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Virtual Design and Construction (VDC) in the Construction Industry: Current Practice and Future Prospects

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The construction industry faces increasing pressures from climate change, resource constraints, and rapid urbanization, driving growing interest in digital practices to improve project delivery. Virtual Design and Construction (VDC) has emerged as a promising approach; however, literature remains fragmented, with limited synthesis of its applications, benefits, and challenges. This study conducts a literature review of 476 publications and an in-depth analysis of 20 influential studies spanning diverse project types and contexts to evaluate the current state of VDC practice and prospects. The review identifies dominant VDC application trends, implementation patterns, maturity trajectories, and shifting implementation priorities across project phases and organizational contexts. Findings indicate a clear shift from early visualization- and coordination-focused uses toward more integrated, platform-oriented implementations that support project control, data-driven decision-making, and lifecycle considerations. Reported benefits evolve accordingly, from error reduction and communication improvement to enhanced schedule reliability, safety planning, and cost transparency through 4D/5D modeling. Persistent challenges include inconsistent definitions, limited standardization, high upfront investment, insufficient long-term validation of return on investment, and workforce gaps. By synthesizing these trends, the study clarifies how VDC has matured as a project delivery methodology and provides evidence-informed insights for researchers and practitioners. The findings underscore the importance of aligning VDC with Lean practices and emerging digital ecosystems, such as digital twins, artificial intelligence, and mobile technologies, to support more effective, resilient, and sustainable digital transformation in construction.

Keywords: Virtual Design and Construction, VDC, Building Information Modeling, BIM, Construction Industry, Project Delivery, 4D/5D Modeling.

Introduction

The Architecture, Engineering, and Construction (AEC) industry is experiencing a profound digital transformation, with VDC emerging as a key innovation that enhances Building Information Modeling (BIM) by integrating design, processes, and interdisciplinary collaboration in real time (Rafsanjani & Nabizadeh, 2023). Reflecting this trend, interest in VDC has surged; searches for *"virtual design and construction"* have increased by approximately 146% over the past five years, underscoring growing industry attention and adoption (*Exploding Topics*, 2025). Beyond the increase in interest, project-level studies report measurable impacts of VDC. In a case study involving MEP (Mechanical, Electrical, and Plumbing) coordination for a large healthcare project in Northern California, BIM/VDC tools yielded substantial results: 20–30% labor savings across MEP

subcontractors, 100% prefabrication for plumbing, virtually zero rework, and dramatic schedule and cost savings, six months shorter timelines and approximately USD 9 million in cost reduction (Khanzode et al., 2008). Despite these clear benefits, scholarly literature remains fragmented, lacking a unified synthesis of where and how VDC succeeds, what challenges persist, and which future directions are most promising. Foundational works elaborate on VDC's conceptual capabilities, integrating product, process, and organizational performance modeling (Del Savio et al., 2022). Empirical studies, on the other hand, document real-world gains in safety, coordination, and efficiency (Khanzode et al., 2008). Still, a comprehensive understanding that brings these perspectives together remains absent. This study addresses these gaps by conducting a structured literature review of VDC in the construction industry. This study seeks to answer the following research questions:
RQ1: What is Virtual Design and Construction (VDC) in the construction context?
RQ2: What are the applications of VDC in construction?
RQ3: What are the main challenges in implementing VDC?
RQ4: What are the benefits of adopting VDC in construction?
RQ5: What key research trends are shaping the future of VDC?
By exploring these questions, this paper clarifies the conceptual foundations of VDC, evaluates its practical applications and limitations, and identifies pathways for future research and implementation. The discussion proceeds with the research methodology in Section 2, followed by the background and conceptual frameworks of VDC in Section 3, and the literature review of its definitions, benefits, and challenges in Section 4. Section 5 considers limitations and future research, while Section 6 concludes with key contributions to both scholarship and practice. This structure provides a logical transition into the background of VDC, which serves as the foundation for the review.

