# Digital Integration and Performance Optimization of Plumbing Systems within MEP Frameworks: A Comprehensive Review of BIM, VDC, Lean, and Sustainable Design Approaches

**Rushikesh Dalpat Parmar**
Final Year Student, M. Tech. (Civil) Construction Engineering & Management, Birla Vishvakarma Mahavidyalaya Engineering College, Vallabh Vidyanagar Rdp17101@gmail.com

**Prof. (Dr.) J. R. Pitroda**
Professor, PG Coordinator Construction Engineering & Management, Civil Engineering Department, Birla Vishvakarma Mahavidyalaya Engineering College, Vallabh Vidyanagar jayesh.pitroda@bvmengineering.ac.in

**Er. Jayesh D. Prajapati**
Research Scholar, Gujarat Technological University, Birla Vishvakarma Mahavidyalaya Engineering College, Vallabh Vidyanagar
jayesh.prajapati@bvmengineering.ac.in

**Dr. Reshma L. Patel**
Assistant Professor, PG Coordinator Environmental Engineering, Civil Engineering Department, Birla Vishvakarma Mahavidyalaya Engineering College, Vallabh Vidyanagar
rlpatel@bvmengineering.ac.in

**Abstract** - Mechanical, Electrical, and Plumbing (MEP) systems collectively define the functional core of any modern building. Within this triad, plumbing systems play a crucial role in ensuring sustainable water management, sanitation, and occupant comfort. Yet, despite technological advancements such as Building Information Modelling (BIM), Virtual Design and Construction (VDC), and Lean Construction, plumbing design and coordination continue to face recurring challenges including rework, spatial conflicts, and inadequate compliance with standards. This review paper synthesizes existing research and case studies most notably, and multiple empirical analyses on plumbing systems in India, China, and Saudi Arabia to provide a comprehensive understanding of digital integration and performance optimization in plumbing systems. The review bridges technological and practical dimensions, covering BIM/VDC-based coordination, prefabrication, Lean process alignment, and sustainability- oriented plumbing design. By integrating both digital frameworks and field-level challenges, it develops a unified roadmap for efficient and resilient plumbing design in the next generation of MEP systems.

**Keywords:** BIM, VDC, Lean Construction, Plumbing Systems, MEP Coordination, Prefabrication, Sustainable Water Management, Digital Twins, Interoperability, Building Performance.

## 1. Introduction

The MEP sector underpins building functionality by integrating systems that ensure comfort, safety, and environmental performance. While structural and architectural components define the visual and physical form, it is the MEP systems that breathe life into built environments [1]. Plumbing, in particular, is vital for water distribution, sanitation, and drainage systems that directly influence sustainability, occupant health, and overall operational efficiency.

However, MEP systems - especially plumbing - remain among the most coordination- intensive elements of construction projects. Studies have shown that MEP installations can account for up to 40 - 60% of total project costs, with plumbing alone comprising 25 - 40% in complex projects such as metro systems or large commercial facilities . Despite the increasing reliance on advanced digital tools, fragmented coordination, design errors, and execution delays persist across the industry.

The rise of BIM, VDC, and Lean Construction has significantly improved inter-trade collaboration, clash detection, and prefabrication efficiency [2] [3]. Simultaneously, the push for sustainability and IoT-enabled smart plumbing systems has opened new research directions for performance monitoring and predictive maintenance. This review combines the theoretical and empirical foundations of these developments, integrating lessons from plumbing-focused studies with digital coordination frameworks to present a holistic perspective.

## 2. Literature Review

**Pradeep et al. (2018)** highlighted the significance of Building Information Modelling (BIM) as a transformative tool in enhancing the design, coordination, and installation efficiency of Mechanical, Electrical, and Plumbing (MEP) systems. The study underscores that although BIM has proven effective in preliminary and detailed design phases, its application during the construction stage remains limited, often causing discrepancies between design intent and actual site conditions. By employing BIM models across various levels of detail (3D to 5D), the research demonstrates substantial benefits in clash detection, constructability analysis, and cost reduction, achieving up to 20% savings in construction costs. Through case studies, including the Arena Mall project, the paper establishes BIM's critical role in improving interdisciplinary coordination, reducing rework, and enabling data-driven decision-making. The authors advocate for integrating BIM beyond the design phase to encompass construction, maintenance, and lifecycle management for sustainable project delivery [4].

