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THE ROLE AND POTENTIAL OF BIM IN DIGITAL DESIGN

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Abstract

This article examines the role of Building Information Modeling (BIM) technologies in digital design on a global scale. The primary focus is on the application of BIM in architectural and MEP (mechanical, electrical, and plumbing) disciplines. A comparative analysis of key BIM platforms (Autodesk Revit, Graphisoft Archicad, Allplan, and Tekla Structures) is conducted, highlighting their functional capabilities and limitations. Based on statistical data and scientific studies, the article assesses the impact of BIM on project performance indicators such as time, cost, quality, and risk. The discussion addresses implementation barriers and future development trends, including artificial intelligence, digital twins, sustainable design, and openBIM standards. The findings confirm that BIM is a critical tool for enhancing the efficiency and quality of design processes in the architecture, engineering, and construction (AEC) industry.

Keywords

BIM, digital design, architecture, MEP systems, building information modeling, Revit, digital transformation, openBIM, design quality, AI in construction, digital twin, ISO 19650 standards

Introduction

The modern architecture, engineering, and construction (AEC) industry is undergoing a digital transformation, with Building Information Modeling (BIM) playing a key role in this process. BIM refers to the process of creating and managing a digital information model of a construction asset throughout its entire life cycle [1]. The use of BIM models significantly increases the efficiency of design and construction by providing clear 3D visualizations, coordinating different project disciplines, and automating routine tasks. BIM technologies help reduce errors, shorten project timelines, and lower costs [1], [2]. Unsurprisingly, over the past decade, BIM has evolved from a tool used by a few early adopters into a new global standard across the industry [1].

The relevance of BIM in digital design is confirmed by global trends. Governments in many countries have introduced mandatory BIM requirements: for example, in the United Kingdom, since 2016, all public projects have required at least BIM Level 2; in Germany, BIM has been mandatory for large infrastructure projects since 2017; in France, BIM has been recommended for major developments since 2022; and in Russia, as of March 2022, BIM is mandatory for all publicly funded projects [1]. As a result, by the early 2020s, the share of companies using BIM in design had reached approximately 70–80% in leading countries such as the UK, Germany, and the Netherlands [1], [3]. Even in countries that adopted BIM later, there has been a rapid increase in interest - for instance, in Russia, the first BIM projects appeared only around 2014–2015, but by 2022, a regulatory framework consisting of 15 national standards (GOST) had been developed, and BIM became mandatory for major projects [3]. Thus, BIM has become an integral component of digital design worldwide, enabling the AEC industry to address challenges of improving quality and productivity.

The aim of this study is to explore the role and potential of BIM in digital design, with a focus on its application in architecture and mechanical, electrical, and plumbing (MEP) systems, through the lens of international experience. The article follows the IMRAD structure. The Methods section describes the methodology of comparative analysis applied to leading BIM tools (Autodesk Revit, Graphisoft Archicad, Nemetschek Allplan, Trimble Tekla, among others) and the data sources used. The Results section presents the outcomes of this analysis, including a comparative overview of BIM platforms and quantitative data on BIM adoption across countries and its impact on design quality indicators. The Discussion section evaluates the benefits, limitations, and future directions of BIM development. This research is relevant to the international academic audience as it synthesizes best practices and performance metrics of BIM in enhancing the quality of digital design globally.

Methods

Research approach. To achieve the stated objectives, a comparative analysis was conducted of the capabilities of major BIM software tools widely used in architectural design and engineering systems. The analysis focused on four comprehensive BIM platforms that dominate the global market: Autodesk Revit, Graphisoft Archicad, Nemetschek Allplan, and Trimble Tekla Structures. Each of these programs addresses various aspects of building information modeling - from architectural and structural design to mechanical, electrical, and plumbing (MEP) systems.

The comparison was based on several criteria, including: supported design disciplines, core functional capabilities (parametric 3D modeling, rendering, drawing and schedule generation), collaboration and coordination tools, file compatibility, support for open standards (e.g., IFC), and known limitations of each environment. Information on the functionality and features of these BIM systems was gathered from official developer documentation and published technical reviews and analytical articles. To ensure objectivity, data from independent sources were also considered, including expert evaluations (e.g., Sandya Devarajan, 2025 [4]) and prior studies on BIM adoption.

Description of tools. Below is a brief overview of the BIM platforms included in the comparative analysis, with an emphasis on their role in architectural and MEP design:

- **Autodesk Revit** – the most widely used BIM system and the de facto industry standard for architects and engineers [4]. Revit was originally developed as an integrated platform for architecture, structural engineering, and MEP design, enabling full coordination of all project disciplines. The software supports intelligent parametric 3D modeling and automatic updating of drawings when changes are made to the model. A key feature of Revit is its advanced collaborative environment (e.g., the BIM 360 cloud service), which allows multiple specialists to work on the same project simultaneously [4]. Revit includes a comprehensive set of built-in tools for engineering systems (HVAC, plumbing, electrical), including the Revit MEP module for modeling building services, along with libraries of equipment components. This makes Revit particularly effective for coordinating architectural design with mechanical and electrical systems. In addition, Revit's open API and widespread adoption have fostered a rich ecosystem of plugins and extensions that expand its functionality (e.g., for generative design, analysis, visualization, etc.). In this study, Revit is used as the baseline reference for evaluating the capabilities of other BIM platforms.
- **Graphisoft Archicad** – one of the first BIM programs, primarily focused on the needs of architects. Archicad is well known for its intuitive interface and ease of use in conceptual building design [4]. The system offers broad capabilities for architectural modeling, including parametric objects and the "Morph" tool for freeform geometry, as well as high-quality visualization (rendering and the BIMx tool for interactive presentations). For collaborative work, Archicad includes the Teamwork feature, which allows multiple architects to work on the same model simultaneously. Archicad supports the openBIM approach, offering full import/export capabilities for the IFC format, as well as compatibility with DWG/DXF, PDF, and other common formats - an important feature for data exchange between project participants [4]. However, a notable limitation of Archicad is its relatively underdeveloped functionality for structural and MEP systems: its built-in tools for analysis and MEP modeling are relatively basic and