Background

VDC has become an essential innovation in the construction industry over the past two decades. The term was first introduced at Stanford University's Center for Integrated Facility Engineering (CIFE) in 2001, where it was framed as a method of integrating multidisciplinary performance models to achieve project objectives. (Kunz & Fischer, 2016). Since then, VDC has been applied in both education and industry, evolving from a concept rooted in digital prototyping into a methodology that underpins Integrated Project Delivery (IPD) and digital transformation. As shown in *Figure 1*, the number of VDC-related publications between 2001 and 2025 has expanded with notable peaks that aligned with industry and technological milestones. While the literature initially concentrated on engineering and technical aspects, recent studies span fields such as business, social sciences, and energy, reflecting the broadening relevance of VDC (Shafiq & Afzal, 2020). However, the same trend analysis also shows a decline in recent years, indicating that although VDC has gained traction, standardized guidance and consistent adoption remain limited.

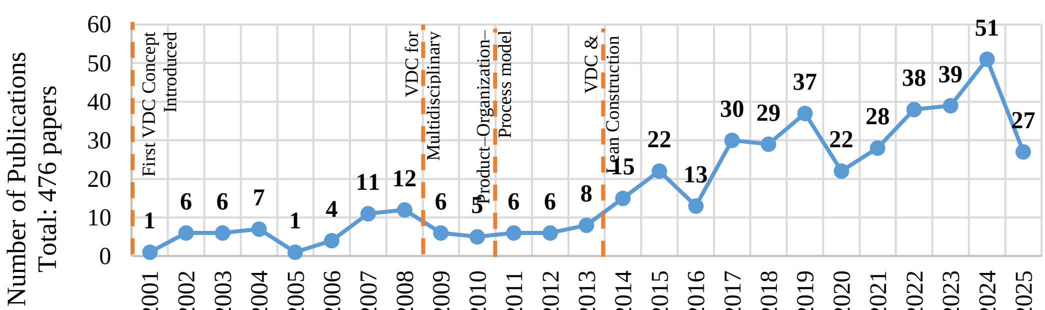

Figure 1. Number of VDC-Related Publications by Year (2001–2025) with essential milestones in the construction sector (Data was retrieved from the SCOPUS database).

Figure 1 illustrates publication trends over time, while Figure 2 provides an illustrative lens for interpreting the thematic evolution discussed in the Results section. This study employs a tree metaphor as a heuristic rather than a formal analytical framework (as shown in *Figure 2*). In this metaphor, the roots represent underlying industry drivers, such as efficiency, sustainability, cost, time pressures, and the need for collaboration, that motivate digital transformation in construction (Beucke et al., 2005). The trunk symbolizes the VDC core, which is structured around the integration of product, process, and organization (POP) models, a concept initially articulated by Kunz & Fischer (2016). Extending outward are the branches, which represent enabling technologies including BIM, Lean Construction, Digital Twins, Artificial Intelligence (AI), and Internet of Things (IoT) solutions that expand the applications of VDC (Alarcón et al., 2013; Alsafouri et al., 2015; Nguyen & Adhikari, 2023). The *"leaves"* signify tangible benefits of adoption, including reduced errors, improved collaboration, efficiency gains, and return on investment (Del Savio et al., 2022; Gilligan & Kunz, 2007). Finally, the canopy symbolizes the future, where VDC increasingly integrates with emerging technologies to foster greater automation, sustainability, and resilience (Rafsanjani & Nabizadeh, 2023; Sacks et al., 2010). This metaphor underscores VDC's evolutionary trajectory: rooted in industry challenges, structured by core methodologies, and continuously branching into new applications and outcomes.

