The authors of this study conducted a comprehensive review of the most current publications published in the areas of lean, BIM, and XR and selected the ten most relevant studies that shed light on the mentioned strengths and weaknesses between 2012 and 2022.

The most important strengths identified in the large majority of studies include the 'Ability to simplify the design and construction process, and focus on concept selection', 'Construction process simulation/visualization', and 'Collaboration in design and construction and use parallel processing-Ability to use multi-skilled teams'. As seen in Table 4, there is ample evidence that the use of LBX in AEC project management is beneficial and desirable. According to Table 4, 'Lack of investment on purchasing, upgrading, and maintenance of Lean-BIM-XR (software-tools-equipment-training of people)' and 'Software and tools compatibility issue' were ranked as the top weaknesses and challenges of the implementation of the LBX system.

Table 4. Overview of the LBX management system's strengths and weaknesses.

Strength and Weakness	Brief Explanation	A	IS	Academic Publications												F
				Reference												
				[49]	[42]	[10]	[67]	[47]	[6]	[48]	[15]	[44]	[79]	[24]	[43]	
Strengths	Ability to simplify the design and construction process and focus on concept selection	√	X	*	*	*	*	*	*	*	*	*	*	*	*	14
	Generation and evaluation of multiple design alternatives	√	X	*	*	*	*	*	*		*	*	*	*	*	13
	Evaluation of conformance to program and client value	√	X		*	*		*	*	*			*	*	*	10
	Early involvement of all parties and multiparty agreements and a reduction in various types of risk	√	X	*	*	*	*	*	*	*		*	*	*	*	13
	Construction safety rules and code checking	√	X		*	*			*	*	*					7
	Better understanding of hazards and identification of potential hazards, warning of unsafe working conditions, and high-quality safety meetings with all visualization information	√	X		*	*			*	*	*					7
	Ability to simplify/expedite verification and validation of activities and ability to standardize the process	√	X	*	*	*	*	*	*	*	*		*	*		12
	Construction process simulation/visualization	√	X	*	*	*	*	*	*	*	*	*	*	*	*	14
	Ability to ensure comprehensive requirements capture	√	X	*	*	*	*		*	*						8
	Easily changed work practices	√	X	*		*	*	*	*	*	*	*	*	*	*	13
	Structured, centralized, defined, easy access, and exchangeable information	√	X	*		*	*		*		*		*	*	*	10
	Predictive analysis of performance	√	X			*			*	*	*				*	7
	Ability to decrease the number of change orders	√	X			*	*	*	*		*	*		*		9
	Ability to obtain required quality the first time	√	X	*	*	*		*	*	*	*	*		*		11
	Collaboration in design and construction and use the parallel processing ability to use multi-skilled teams	√	X	*	*	*	*	*	*	*	*	*	*	*	*	14

Table 4. *Cont.*

Strength and Weakness	Brief Explanation	A	IS	Academic Publications												F
				Reference												
				[49]	[42]	[10]	[67]	[47]	[6]	[48]	[15]	[44]	[79]	[24]	[43]	
Weaknesses	Culture of companies and resistance to change from traditional working practices	√	X			*			*		*					5
	Lack of investment in purchasing, upgrading, and maintenance of Lean-BIM-XR (software, tools, equipment, and training of people)	√	X	*	*			*	*			*	*			8
	Cost of hiring additional employees to implement Lean-BIM-XR	√	X			*		*	*	*			*			7
	Lack of integration between technologies and processes	√	X		*	*	*		*		*		*		*	9
	Lack of understanding and awareness about benefits and final value clearly for teams	√	X			*		*	*	*		*				7
	Lack of a common agenda between teams	√	X			*	*		*		*					6
	Lack of a comprehensive data management system and finding the right business model	√	X				*		*						*	5
	Software and tools compatibility issues	√	X		*	*		*	*	*			*			8
	Issues with data and model exchange between them	√	X			*	*		*		*		*			7
	The market is constantly evolving and developing with new emerging software, tools, and technologies	√	X			*			*							4

Notes: √ = mentioned; * = mentioned; BIM = building information modeling; XR = extended reality; authors' lessons learned = A; frequency = F.

6. Discussion, Practical Implications, and Open Challenges

This research aims to introduce a framework for enhancing AEC project delivery management by utilizing emerging technologies and methodologies. An LBX management model has been developed and introduced as part of this research. The LBX system integrates all the proposed technologies and methodologies currently in existence and on their path of evolution. This research has contributed to the collaborative use of these emerging technologies and methodologies as an LBX system to create, capture, analyze, manage, and visualize construction data, information, and reports for more efficient and effective project management.