**Parti et al. (2019)** developed a structured process model for Building Information Modeling (BIM)-based Mechanical, Electrical, and Plumbing (MEP) design, focusing on geothermal heat pump systems to improve design coordination, data management, and project efficiency. The study emphasized that MEP systems significantly influence building performance, operational cost, and sustainability, making high-quality digital modeling essential. Through a Business Process Model and Notation (BPMN) framework, the research mapped workflows, stakeholder responsibilities, and data exchanges across different design phases, identifying key parameters that ensure accuracy and information consistency in BIM environments. Prior studies reviewed by the authors, revealed that poor coordination and unclear responsibility distribution among stakeholders often lead to delays, data redundancy, and rework in MEP design. To mitigate these issues, the paper proposed a systematic process model integrating heat pump data parameters classified and rated based on design stage relevance and importance. The results showed that parameters defined early in the design stage have the highest impact on overall project performance, underscoring the importance of early BIM integration. Additionally, expert evaluations validated the model's practical applicability in enhancing data transparency, reducing coordination conflicts, and facilitating automated model checking. The study concluded that standardized BIM-based process modeling, supported by parameterized data structures, can significantly enhance MEP design efficiency, interoperability, and sustainability, particularly for energy-intensive systems like geothermal heat pumps [1].

**Hauer et al. (2020)** examined the critical role of Building Information Modeling (BIM) in improving the quality and interoperability of Mechanical, Electrical, and Plumbing (MEP) data models through the Austrian research project metaTGA. The study highlighted that while BIM has become increasingly prevalent across the construction and real estate sectors, the consistent and reliable application of BIM in MEP design remains constrained by fragmented data structures, incompatible standards, and information losses during data exchange. Prior literature reviewed by the authors emphasized that MEP systems are vital to building performance, energy efficiency, and occupant comfort, yet they face persistent coordination challenges due to inconsistent modeling practices and inadequate data integration. To address these limitations, the metaTGA initiative developed a standardized openBIM approach that defines high-quality metadata, ensures accurate parameter mapping, and integrates IFC-based interoperability for seamless data transfer between BIM tools. The research demonstrated that defining uniform parameters, streamlining geometry, and adopting metadata management platforms like BIMQ significantly enhance MEP model usability and lifecycle relevance. Furthermore, the authors noted that integrating automated quality checks through software such as Solibri and

Revit can improve data consistency, reduce rework, and strengthen collaboration among stakeholders. Overall, the paper concluded that standardized, manufacturer-neutral MEP BIM models, supported by openBIM protocols, can substantially enhance data quality, interoperability, and efficiency throughout building design, construction, and operation phases [5].

**Wu et al. (2022)** emphasized that the productivity of Mechanical, Electrical, and Plumbing (MEP) installations is heavily influenced by project complexity, coordination inefficiencies, and rework, all of which can be mitigated through the adoption of Building Information Modelling (BIM). The study synthesizes prior literature on construction productivity and BIM- enabled management practices, revealing that while earlier research demonstrated substantial improvements in design coordination, clash detection, and information management, few studies have quantitatively identified the contextual factors that drive such productivity gains. Drawing insights from earlier works, the authors integrated 24 impact factors across organizational, managerial, technical, and personnel dimensions through expert consultation and analytical hierarchy process (AHP) evaluation. Their findings highlight that project delivery method, contract type, and quality control are among the most significant determinants of on-site productivity. The paper thus advances understanding by providing an empirically validated framework for assessing the critical factors influencing MEP installation efficiency in BIM-integrated projects [6].

**Khan et al. (2023)** examined the prevalent issue of rework in MEP system installation and its detrimental impact on project performance, drawing insights from a case study on the Riyadh Metro Project in Saudi Arabia. Using a quantitative research approach with survey data from
130 construction professionals, the study identifies key factors contributing to rework, including poor coordination between design and construction teams, inadequate supervision, and lack of skilled workforce. Statistical analysis through SPSS reveals that rework significantly affects project quality, time, and cost - where quality-related impacts rank the highest. The authors emphasize that effective communication, timely design approvals, and compliance with standards are crucial to mitigating rework-related inefficiencies. The study provides actionable recommendations for project stakeholders to enhance performance and minimize waste in large-scale MEP installations [7].