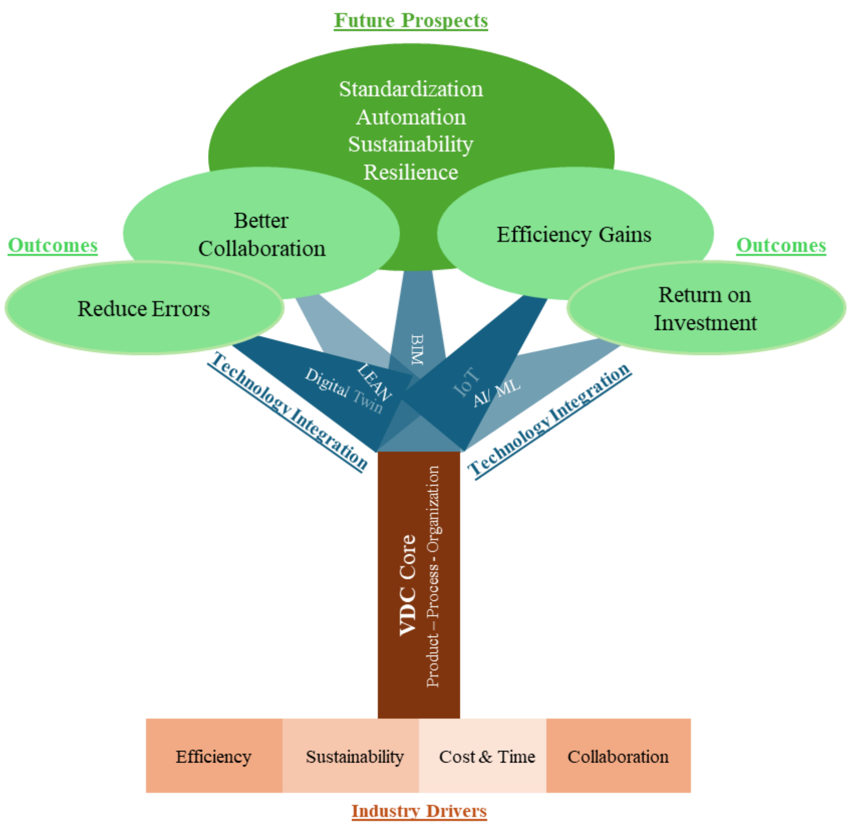

Figure 2. Tree Metaphor for Virtual Design and Construction (VDC)

The literature describes a wide range of VDC applications across the project lifecycle. During the design stage, VDC supports constructability reviews, clash detection, and collaborative workflows, enabling stakeholders to evaluate options virtually before physical implementation (Knotten & Svalestuen, 2014;

Leite, 2012). At the construction stage, VDC enhances scheduling, cost management, and safety visualization, integrating multiple information dimensions to support coordinated project delivery (Khanzode et al., 2008; Lee et al., 2020). In the operations phase, some research examines the use of digital models for facility management tasks, including tracking asset information and linking lifecycle data (Said & Reginato, 2018). Collectively, these studies illustrate the range of contexts in which VDC has been applied across design, construction, and operational settings. The benefits of VDC adoption are consistently reported across case studies and empirical research. Studies have shown measurable improvements in cost savings, schedule adherence, and collaboration (Barlish & Sullivan, 2012; Franz & Messner, 2019). Structured ROI analyses confirm reductions in design errors and rework, yielding efficiency gains and more predictable project outcomes (Stowe et al., 2015). VDC also strengthens teamwork and communication, which Franz et al. (2017) found to be directly correlated with project performance. Additional benefits include improved safety, enhanced stakeholder decision-making, and higher design quality (Alsafouri et al., 2015; Matinaro & Liu, 2015). These findings are reported across a variety of project types and organizational contexts.