often require integration with external applications such as DDS-CAD or Rhino/Grasshopper for more advanced workflows. This has been highlighted in various reviews, where Archicad is noted to fall short of Revit in terms of engineering and structural modeling capabilities [4]. Nevertheless, in architectural design, Archicad remains one of the leading platforms due to its designer-oriented focus and efficient modeling performance.

- **Nemetschek Allplan** – a German BIM platform that is particularly popular in Europe, especially among structural engineers. Allplan was originally developed as a computer-aided design (CAD) system that combines 2D drafting and 3D modeling within a unified workspace - often referred to as hybrid modeling [4]. This makes Allplan particularly well suited for generating conventional project documentation (plans, sections, schedules) in parallel with the development of an information model. The program is renowned for its strong capabilities in structural detailing, especially for reinforced concrete: it includes advanced tools for modeling rebar, construction joints, and for automatically generating concrete and steel specifications [4]. Allplan supports the IFC format and other open standards, ensuring compatibility with external analysis software and other BIM platforms - for example, integration with SCIA Engineer for structural analysis. For interdisciplinary collaboration, Nemetschek offers the Bimplus cloud service, integrated with Allplan, which enables coordination of models across different disciplines. A major strength of Allplan is its application in infrastructure and civil engineering projects - such as bridges and roads - due to its precision and its ability to handle large-scale terrain models [4]. One limitation, however, is its relatively limited adoption outside Europe and a smaller library of pre-built objects compared to Revit [4]. Nonetheless, Allplan demonstrates high efficiency in projects that require detailed structural modeling and the integration of architectural and engineering analysis.

- **Trimble Tekla Structures** – a specialized BIM system designed for structural engineers, focused on detailed modeling of steel and reinforced concrete structures. Tekla enables the creation of highly detailed models of a building's load-bearing framework, down to every bolt, weld, and rebar segment [4]. One of Tekla's distinguishing features is its ability to directly generate construction drawings (shop drawings) and fabrication data (for steel and concrete) from the model. This makes the software widely used in steel and precast concrete factories for producing detailed part drawings, specifications, and CNC fabrication data. Tekla Structures includes powerful tools for clash detection and design error checking, which significantly facilitate the coordination of structural components with architectural and MEP systems [4]. In addition, Tekla integrates with construction management and cost estimation software, allowing the model to be used throughout the building process. Limitations: Tekla is not intended for architectural modeling or MEP systems design - it is typically used alongside other BIM tools that handle those domains [4]. Moreover, Tekla requires specialized training; compared to general-purpose BIM platforms, its interface is more technical, aimed at engineers, and contains a wide range of parameters for fine-grained detailing, resulting in a relatively steep learning curve for new users [4]. Nonetheless, within its niche of structural modeling, Tekla is a market leader and is frequently employed during the detailed design and fabrication stages of construction projects.

Thus, for the purposes of this study, a comprehensive overview of leading BIM tools was compiled, covering both architectural and engineering design. The comparative analysis was conducted by aligning declared functional specifications (see Results, Table 1) with known limitations reported in the literature and identified through practitioner experience.

In addition, the research methodology included the collection and analysis of statistical data on BIM adoption and its impact on project outcomes. International reports, surveys, and academic articles containing quantitative indicators were reviewed - such as the percentage of BIM use among companies in different countries, the dynamics of BIM adoption, and measurable effects of BIM (e.g., time savings, cost reduction, and decreased errors and rework). These data, sourced from reputable organizations (industry reports, market research, and scientific publications), are synthesized in the Results section in the form of tables, charts, and diagrams. A comparative statistical analysis method was applied, contrasting metrics from countries with mandatory BIM regulations versus those without, as well as comparing project outcomes using BIM against those using traditional design methods. The reliability of the data was ensured through cross-referencing multiple sources and including citations to primary references throughout the text.

Results

Comparative characteristics of BIM platforms. Based on the conducted analysis, a comparative table was developed to summarise the key features of the four BIM platforms reviewed (Table 1). The table highlights the main application areas of each platform, their core functional capabilities, as well as some of their known limitations.