**Akbari et al. (2024)** conducted an in-depth exploration of how integrating Building Information Modelling (BIM) and sustainable construction practices can address critical challenges in project execution, efficiency, and lifecycle management. The study emphasized that traditional construction methods often suffer from inefficiencies, such as poor coordination among trades, design inconsistencies, and a lack of real-time information sharing, which collectively lead to cost and time overruns. Through a detailed analysis of previous studies and emerging practices, the paper established that BIM's multidimensional capabilities - from 3D visualization to 5D cost management offer transformative potential in enhancing project coordination, clash detection, and design optimization. Prior research reviewed in the paper demonstrated measurable benefits, including improved constructability, enhanced interdisciplinary communication, and reduction of rework through digital simulation and model-based collaboration. Furthermore, the authors highlighted that despite these advancements, barriers such as insufficient training, lack of interoperability, and limited stakeholder engagement continue to hinder widespread BIM adoption in developing contexts. To address these limitations, the paper advocates for the integration of BIM with sustainable design frameworks and digital project management tools, fostering holistic project delivery that balances technical efficiency with environmental responsibility. Ultimately, the study provides a comprehensive perspective on leveraging BIM as both a technological and managerial instrument to achieve higher productivity, sustainability, and decision-making accuracy across construction project lifecycles [8].

**Goswami et al. (2025)** investigated the multifaceted challenges associated with Mechanical, Electrical, Plumbing, and Fire (MEPF) services during retail store setup in Indian shopping malls, focusing on their effects across project life cycle stages. The study identified that time and cost overruns frequently arise from inadequate planning, insufficient coordination, and lack of technological integration during design and execution. Through case studies conducted in Pune, Navi Mumbai, and Bengaluru, the authors observed recurring problems such as inadequate drainage systems, design miscalculations, communication gaps, and delayed approvals, all of which contributed to inefficiencies and rework. Their findings underscore that the planning phase is the most critical, with errors at this stage propagating through later phases, ultimately compromising project timelines, cost control, and quality. The research advocates for early site inspections, improved stakeholder communication, and the use of advanced technologies such as Building Information Modeling (BIM) and drones to enhance visualization, coordination, and quality assurance. Furthermore, the authors emphasize the importance of integrating risk management strategies within the project life cycle to systematically address potential MEPF challenges and mitigate associated time and cost impacts. The study concludes that proactive planning, technology integration, and structured stakeholder engagement are essential to ensure efficiency, safety, and sustainability in retail MEPF service execution [9].

**Hong et al. (2025)** investigated the transformative potential of Building Information Modeling (BIM) in promoting sustainable and efficient construction practices across various stages of project delivery. The study's literature synthesis revealed that the traditional construction industry is challenged by fragmented workflows, design inconsistencies, and a lack of coordination among stakeholders, leading to cost overruns and delays. Prior studies demonstrated that BIM serves as an integrative digital platform that enhances visualization, collaboration, and lifecycle management by providing real-time data accessibility and multidisciplinary coordination. The authors reviewed earlier research emphasizing BIM's role in facilitating energy modeling, material optimization, and lifecycle cost analysis, highlighting its ability to support sustainable design and operational efficiency. Despite these advantages, the paper identified that BIM implementation remains limited in many developing regions due to inadequate training, high initial costs, and interoperability challenges among software systems. To overcome these barriers, the study advocates for a systematic integration of BIM with sustainability frameworks and smart technologies such as IoT and cloud-based project management systems. The authors concluded that BIM's comprehensive capabilities not only improve project accuracy and resource utilization but also enable data-driven decision-making, thereby contributing to sustainable development goals and the digital transformation of the construction industry [10].

## 3. Plumbing Systems within the MEP Framework

### 1. Role and Significance

Plumbing systems ensure the circulation of potable water, safe drainage, and waste disposal, forming the lifeline of buildings. They interface intricately with HVAC and electrical systems creating dependencies that, if not properly managed, can lead to conflicts, rework, and performance degradation. In infrastructure such as metros and hospitals, plumbing systems contribute significantly to overall service reliability and safety.

### 2. Economic and Operational Impact

MEP systems collectively influence both construction cost and project duration. Rework and uncoordinated installations in plumbing can lead to 12% additional costs and extend schedules by up to 26%. Delays in testing, commissioning, or procurement of plumbing components - such as pumps, tanks, and valves - further amplify project inefficiencies. Early digital integration mitigates these impacts by allowing virtual prototyping and prefabrication planning before site execution [11].

### 3. Regulatory Context and Standards

National and international codes - such as NBC 2016 (Part 9: Plumbing Services), IS 1172, IS 2065, and Uniform Plumbing Code (UPC) - mandate hygienic, efficient, and safe plumbing design. Compliance with these standards ensures the reliability of water supply, drainage, and fire protection systems. Adherence to these codes remains a critical quality and safety determinant during project delivery.