Despite these advantages, significant challenges still constrain widespread VDC adoption. Technological challenges include interoperability limitations, the complexity of multi-dimensional modeling, and the lack of automation in constructability evaluation. (Li et al., 2009). Organizational barriers often stem from resistance to change, unclear ownership of digital models, and insufficient standard operating procedures (Filho et al., 2016; Shafiq & Afzal, 2020). Economic concerns persist as well, with many firms hesitant to invest heavily in VDC without more unmistakable evidence of return on investment (Rafsanjani & Nabizadeh, 2023). To overcome these barriers, researchers have called for unified frameworks for performance measurement and evaluation (Majumdar et al., 2022), but consensus remains limited. Several studies emphasize organizational and process-related factors that influence VDC adoption. Commonly cited factors include leadership support, workforce training, and stakeholder engagement throughout project delivery (Antwi-Afari et al., 2018). Knotten & Svalestuen (2014) emphasize the role of transparent metrics in improving design management, while Gerber et al. (2010) examine the relationship between VDC practices and Lean Construction principles, focusing on shared objectives related to coordination and workflow planning. These studies describe organizational conditions that are frequently referenced in discussions of VDC implementation.

Looking forward, VDC research is increasingly focused on integration with emerging technologies and future-proofing construction practices. Rafsanjani & Nabizadeh (2023a) argue that combining VDC with digital twins, artificial intelligence (AI), and IoT can enhance predictive analytics and real-time decision-making. Mobile and wearable technologies are also examined as mechanisms for providing on-site access to model-based information and safety-related data (Alsafouri et al., 2015). In addition, several authors highlight the need for more consistent evaluation approaches, including standardized ROI frameworks and longitudinal studies, to assess VDC implementation over time and across regions (Said & Reginato, 2018; Stowe et al., 2015).

Methodology

This study employed a structured literature review to identify, screen, and synthesize existing studies in the construction field. Literature searches were conducted using the Scopus database, which indexes leading peer-reviewed journals and conference proceedings in construction management, engineering, and digital technologies. The search was limited to publications from 2000 to 2024, reflecting the emergence of VDC as a formal concept and capturing its subsequent development. Targeted keyword combinations were used, including *"VDC," "Virtual Design and Construction,"* combined with *"Construction"* or *"Building."* To broaden the scope, additional keywords, including *"Building Information Modeling"* and *"BIM,"* were incorporated, ensuring that newer approaches and related concepts were captured. Only peer-reviewed journal articles and conference papers published in English were considered. Studies included if they (1) explicitly addressed VDC or closely aligned VDC-based practices in construction, (2) reported applications, implementation strategies, benefits, challenges, or future research directions, and (3) contributed empirical evidence, conceptual frameworks, or systematic analysis relevant to construction projects. Studies were excluded if they focused solely on generic BIM without a VDC context, addressed non-construction industries, or lacked sufficient methodological or conceptual detail. The initial search yielded 476 publications across disciplines, including engineering, computer science, energy, environmental science, and multidisciplinary outlets. From this pool, studies explicitly addressing VDC in the building sector were identified as the core dataset. To provide a focused analysis, 20 of these studies were examined in depth based on their relevance, scholarly contribution, and coverage of key themes. The review emphasized that definitions, applications, implementation challenges, documented benefits, and key trends are shaping future research on VDC in the construction industry. This methodological approach allowed the study to map the current state of VDC, highlight emerging trends and constraints, and identify knowledge gaps in the literature. By synthesizing findings across the selected publications, the research provides a comprehensive overview of VDC in the construction industry, ensuring alignment with the research objectives outlined in the abstract and discussion sections.

Results & Discussion

Building on the methodology, which identified and reviewed 20 key academic papers on VDC, the results synthesize the diverse perspectives, definitions, and findings from this body of literature. To provide clarity and avoid misconceptions, the analysis organizes the reviewed studies into five central themes: definitions of VDC, its applications, the main challenges to adoption, the benefits of implementation, and future research directions. This structured approach enables a comprehensive understanding of how VDC has been conceptualized and applied across the construction industry, while also highlighting areas of consensus and ongoing debate.

Question #1: What is Virtual Design and Construction (VDC) in the construction context?