***Table 1**. Comparison of capabilities of popular BIM systems for architectural and engineering design.*

Platfo	Deve	Primary	Key Features and Capabilities

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rm	loper	Purpose	(for AEC/MEP)
Autodesk Revit	Autodesk (USA)	Universal BIM system for architecture, structures, and MEP	Parametric 3D modeling; integration of all disciplines (architecture + MEP); cloud-based collaboration (BIM 360); automatic updating of drawings and schedules; extensive ecosystem of plugins and add-ons [4].
Graphisoft Archicad	Graphisoft (Nemetschek, Hungary)	BIM for architectural design (basic support for structures and MEP)	Intuitive interface and modeling tools for architects; Teamwork feature for collaborative design; built-in photorealistic visualization tools; support for openBIM (IFC import/export) [4]. Limitation: relatively weak capabilities for structural and MEP calculations [4] (requires integration with external tools for complex engineering tasks).
Nemetschek Allplan	Nemetschek (Germany)	BIM for architecture and structural engineering (focus on concrete and infrastructure)	Hybrid 2D/3D modeling (integration of drawings and model); advanced tools for reinforcement and structural detailing; support for open formats (IFC, DWG, etc.); Bimplus cloud platform for team coordination [4]. Notable for its use in infrastructure projects (e.g., bridges, roads) due to its high model accuracy [4].
Trimble Tekla Structures	Trimble (USA/Finland)	BIM system for structural design and detailing (steel, reinforced concrete)	Highly detailed modeling of load-bearing structures and connections; powerful clash detection and model consistency checks; integration with fabrication and construction (generation of shop drawings, specifications, CNC data); parametric design of complex structural forms [4]. Limitations: minimal support for architectural finishes and MEP;

			requires specialized training (complex interface for beginners) [4].

As shown in Table 1, Revit offers the most comprehensive range of capabilities for integrated building modeling (from architecture to engineering systems), making it the dominant choice among large firms [4]. Archicad stands out for its user-friendly interface and powerful architectural design tools; however, its application in projects with complex engineering systems may require supplementary solutions [4]. Allplan excels in the detailing of structural components (e.g., reinforcement drawings) and is frequently used in combination with analytical tools and for infrastructure-related tasks [4]. Tekla Structures is highly specialized, complementing the aforementioned platforms during the detailed design and construction planning stages - particularly for model delivery to fabrication facilities for steel components [4].

Thus, the comparison of BIM tools shows that each platform has its distinct strengths: Revit for versatility and coordination, Archicad for architect-oriented usability, Allplan for advanced structural detailing, and Tekla for precision in structural modeling. Collectively, these tools cover the full spectrum of needs in digital design for buildings and infrastructure.

BIM adoption across countries. An analysis of the collected statistical data confirms that the level of BIM adoption varies significantly by country, although the general trend is a widespread increase in its use. Figure 1 presents estimates of the share of design firms using BIM technologies in selected countries (based on data from approximately 2020–2023). Leading the way are countries where governments have actively promoted BIM: for example, in the Netherlands, by the 2020s, approximately 80% of architectural firms had adopted BIM [3]; in the United Kingdom, around 73% of firms were using BIM by 2020 (compared to just 13% in 2011) [1]; and in Germany, about 70% - primarily architecture and engineering firms - had transitioned to BIM [1], [3]. High adoption rates are also observed in the United States, where recent surveys show that approximately 70% of architects and engineers use BIM platforms [2], and 100% of large architectural firms incorporate BIM into their workflows [2]. In Singapore, as a result of a government-led initiative, BIM adoption reached around 65% by 2020, with annual productivity growth in construction estimated at approximately 2% due to BIM technologies [5].

At the same time, some countries are still in the early stages of BIM implementation. For example, in Poland, fewer than half of firms (~43%) use BIM [1], and in Russia, prior to the introduction of mandatory BIM requirements, only about 12% of organizations were using it [1]. However, following the implementation of mandatory BIM for public projects in Russia in 2022, a sharp increase in adoption is expected [3].

Overall, the global landscape of BIM adoption remains uneven (Figure 1): countries in Western Europe, North America, and advanced Asian economies (such as Singapore, China, and South Korea) exhibit a high degree of construction digitization, whereas emerging markets are only beginning to transition to BIM [6].