## 3.1. Challenges in Plumbing Design, Installation, and Maintenance

### 1. Design-Stage Challenges

1. Space Allocation Conflicts: Insufficient shaft and ceiling space often constrain plumbing routes, leading to redesigns.
2. Coordination Gaps: Disconnected workflows between structural, architectural, and MEP designers result in clashes.
3. Compliance Complexities: Projects involving international collaborations often face inconsistencies in applying multiple standards.

4. Sustainability Neglect: Water-efficient designs are often deprioritized in favour of cost minimization.

**2. Installation Challenges**

1. Trade Conflicts: Poor sequencing between plumbing, HVAC, and electrical installations remains a major source of rework.
2. Procurement Bottlenecks: Delayed delivery of long-lead plumbing materials disrupts workflows.
3. Skill Shortages: Lack of trained plumbers causes defects, leakages, and misalignment of fixtures.

**3. Operational and Maintenance Challenges**

1. Leakages and Failures: Result from poor-quality materials or workmanship.
2. Access Restrictions: Maintenance is often hindered by poor design foresight.
3. Lifecycle Inefficiency: Absence of IoT or smart monitoring systems leads to undetected water and energy losses.

Table 1: Key Challenges in Plumbing Systems across Project Stages

| Project Stage | Challenge | Description / Impact | Reference |
|---|---|---|---|
| **Design Stage** | Space Allocation Conflicts | Insufficient shaft and ceiling space constrains plumbing routes, often necessitating redesign and rework. | [12] |
| | Coordination Gaps | Lack of integration among structural, architectural, and MEP disciplines results in frequent design clashes. | [13] |
| | Compliance Complexities | International projects face inconsistencies in applying multiple plumbing and building standards. | [13] |
| | Sustainability Neglect | Water-efficient and sustainable plumbing solutions are often overlooked due to cost-driven priorities. | [14] |
| **Installation Stage** | Trade Conflicts | Poor sequencing between plumbing, HVAC, and electrical systems causes workflow clashes and rework. | [15] |
| | Procurement Bottlenecks | Delay in delivery of long-lead plumbing materials disrupts the construction schedule. | [13] |
| | Skill Shortages | Inadequate training of plumbing personnel leads to leakages, fixture misalignments, and installation defects. | [14] |
| **Operational and Maintenance Stage** | Leakages and Failures | Result from inferior material quality and poor workmanship, increasing maintenance cost. | [16] |
| | Access Restrictions | Poor spatial planning hinders accessibility to plumbing components, complicating repairs. | [17] |
| | Lifecycle Inefficiency | Absence of IoT-based monitoring systems results in undetected water and energy losses. | [17] |

**3.2. Evolution of BIM and VDC for MEP Coordination**

**1. From 2D Overlays to Digital Collaboration**

Historically, coordination involved manual overlay of 2D drawings - a time-consuming process prone to errors. The adoption of BIM/VDC has revolutionized this by enabling 3D/4D/6D coordination, integrating time and cost dimensions into MEP design [12].

**2. Case Studies and Measured Benefits**

In the Camino Medical Group Project, BIM/VDC implementation yielded 100% plumbing prefabrication and zero field conflicts, reducing labour costs by 20–30%. The Stanford Medical Centre project reported similar benefits, achieving measurable schedule compression through integrated coordination meetings.

**3. BIM as an Information Backbone**

BIM consolidates all MEP data within a centralized model, allowing design visualization, interference checking, and simulation [15] [16]. Its role in plumbing coordination includes:

1. Automated clash detection between pipes, ducts, and structures.
2. Prefabrication-ready modelling for risers and pods.
3. Integration of manufacturer metadata for IFC-based interoperability.

### 3.3. Process Modelling and Data Interoperability

**1. The MetaTGA Framework**

The MetaTGA initiative focuses on improving BIM data quality for MEP systems through structured metadata and open standards. It standardizes parameters across tools like Revit and DDS-CAD, ensuring consistency during import/export processes. This enhances reliability in multi-software collaboration [5].