In both industry and academia, several definitions of VDC are still in use, leading to varied interpretations and misunderstandings of the concept. In the construction context, VDC is best understood as a model-based methodology that integrates people, processes, and technologies to enhance project delivery throughout the life cycle. Scholars consistently emphasize that VDC relies on integrated, multidisciplinary computer models that combine product design, construction methods, organizational structures, and performance objectives to align projects with business goals (Filho et al., 2016; Kunz & Fischer, 2020). These models offer visual and data-driven representations that enhance communication, minimize errors, and facilitate more efficient planning and execution (Beucke et al., 2005; Hassan et al., 2018). Unlike traditional document-centric practices, VDC promotes data-centric decision-making, enabling stakeholders to evaluate alternatives virtually before construction begins (Lee et al., 2020). By linking BIM with performance objectives, VDC also creates opportunities to reduce waste and strengthen Lean-oriented project delivery (Alarcón et al., 2013).

Question #2: What are the applications of VDC in construction?

The industry is applying VDC in the building sector due to its diverse potential applications. These applications are wide-ranging, supporting activities from early design through facility operation. VDC allows projects to be virtually built before actual construction, improving design choices, coordination, and constructability analysis (Filho et al., 2016). For instance, it is applied in bidding and tendering stages to provide transparent information, engage contractors early, and enhance decision-making on constructability and operational issues (Hassan et al., 2018). VDC also supports design coordination by reducing errors and information requests, particularly in complex systems such as MEP (Filho et al., 2016; Said & Reginato, 2018). Visualization technologies, including photorealistic imaging, interactive 3D models, and VR-based tools, enhance stakeholder communication and bid presentations (Beucke et al., 2005). Beyond design and planning, VDC facilitates production measurement and project monitoring through 4D and 5D modeling, linking cost and schedule data to improve project control (Lee et al., 2020; Majumdar et al., 2022). Applications further extend to safety training, active health monitoring, and mobile VDC use, which make construction processes more transparent and accessible in the field (Alsafouri et al., 2015; Shafiq & Afzal, 2020). In facility management, modeled assets can be tracked and maintained throughout the operational phase, ensuring long-term efficiency (Lee et al., 2020). Collectively, these applications demonstrate VDC's value in enhancing collaboration, mitigating project risks, and improving overall productivity and safety across the built environment (Kunz & Fischer, 2020; Matinaro & Liu, 2015). Several of these applications underpin the benefits discussed in Q4, particularly in relation to coordination, safety, and project control.

Question #3: What are the main challenges in implementing VDC?

Although VDC shows potential for improving construction efficiency and integration, several challenges continue to hinder its implementation. A significant barrier is the fragmentation and inadequacy of existing scheduling practices, which require superintendents to manually integrate production and master schedules to obtain realistic project progress (Garcia-Lopez & Fischer, 2014). The adoption of VDC also demands substantial cultural and behavioral changes in industry practices, as well as defined constructability approaches to convert tacit, experience-based knowledge into computable processes (Filho et al., 2016; Leite, 2012). Technical challenges include difficulties in detecting soft conflicts, misalignment in performance model definitions, and the complexity that arises when integrating high-dimensional VDC-BIM models (Lee et al., 2020; Majumdar et al., 2022). Organizational barriers, including the lack of standard operating procedures, limited understanding of return on investment, and the absence of validated implementation strategies, further complicate adoption (Alarcón et al., 2013; Shafiq & Afzal, 2020). Financially, VDC requires considerable investment in software, hardware, and skilled personnel, leading to disputes about cost allocation and uncertain business value (Li et al., 2009; Rafsanjani & Nabizadeh, 2023). Moreover, ongoing debates about what project data should be gathered and how it should be structured highlight the need for more straightforward implementation guidelines (Yee et al., 2013). Together, these challenges demonstrate that successful VDC implementation necessitates not only technological readiness but also aligned processes, standardized frameworks, and a commitment to change across the industry.