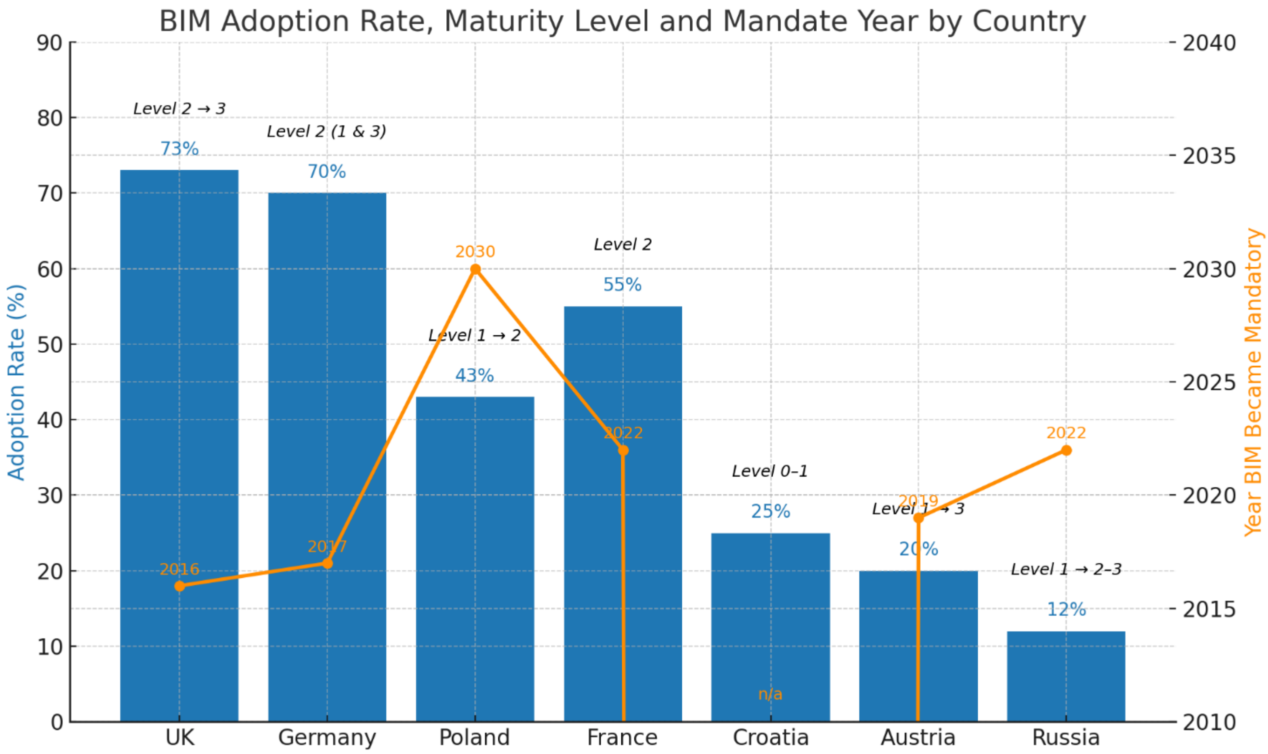

Figure 1. BIM adoption rate (% of companies using BIM) in selected countries worldwide [1], [3], [5].

As shown in Figure 1, there is a noticeable correlation between government policy and the extent of BIM adoption: leading countries (such as the United Kingdom, Singapore, South Korea, and the Nordic nations) have introduced national standards or mandates for BIM implementation, while countries without centralized incentives exhibit significantly lower adoption rates [3]. This policy trend is driven by a desire to improve industry efficiency: governments are investing in BIM as a tool to reduce costs and enhance the quality of infrastructure projects [3].

Impact of BIM on design quality and project efficiency. Quantitative findings from various studies highlight the substantial benefits of implementing BIM compared to traditional methods. Numerous publications report measurable improvements in project performance due to BIM. For example, according to a comparative analysis of projects in the United States, BIM adoption leads to approximately a 25% reduction in required labour due to the elimination of

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redundant work and clashes, while also increasing overall labour productivity by 25% [2]. One study documented a 5% reduction in total project cost and a 5% acceleration in construction timelines when BIM modeling was used - primarily due to improved scheduling and fewer delays [2].

Another efficiency-focused study found that BIM can reduce the duration of design and planning phases by up to 20%, cut material and resource waste by about 15%, and decrease the risk of schedule overruns by up to 30% [2]. Additionally, BIM helps reduce unforeseen costs related to risk by an average of 25%, owing to more accurate planning and control enabled through the model [2].

Overall, the transition to BIM processes has a clearly positive impact on design quality: the accuracy and consistency of construction drawings improve, the number of clashes between architectural and engineering components is reduced by nearly an order of magnitude, and the amount of rework required on-site decreases significantly [2]. Thanks to a centralized digital model, all stakeholders - architects, structural engineers, MEP designers, and contractors - work from a single, up-to-date source of information, which enhances communication and project coordination. For example, in the execution of large-scale projects in the UK and the US, BIM-based information exchange was reported to be substantially more effective compared to traditional drawings [2].