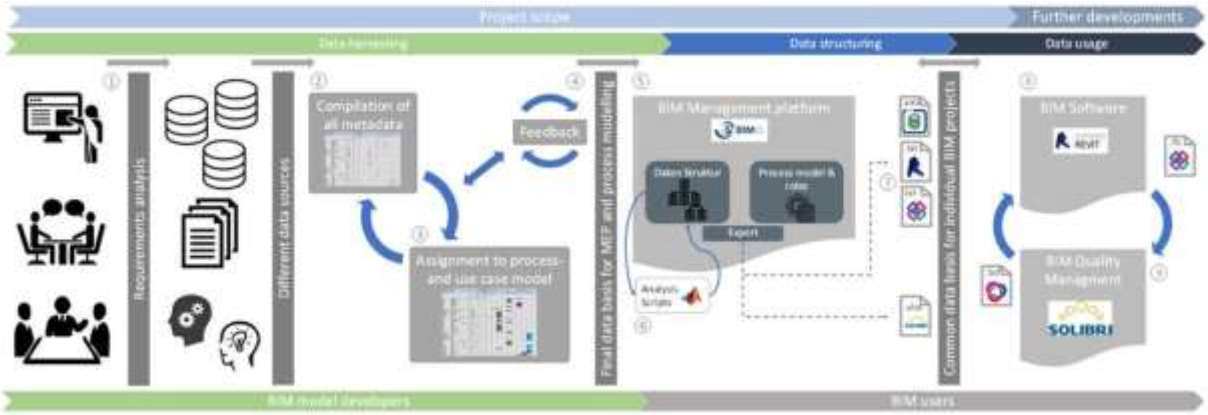


Figure 1: Process overview of the metaTGA approach of developing MEP BIM models [5]

**2 BPMN Framework for MEP Process Mapping**

The Business Process Model and Notation (BPMN) approach defines process flows for MEP systems, capturing design dependencies and information exchange. When applied to geothermal and plumbing systems, BPMN supports:

1. Defined stakeholder roles.
2. Transparent parameter dependencies.
3. Efficient coordination sequencing.

**3 Interoperability and ISO Standards**

Combining ISO 19650 (information management) with ISO 23386 (metadata definition) allows seamless BIM data governance. Open BIM principles enhance collaboration across platforms, supporting cloud-based CDEs for real-time design coordination.

### 3.4. Lean Integration and the IVL Methodology [14] [18]

**1. Concept and Framework**

Proposed the Integrated Virtual Design and Lean (IVL) method, merging Lean Construction with VDC. The approach aligns people, processes, and technology through:

1. Collaborative “Big Room” environments.
2. Shared goals and performance metrics.
3. Waste reduction via pull planning and real-time coordination.

**2. Application in MEP Coordination**

IVL case studies show that:

1. RFIs reduced by 90%.
2. Prefabrication rates increased 40–50%.
3. Field rework dropped below 0.2%.
4. Schedules shortened by up to six months.

Lean thinking thus enhances BIM/VDC performance by integrating human factors and systematic workflow management [14] [18].

Proposed the Integrated Virtual Design and Construction and Lean (IVL) method for coor dination of MEP systems. The IVL Method is illustrated in the Figure 2.


Figure 2: IVL Method for Coordination of MEP Systems [14] [18]

### 3.5. Advancements in Plumbing Systems

**1. Prefabrication and Modularization**

Prefabricated risers, pods, and pipe racks reduce site work, ensuring quality and consistency.

BIM-generated fabrication drawings enable accurate assembly and installation.

**2. IoT and Smart Plumbing**

IoT integration facilitates:

1. Real-time leak detection through smart sensors.
2. Predictive maintenance using data analytics.
3. Water efficiency optimization via automated valves.

**3. Digital Twins**

Digital twin technology extends BIM's utility into operations, linking sensors to live performance dashboards for fault prediction and water conservation tracking [19].

### 3.6. Rework Impacts and Mitigation

**1. Root Causes**

1. Design-construction mismatches.
2. Unskilled labour and inadequate supervision.
3. Late-stage client-driven design changes.

**2. Quantified Impacts**

1. 12% additional cost from plumbing rework.
2. 20–26% project time overruns.
3. 15–25% reduction in productivity in uncoordinated MEP installations.

**3. Mitigation Strategies**

1. BIM-based early clash detection.
2. Standardized design review protocols.
3. Digital supervision using AR/VR overlays for field validation.
4. Contractual clarity on coordination responsibilities.

### 3.7. Sustainability and Future-Oriented Design

**1. Green Plumbing Practices**

Adoption of rainwater harvesting, greywater recycling, and low-flow fixtures aligns plumbing design with SDG 6 – Clean Water and Sanitation. The NBC 2016 encourages separate systems for potable and non-potable water to avoid contamination.