Question #4: What are the benefits of adopting VDC in construction?

The VDC concept primarily benefits professionals, including facility managers, architects, engineers, developers, builders, and owners. The adoption of VDC in the construction industry offers a wide range of benefits that enhance efficiency, collaboration, and project performance throughout the entire life cycle. At its core, VDC improves communication by providing shared, visual, and data-rich models that facilitate more effective coordination among stakeholders, thereby reducing misunderstandings, disputes, and delays (Beucke et al., 2005; Hassan et al., 2018). These benefits extend to project planning and management, where VDC reduces project duration, enhances workflow, and improves management efficiency (Leite, 2012). By integrating Lean principles, VDC activates process improvements that minimize waste, support constructability, and strengthen delivery systems (Alarcón et al., 2013; Filho et al., 2016). On the technical side, it enhances design quality, enables error detection and correction, and facilitates the prefabrication and rehearsal of construction plans, thereby reducing risks and rework (Li et al., 2009; Matinaro & Liu, 2015). Safety outcomes also benefit, as VDC supports proactive hazard detection and enhances on-site safety training (Shafiq

& Afzal, 2020). Beyond construction, VDC facilitates facility management by reducing technical barriers for clients, enabling efficient data sharing, and enhancing long-term decision-making (Lee et al., 2020; Rafsanjani & Nabizadeh, 2023). Collectively, these advantages demonstrate that VDC is not only a visualization and coordination tool but also a transformative framework for achieving higher quality, safer, and more sustainable project delivery (Kunz & Fischer, 2020).

Question #5: What key research trends are shaping the future of VDC?

Research on VDC has evolved in parallel with technological advancement and changing project delivery practices in the construction industry. Early studies in the mid-2000s framed VDC primarily as a visualization and coordination tool, emphasizing 3D and 4D modeling, photorealistic representations, and schedule simulation to improve communication and constructability during design and preconstruction (Beucke et al., 2005). During this phase, VDC was positioned as an extension of BIM-enabled modeling to reduce design errors and enhance planning accuracy. Between the late 2000s and early 2010s, research shifted toward process integration and decision support, redefining VDC as a data-centric project delivery approach. Studies increasingly emphasized interdisciplinary collaboration, early contractor involvement, and alignment of product, organization, and process models to support decision-making (Kunz & Fischer, 2016; Li et al., 2009). Concurrently, researchers explored integrating VDC with Lean construction principles, highlighting its potential to support production planning, workflow reliability, and performance-based management.

Recent VDC research demonstrates a clear shift from exploration implementation toward metric-driven validation and organizational scalability. Current studies emphasize standardized performance metrics, prospective validation, and comparable ROI frameworks as prerequisites for institutionalizing VDC across projects and firms (Kunz & Fischer, 2020; Majumdar et al., 2022). This trend reflects a maturation of VDC from project-specific experimentation to repeatable delivery practice. At the technological frontier, VDC is increasingly positioned as an enabling layer within integrated digital ecosystems, supporting the convergence of digital twins, data-driven analytics, and real-time decision support across the project lifecycle (Rafsanjani & Nabizadeh, 2023). In addition, research consistently identifies organizational readiness, leadership, workforce capability, and process alignment as the primary determinants of sustained VDC adoption, often outweighing technological factors alone (Del Savio et al., 2022; Shafiq & Afzal, 2020). Collectively, these trends illustrate VDC's progression from visualization-based innovation to a performance-driven, digitally enabled project delivery paradigm.