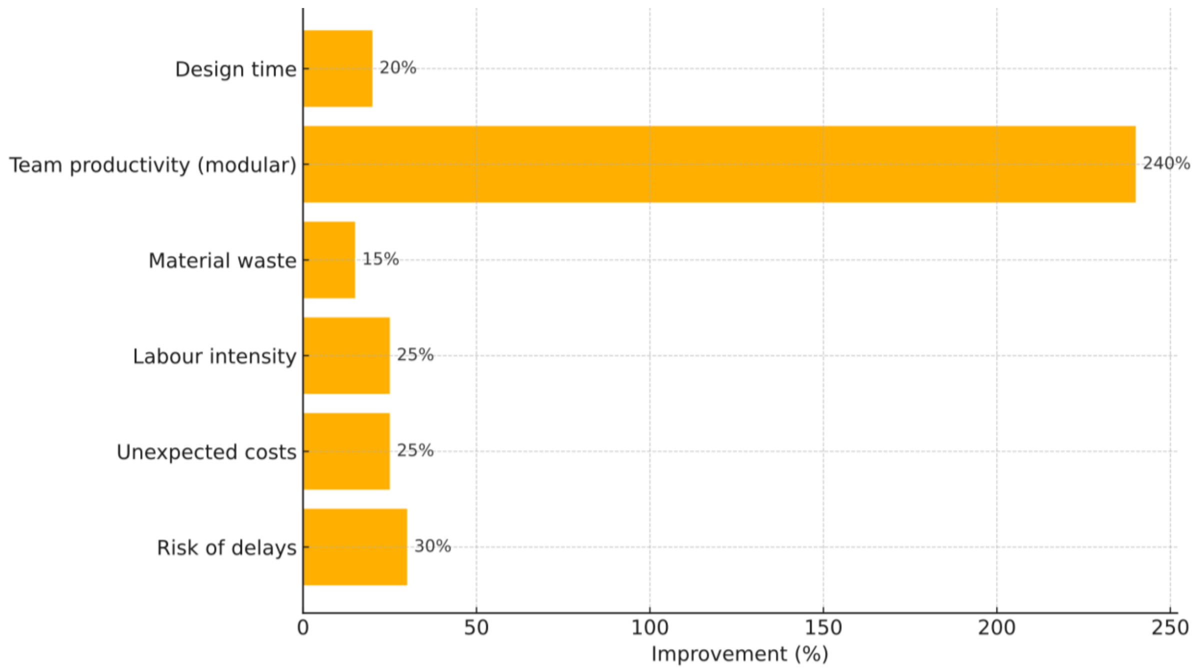

Figure 2. **Examples of BIM's impact on project performance indicators (based on various sources): reduction in delay risks, decrease in unforeseen costs (risks), reduction in labour intensity and material waste, faster planning, and increased team productivity [2].**

Interestingly, some studies observed dramatic increases in productivity at certain stages of construction. In projects using prefabricated modules supported by BIM, labour productivity during installation increased by 75–240% [2]. This is largely due to BIM's ability to detect and resolve issues in advance, as well as to support modular construction techniques. As a result, the volume of rework and on-site changes is significantly reduced [2] - a metric directly linked to the quality of the initial design solution.

It is important to emphasize that the improvement in design quality enabled by BIM is reflected not only in quantitative metrics such as time and cost, but also in the enhanced quality of the design solution itself. A BIM model offers a more comprehensive understanding of the future building: the architect can better align form with function, the engineer can optimize systems (e.g., duct routing in relation to structural elements), and the client can visualize the design at early stages and request modifications that enhance the building's usability. As a result, projects demonstrate higher operational performance, fewer design errors are carried over into the construction phase, and both safety and end-user satisfaction are improved [2].

Thus, the findings of this study highlight the significant potential of BIM: on the one hand, modern BIM platforms enable integrated digital design of all building systems; on the other hand, empirical data confirms substantial benefits of BIM in terms of project efficiency and quality. These results are discussed in more detail in the next section, including an analysis of the underlying factors, current barriers, and future prospects for BIM development.

Discussion

Advantages of BIM for Architecture and MEP. The results confirm that the implementation of BIM technologies delivers numerous advantages throughout all stages of a building's life cycle - from concept to operation. One of the key strengths of BIM is interdisciplinary coordination: all disciplines (architecture, structures, HVAC, electrical, plumbing, etc.) are integrated within a single digital model. This enables automatic clash detection (e.g., a duct intersecting a beam) and allows issues to be resolved during the design phase rather than on the construction site. As a result, the number of errors and rework is significantly reduced, and the quality of the produced design documentation improves [2]. In practice, the BIM model becomes the single source of truth: all plans, sections, and specifications are generated directly from it, eliminating discrepancies between drawings. When changes are made to the design, the documentation updates automatically, removing human error and enhancing the project's accuracy.

For architects, BIM unlocks new opportunities for creativity and analysis. Tools for parametric design and generative design based on BIM models have emerged, allowing architects to rapidly create and evaluate dozens of variations in building form, façade configurations, and layouts using optimization algorithms - something that was difficult in the 2D drafting era. Moreover, the BIM model inherently contains a 3D visualization, enabling both the architect and the client to better understand the final result, and even conduct virtual walkthroughs of the building (using BIM-powered VR/AR technologies). All of this contributes to improved architectural decision-making and better alignment with client expectations.

For MEP engineers (mechanical, electrical, and plumbing - including HVAC, power supply, water supply, and other systems), BIM enables conflict-free system layout. Using BIM tools such as Revit MEP, it is possible to create detailed models of all building services inside and around the building, and automatically check for issues such as pipe clashes with columns, sufficient service clearance, or compatibility between electrical loads and HVAC systems. Previously, these challenges were addressed "on-site" or through numerous iterations between disconnected 2D drawings. BIM provides an integrated solution from the outset: all MEP systems are optimally routed in coordination with the architectural design. This directly improves the quality of engineering design - enhancing energy efficiency (via precise calculations), system reliability (through scenario simulations), and ease of maintenance (with access zones modeled in advance). In practice, the use of BIM for MEP has been shown to reduce design changes during construction and improve system performance after commissioning [2].

In addition, BIM facilitates collaborative work within large design teams. Architects, structural engineers, and MEP specialists no longer operate in an information vacuum - BIM platforms (via cloud services or local networks) allow all parties to access the latest version of the model, leave comments, and track revisions. For example, in Revit or BIM 360, multiple users can simultaneously work on different areas of the model and merge their contributions. This accelerates the design process and reduces inter-team conflicts. Communication improves significantly: instead of exchanging dozens of separate drawings, teams work with a single BIM file or shared access point, where everything is clearly represented in 3D. As noted in several reviews, this streamlines information exchange [2], enabling faster and better-informed decision-making based on accurate model data rather than assumptions.