This research also developed an LBX project delivery management model based on process modeling and IDEF0 language, provided guidelines for using various available technologies within the LBX framework, and examined the importance, strengths, and challenges of the LBX model. The LBX system optimizes data and information for decision-making at the pre-construction, construction, operation, and maintenance stages of any type and size of a construction project.

The adoption of LBX in the AEC industry has resulted in several successful implementation scenarios, which have demonstrated tangible benefits in terms of improved communication, coordination, and sustainability. One example of a successful LBX implementation is the Istanbul Grand Airport project, which utilized LC principles, BIM, and XR technology to coordinate and manage the construction process [107]. The project team utilized BIM models to optimize the design and construction phases, resulting in a reduction in project duration and cost savings. XR technologies were also used to simulate construction activities, identify and resolve conflicts, and provide virtual training for workers. This example demonstrates the potential of LBX technologies to optimize construction processes, reduce costs, and enhance communication and coordination among project stakeholders.

Due to recent developments in immersive technology and approaches, AEC professionals are changing the way they interact with people, information, and experiences. Implementing LBX bridges gaps and addresses issues in the AEC business like never before. This model helps facilitate all the project processes and activities to focus on concept selection. It also helps stakeholders to generate and evaluate multiple design alternatives for evaluating conformance to the program and increases client satisfaction. Moreover, with LBX, all parties can have early involvement (at the office or hybrid) in the project to obtain multiparty agreements to reduce various types of risk. This model framework aids in project safety management by checking construction safety rules and codes and alerting site personnel to potential hazards.

One of the system's largest challenges is the high cost of the software, plugins, apps, headsets, PC hardware, and installation. Additionally, the proliferation of data creates a vulnerability layer for cyber attacks that can be a barrier to entry for many businesses, specifically in the AEC industry. Some of the main challenges of the proposed integration are the culture of companies and a resistance to change from traditional working practices, the lack of investment in purchasing, upgrading, and maintenance of Lean-BIM-XR (software, tools, equipment, and training of people), the high costs of recruiting more staff to apply lean, BIM, and XR, insufficient process and technology integration, the lack of knowledge and awareness of the evident advantages and ultimate value for teams, the lack of a shared goal throughout the parties and teams, the lack of a comprehensive data management system and finding the right business model, software and tool compatibility issues, issues with data and model exchange between them, and the market, which is constantly evolving and developing new emerging software, tools, and technologies.

7. Conclusions

In the contemporary construction sector, corporations are compelled to enhance their level of agility to sustain their competitiveness amidst the highly cut-throat nature of the industry. This requires investment in new technologies and concepts and the adoption of a new culture, new skills, and processes. However, implementing these changes across an entire construction company can be challenging, which is why a comprehensive new framework and body of knowledge are necessary. In this paper, a proposed LBX project delivery management framework is presented for the design, construction, and operation phases of AEC projects.

The LBX model integrates modern construction management tools and procedures such as lean, BIM, and XR. This integration has the potential to significantly enhance sustainability in the AEC industry by improving project performance, reducing waste, and increasing energy efficiency. By combining the strengths of each technology, stakeholders can create more accurate digital models of a project, simulate the design in XR, and use LC principles to minimize waste and reduce the environmental impact of the project.

The LBX approach has the potential to reduce project costs and schedule overruns while promoting sustainability by reducing the environmental impact of the projects. However, there are some challenges associated with the technology, software, and platforms used in the LBX system. These challenges include the high-cost issues for most headsets, BIM and XR software, lean and BIM platforms, training of employees, and also the technical issues such as content generation for XR, the confusing complexity of the BIM to XR process, management's inability to comprehend the true scope and purpose of the project, interoperability, and security concerns associated with file sharing.

Despite these challenges, the overall findings of this paper suggest that LBX project delivery management systems should be deployed and actively developed to optimize the advantages of all AEC projects, regardless of the project procurement techniques or the project governance approaches. This research provides a constructive roadmap and suggestions for design teams, owners, contractors, subcontractors, construction managers, project managers, and any other stakeholders involved in the project. The LBX project delivery management framework presented in this paper has the potential to revolutionize the construction industry by improving project efficiency, reducing waste, and increasing sustainability. While there are challenges associated with the technology, software, and platforms used in the LBX system, the benefits of its implementation outweigh the costs. Therefore, construction firms should consider adopting the LBX model to stay competitive in today's fast-paced and ever-changing industry.

Future Works: The body of results shows the applicability of the LBX integration for a variety of AEC analysis scenarios. Future directions of research will focus on implementing the proposed LBX model of the framework in real-world scenarios, which will be executed by certain construction firms in the United States. Additionally, researchers might also want to investigate the proposed LBX model applications on several metaverse platforms, such as IrisVR prospects and Spatial, to improve the ability and quality of visualization, communication, collaboration, and enhancement of the interaction interface for different AEC projects.

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