Recommendations, Limitations, and Future Research

This study establishes VDC as a mature delivery framework whose effectiveness depends on disciplined implementation rather than isolated digital use. The findings indicate that performance gains occur when VDC practices are embedded in project governance and aligned with BIM Execution Plans (BEPs), thereby enabling consistency across projects. To scale impact, VDC should function as an operational system integrated with Lean Construction, supporting production planning and workflow control. Emerging technologies, including 4D/5D modeling, digital twins, and AI, should be applied selectively to enable real-time decision-making and lifecycle use. Sustained investment in training and capability development remains essential, as workforce readiness continues to constrain adoption. Collaborative procurement approaches, such as IPD, further support early stakeholder engagement and VDC-enabled workflows. Despite these promising recommendations, this study acknowledges several limitations in both the literature and practice of VDC implementation. One key issue is that much of the existing evidence relies on case studies and anecdotal reports, limiting its generalizability across contexts. Additionally, there remains a lack of longitudinal data on project performance with and without VDC, which makes it challenging to measure sustained benefits. Furthermore, regional and organizational differences, such as contractual frameworks, digital maturity, and workforce training, restrict comparability between studies. Finally, technical limitations persist, including interoperability challenges, insufficient integration with scheduling procedures, and the high cost of adopting software and hardware. Together, these limitations show the ongoing challenges of scaling VDC practices globally across the construction. To address these challenges, future research should pursue several interconnected directions. First, studies should develop robust industry-wide metrics and maturity models, such as VDC scorecards, to evaluate adoption levels and return on investment across different project types. Second, researchers should examine the integration of VDC with emerging technologies, including digital twin platforms, AI-driven predictive analytics, IoT sensors, and AR/VR, to enhance design, construction, and operational phases. A third important direction concerns mobile and field applications, as expanding studies on mobile VDC adoption, using tablets, wearables, and cloud-based tools, will help bridge the gap between office and field operations. Moreover, future research should continue to validate the integration between VDC and Lean Construction, using empirical and cross-project studies to establish frameworks that optimize both approaches simultaneously. In terms of lifecycle applications, further work is needed to investigate how VDC can support asset management, maintenance scheduling, and sustainability assessment beyond the construction phase. Lastly, longitudinal and comparative case studies across different regions are required to capture long-term impacts and account for cultural, contractual, and regulatory variations. Accordingly, this review demonstrates that while VDC enhances collaboration, efficiency, and project delivery, its adoption is hindered by fragmented practices, high costs, and a lack of established standards. At the same time, opportunities such as integration with BIM and Lean highlight promising directions for advancement. These findings lay the groundwork for the conclusion, which highlights the broader implications and outlines pathways for achieving more effective and sustainable digital transformation in the construction industry. In addition, the tree metaphor (Figure 2) provides a valuable lens for interpreting future VDC adoption pathways, where continued growth is less likely to follow a single linear trajectory and more likely to involve selective branching based on organizational readiness, project delivery context, and integration priorities.

Conclusions

Over the past two decades, Virtual Design and Construction (VDC) has come a long way. VDC adoption reflects ongoing efforts to address inefficiencies and coordination challenges while responding to rising expectations for sustainable and efficient delivery. Rather than cataloging tools or applications, the study traces how VDC practices have evolved from early visualization-focused uses toward more integrated implementations that support data-driven decision-making across project phases. Our research contributes to the body of knowledge by providing an in-depth, literature-based understanding of the longitudinal evolution of VDC practices, including dominant trends, maturity trajectories, and shifting implementation priorities. Our study suggests that viewing VDC as an integrated delivery methodology, rather than a collection of isolated tools, can help organizations better align technology investments with project processes and organizational capabilities, and support more effective, data-driven decision-making. Our study proposes a trend-based perspective on VDC adoption, demonstrating that implementation follows divergent maturity paths shaped by leadership, delivery context, and integration with complementary practices such as Lean construction. Our study benefits researchers by consolidating fragmented literature into a coherent longitudinal synthesis and practitioners by offering evidence-informed insights to guide strategic planning and implementation. Although there are some limitations, including reliance on published studies and limited empirical validation of return on investment, our findings are helpful to informing future research, supporting more intentional VDC adoption, and achieving a more sustainable, resilient, and digitally enabled construction industry.

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