As a result, the factors discussed above - coordination, parallel work, and visualization - lead to substantial time and cost savings. The Results section presents quantitative evidence supporting this: BIM helps shorten design timelines, reduce labour hours, and eliminate material waste. These metrics reflect not just cost savings, but higher-quality and more sustainable projects. For example, a 15% reduction in material overuse [2] demonstrates that designers using BIM can more accurately estimate resource requirements, thereby reducing waste - a sign of better planning. Similarly, a 20–30% decrease in delay risks indicates more reliable, well-coordinated projects that are more likely to be delivered on schedule [2].

Finally, BIM adds value in the operation phase of a building's life cycle. The digital model handed over to the facility management team (commonly known as as-built BIM or 6D model) contains comprehensive data on equipment, materials, specifications, and documentation - effectively serving as a digital passport of the building. This significantly enhances property management, simplifying maintenance planning, renovations, and condition monitoring. For example, having a detailed BIM model of MEP systems enables maintenance personnel to quickly locate the right valve or cable in the real building, since everything is documented in the 3D model. As a result, the safety and efficiency of building operations improve, directly reflecting the quality of BIM-based design.

In summary, the benefits of BIM for project quality are multifaceted: reduced errors, improved coordination, enhanced transparency and predictability, accelerated innovation (through simulations and generative design), and improved communication among all project stakeholders. These factors position BIM not merely as a technology, but as a transformative approach to design - one that is fundamentally oriented towards quality and efficiency.

Limitations and Current Challenges of BIM Implementation. Despite its clear advantages, the widespread adoption of BIM faces a number of technical and organisational challenges. One of the main barriers - especially for small companies and emerging markets - is the high initial cost of transitioning to BIM. This includes the purchase of expensive software, powerful hardware for 3D modelling, and training for personnel, all of which require substantial investment [7].

According to research, the cost of software packages and updates, along with the need for staff training, are among the key limiting factors for BIM adoption in small and medium-sized enterprises [7]. Management of such firms often doubts the return on investment from BIM, fearing that the steep learning curve and workflow restructuring may not bring immediate results [7].

In fact, BIM implementation requires cultural change within the organisation: established processes must evolve, new roles (such as BIM Manager or BIM Coordinator) need to be introduced, and closer interdepartmental collaboration is essential [7]. Resistance to change and lack of executive-level support have been cited in surveys as some of the most significant obstacles to successful BIM integration [7].

Another Significant Challenge – Skills Shortage. Another major challenge is the shortage of qualified personnel. BIM modellers and developers require a new skill set - including proficiency in specialised software, understanding of standards such as IFC, and 3D coordination competencies. As a result, a skills gap is emerging: the labour market lacks specialists with practical BIM experience, and retraining existing staff tends to progress slowly [7].

Consequently, even when companies have the necessary software, they often fail to fully realise the potential of BIM due to insufficient expertise. The problem is exacerbated by the fact that traditional education systems (universities, professional courses) are lagging behind - BIM is still not systematically included in the curricula for architects and engineers [8]. This has been widely acknowledged: the lack of workforce preparation and insufficient understanding of BIM workflows within organisations often slows down digital transformation [7].

Resistance to change among staff also remains a barrier. Some experienced professionals, accustomed to working in 2D environments for many years, resist learning new tools, which creates an internal obstacle to adopting BIM [7].

Technical Limitations and Interoperability. Despite the wide range of BIM platforms available on the market today, they are not always fully interoperable. The issue of data compatibility remains a pressing concern: models created in different software environments (e.g. Revit, Archicad, Tekla) may lose information when exchanged through open formats such as IFC [7]. Differences in parametric object libraries, discrepancies in material databases, and proprietary (closed) data structures all contribute to difficulties in collaboration between organisations using different tools.

According to surveys, over 60% of professionals cite data exchange problems as a major barrier to effective BIM collaboration [9]. While openBIM standards (e.g. IFC, BCF) are gradually improving, they still cannot guarantee complete fidelity when exchanging complex models. In practice, this often requires manual adjustments after the exchange, which increases project overheads.

Another technical challenge relates to model performance at large scale. Extensive projects - such as high-rise buildings or airports - can generate extremely heavy files, which demand not only high-performance hardware but also well-designed model segmentation strategies (e.g. by zones or disciplines). Without this, software responsiveness drops significantly, and teamwork becomes difficult. Nevertheless, software vendors are continuously optimising their engines, introducing features such as cloud-based processing, which helps gradually mitigate this barrier.

Legal and Contractual Aspects. The transition to BIM introduces complex legal and contractual challenges, particularly regarding responsibility and the legal status of the digital model - issues that remain unresolved in many jurisdictions. In traditional design workflows, legal liability is assigned based on drawings and documentation. However, in BIM-based projects, a shared model is developed collaboratively by architects, engineers, and contractors. This raises the question: who is legally accountable for the model's content?

Disputes often arise over intellectual property and ownership. For instance, clients who fund the project may claim full ownership of the BIM model, while design professionals may view the model as their intellectual output [7]. Clarifying rights over jointly developed models - especially at BIM Level 3, where inputs from multiple parties are fully integrated - is a legal grey area, with solutions varying widely across contracts.

Another issue is related to liability and guarantees: if construction is executed based on a BIM model, who bears the risk of errors? For example, if a mistake in the model leads to a construction defect, should responsibility fall on the designer, the builder, or the data input provider? In some cases, the BIM model might be viewed as a product, triggering product liability regulations [7].

Legal experts note the need for BIM-specific contract appendices, explicitly defining the distribution of responsibilities and risk ownership. While some countries (e.g., the UK and Singapore) have already developed standard BIM contractual frameworks, in most regions, such issues are still addressed on a case-by-case basis.

Another critical legal issue concerns **confidentiality and data protection.** The shift to digital models entails storing vast amounts of project information on cloud platforms and servers, and sharing data over the Internet. This makes cybersecurity essential - BIM models must be protected from unauthorised access, with data encryption, secure backups, and compliance with data protection laws (such as GDPR, especially if personal data is involved) [9].

However, the construction industry is not traditionally attuned to IT-related risks, which gives rise to a new set of challenges: ensuring that the BIM model is not lost, altered, or tampered with, maintaining version control, and establishing legal recognition of digital files in dispute resolution. There have been documented cases where courts questioned the reliability of digital drawings, citing the ease with which they could be modified retroactively [7].

As a result, the development and adoption of BIM-related standards and protocols has become a priority. Key examples include the international ISO 19650 standard (Information management using BIM), and national frameworks like PAS 1192 in the UK or Russian BIM GOSTs. These standards provide unified rules for file naming conventions, data structure, and access control, aiming to reduce both technical and legal risks in the implementation of BIM.

In summary, the primary limitations of BIM today are not rooted in the technology itself, but rather in the transitional barriers associated with its widespread adoption. These include the need for investment in software and staff training, organisational restructuring, the establishment of new collaborative standards, and the development of qualified users along with appropriate legal frameworks.

While large enterprises and public-sector clients have largely overcome these challenges, small businesses and conservative markets often lag behind. Therefore, ongoing efforts must focus on improving data interoperability standards, expanding BIM education and training programmes, and developing legal and regulatory frameworks. This will help ensure that the benefits of BIM become universally accessible across the construction and architectural sectors.

Future Directions of BIM Development.

Looking ahead, it is evident that Building Information Modeling (BIM) will continue to evolve as the core of digital transformation in the construction industry, integrating with advanced information technologies and addressing an increasingly broader range of tasks across the entire lifecycle of built assets. Several key trends are expected to shape the future development of BIM in the coming years:

1. Integration of BIM with Artificial Intelligence (AI) and Automation. One of the most promising directions is the incorporation of artificial intelligence (AI) and machine learning algorithms into BIM processes. Experimental systems have already demonstrated the ability to automatically detect and resolve clashes within BIM models, potentially reducing by up to 15% the time typically spent on manual checks by engineers [9]. AI-driven algorithms can analyse extensive libraries of existing projects to identify patterns and suggest optimal design solutions - such as spatial layouts, structural schemes, or routing of mechanical and electrical systems. Studies indicate that integrating AI with BIM may increase design productivity by 20–30% and reduce construction costs by up to 20% through more rational decision-making [9]. Particular attention is being paid to generative design - an approach in which architectural or structural models are partially generated automatically based on predefined parameters. For instance, algorithms can generate hundreds of facade design alternatives within minutes and evaluate them based on solar

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exposure, energy efficiency, or aesthetic criteria. This capability significantly accelerates design exploration and supports more informed decision-making. Additionally, AI is already being utilised for risk analysis and safety management. The sAIfety platform, for example, uses BIM data and on-site sensors to predict hazardous zones, resulting in a reported 40% reduction in construction site incidents [9]. It is expected that artificial intelligence will become an integral component of next-generation BIM tools, automating routine tasks, enhancing analytical capabilities, and enabling designers and engineers to focus on critical and creative aspects of the project development process.

2. Digital Twins and BIM in the Operation Phase. While BIM is currently predominantly associated with the design and construction phases (3D/4D/5D modelling), a key emerging trend is the evolution toward 7D BIM and the integration of Digital Twin technologies. A Digital Twin represents a dynamic link between a building's BIM model and real-time data collected via Internet of Things (IoT) sensors and Building Management Systems (BMS). This integration enables real-time monitoring, simulation, and optimisation of building performance throughout its entire lifecycle. Pilot implementations of Digital Twins in the built environment have already demonstrated operational cost reductions of up to 25%, particularly in energy consumption and maintenance, through real-time data analytics conducted within the BIM environment [9]. For example, when a BIM model is connected to a BMS platform, it can continuously monitor temperature, energy usage, and equipment status, and autonomously adjust systems or issue optimisation recommendations. This results in more intelligent, responsive, and sustainable building operations. In the near future, it is anticipated that every major building or infrastructure project will be paired with its own Digital Twin, unlocking significant advances in facility management. Potential applications include predictive maintenance, lifecycle cost planning, emergency evacuation simulations, and scheduling of service operations - all conducted and validated within the digital environment. However, the full realisation of this potential requires further standardisation of data exchange protocols between BIM platforms and BMS/IoT systems, as well as robust cybersecurity measures to prevent vulnerabilities in connected devices from compromising BIM data integrity.

3. BIM for Infrastructure and Urban Scale (CIM). The concept of Building Information Modeling (BIM) is expanding beyond individual buildings to encompass infrastructure assets - such as bridges, roads, and utility networks - and even entire urban environments. This evolution has given rise to the concept of City Information Modeling (CIM), which integrates BIM models with geospatial data (GIS), infrastructure networks, and environmental simulations to create a digital twin of the urban fabric. The primary objective of CIM is to support holistic urban planning and management. For instance, CIM enables simulation of the impact of a new building on traffic flow, solar access in adjacent districts, or load on utility networks. Several pioneering cities - such as Singapore and Helsinki - have already developed comprehensive 3D digital models of their urban territories as part of their smart city initiatives. This integration of BIM and GIS provides significant benefits for both public administration and design professionals. Urban planners can make data-driven decisions with a broader contextual understanding, while emergency services can improve response strategies through access to detailed digital maps of infrastructure and utilities. For architects and engineers, the application of BIM at the urban scale facilitates context-aware design, enhancing the quality and sustainability of planning solutions by accounting for surrounding spatial conditions, environmental constraints, and long-term infrastructural integration.

4. Integration of BIM with Construction 4.0 Technologies. The future of the construction industry is increasingly associated with the paradigm of Construction 4.0, which encompasses robotics, 3D printing, modular construction, the Internet of Things (IoT), and other digital innovations - with BIM serving as the foundational technology enabling their integration. One of the key directions in this context is Design for Manufacturing and Assembly (DfMA) - an approach that emphasizes designing building components for off-site fabrication and efficient on-site assembly. BIM is ideally suited for DfMA because it allows for the decomposition of a building into discrete components, the specification of tolerances and connections, and the direct transmission of production-ready models to factories, including data for CNC machinery. As highlighted earlier (see Figure 2), modular construction methods - such as Prefabricated Prefinished Volumetric Construction (PPVC) - supported by BIM can increase construction site productivity by up to 50% and reduce on-site labour requirements by 25–40% [5]. Looking ahead, BIM is expected to become increasingly integrated with CAD/CAM systems, enabling designers to generate digital models that are directly translatable into fabrication and construction workflows - be it 3D printing of concrete structures or robotic crane operations. This evolution positions BIM not merely as a documentation tool, but as a central control model for automated construction, fundamentally transforming its role in the built environment lifecycle.

A related area of development is the use of Augmented Reality (AR) and Virtual Reality (VR) technologies directly on construction sites. Already today, there are solutions where construction crews employ AR headsets to overlay BIM models onto real-world environments, enabling precise on-site installation according to the digital design. This significantly reduces assembly errors. In the near future - especially as BIM models become a standard requirement for every project - such technologies are expected to become ubiquitous. For instance, an HVAC installer could use a tablet or AR glasses to visualise the exact routing of ducts behind a suspended ceiling, avoiding accidental damage. Similarly, cable trays and other systems could be checked in real time for correct placement against the BIM model. This fusion of BIM and immersive technologies will enhance construction accuracy, safety, and overall workflow efficiency.

5. Strengthening the Focus on Sustainability and Energy Efficiency through BIM. The global Sustainable Development Goals (SDGs) necessitate the construction of energy-efficient and environmentally responsible buildings. BIM already enables energy analysis at early design stages - for instance, through models integrated with heat loss calculations, lighting simulations, and airflow analysis. In the future, such tools will become more precise and likely mandatory. The emergence of standards such as “Green BIM” is anticipated, requiring that the information model include data on the carbon footprint of materials, recyclability, and energy consumption of each element. The synergy between BIM and simulation tools will allow for the optimisation of building design based on reduced CO_2 emissions and resource efficiency. Furthermore, AI-powered algorithms, trained on thousands of building models, will be able to suggest balanced design solutions that satisfy both technical requirements and environmental constraints. As a result, BIM will evolve into a central platform for achieving sustainability - ranging from selecting low-carbon materials to operating buildings with optimal energy use through digital twins.

6. Standardisation and Regulation of BIM Processes. To fully realise the aforementioned trends, ongoing development and harmonisation of standards are essential. ISO 19650 and similar frameworks for information management are expected to gain wider global adoption, providing a unified methodology for BIM implementation. New standards will likely emerge to address BIM integration with AI, facility management systems, and other technologies. Furthermore, more countries are expected to introduce mandatory BIM requirements at the legislative level - following the examples of the UK, Singapore, and Russia - which will drive workforce development and the localisation of BIM norms. It is anticipated that within 5–10 years, proficiency in BIM tools will become a fundamental and universally expected skill for engineers, much like CAD proficiency is today.

Conclusion

Having analysed the role and potential of Building Information Modelling (BIM) in digital design, it is evident that BIM has already proven its effectiveness and is becoming a global standard. However, its full potential is yet to be realised. The key advantages of BIM - improved project quality, cost reduction, and accelerated construction - are substantiated by empirical data and professional practice [2]. Existing limitations, such as high initial costs, the need for specialised training, and lack of standardisation, are gradually being overcome as technologies mature and experience accumulates. Future developments - particularly the integration of BIM with artificial intelligence (AI), digital twins, and modular construction - are expected to position BIM as a central component in the paradigm of "smart" construction and building operation. In the long term, BIM is likely to evolve into a comprehensive platform for managing the entire building lifecycle, offering an unprecedented level of control, efficiency, and quality in the architecture, engineering, and construction (AEC) sector.

The international scientific community faces a range of research challenges along this path, from the development of new optimisation algorithms for BIM-based models to the exploration of social and organisational aspects of implementation. Nevertheless, it is already clear that digital design supported by BIM is not a passing trend, but a fundamental shift in design methodology - one that will shape the future of architecture and construction in the 21st century.

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