**2. Policy and Regulatory Reforms**

Governments should incentivize modular plumbing systems, enforce IoT integration for leak monitoring, and update codes to reflect new materials and digital practices.

**3. Workforce Upskilling**

Digital transformation requires workforce readiness. Training plumbers and MEP technicians in BIM, data management, and prefabrication technologies ensures sustainable adoption.

## 4. Discussion and Research Outlook (Refer Table 2)

**1. Integration Barriers**

The convergence of BIM, VDC, and Lean is hindered by:

1. Proprietary software limitations.
2. Organizational inertia.
3. Inconsistent contractual structures.

**2. Opportunities for Research**

1. Development of AI-driven coordination algorithms for MEP systems.
2. Integration of blockchain-based data validation in BIM environments.
3. Performance-based metrics for digital twin-enabled facility management.

**3. Implications for Dissertation Research**

This unified framework provides a foundation for further research in:

1. Smart plumbing design optimization.
2. Integration of digital twins with predictive analytics.
3. Comparative evaluation of MEP workflows across international contexts.

Table 2: Conceptual roadmap for future MEP digitalization and smart plumbing research

| Stage | Focus Area | Core Objective | Digital Tools / Enablers |
|---|---|---|---|
| **1. Digital Documentation** | BIM Integration | Centralize plumbing layouts and asset data. | BIM, 3D Scanning |
| **2. Intelligent Design** | AI-Driven Modelling | Automate routing, clash detection, and hydraulic simulation. | AI, ML Algorithms |
| **3. Smart Monitoring** | IoT-Enabled Plumbing | Real-time leak detection, flow tracking, and predictive alerts. | IoT Sensors, Cloud Dashboards |
| **4. Data Interoperability** | Unified Information Framework | Ensure seamless exchange between design, construction, and facility stages. | Open BIM, APIs, Data Standards |
| **5. Sustainable Performance** | Resource Efficiency | Optimize water–energy use and enable greywater recycling. | Digital LCA, Simulation Tools |
| **6. Secure Operations** | Cyber & Data Governance | Protect sensor data, ensure reliability of connected systems. | Encryption, Blockchain, Edge Computing |
| **7. Human–Digital Synergy** | Skill Transformation | Enable digital literacy and AR/VR-based maintenance support. | AR/VR, Training Simulations |
| **8. Autonomous Plumbing Systems** | Self-Healing Networks | Enable predictive maintenance and adaptive water distribution. | Digital Twins, AI Control Systems |

## 5. Conclusion

The seamless integration of digital coordination tools with practical plumbing design principles is driving a new era of intelligent, efficient, and sustainable construction management.

1. The integration of BIM, VDC, and Lean methodologies has transformed modern construction management through enhanced digital coordination.
2. Global case studies demonstrate significant gains in project coordination, cost efficiency, and sustainability outcomes.
3. Plumbing systems have evolved from isolated components to integral elements driving digital transformation in MEP design.
4. Both academia and industry must embrace integrated, data-driven, and performance-based design practices.
5. Future-ready plumbing will rely on BIM for lifecycle insight, Lean for process optimization, and IoT-enabled digital twins for intelligent and sustainable system performance.

**Acknowledgement**

The authors sincerely acknowledge Prof. (Dr.) Vinay Patel, Principal, Birla Vishvakarma Mahavidyalaya Engineering College (BVM), and Prof. (Dr.) Sanjay Dhiman, Head and Professor, Civil Engineering Department, BVM, Vallabh Vidyanagar, Gujarat, India, for their encouragement and valuable infrastructural support in facilitating this research.

## References

[1] R. Parti, S. Hauer, and M. Monsberger, "Process model for BIM-based MEP design," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 323, no. 1, pp. 1–9, 2019, doi: 10.1088/1755-1315/323/1/012045.

[2] M. B. Patel, J. Pitroda, and J. J. Bhavsar, "Success Factor for Smart Infrastructure Development through Lean Management: A Review," *E-Proceedings Natl. Conf. Emerg. Trends Eng.*, vol. 1, no. 12, pp. 90–100, 2016.

[3] D. S. Patel and J. R. Pitroda, "Application of Lean Tools in Construction of Real Estate Project," *Int. J. Eng. Sci. Res. Technol. ISSN 2277-9655*, vol. 10, no. 4, pp. 43–54, 2021.
[4] R. Pradeep, B. Srinivas, and J. E. Manikanta, "Building Information Modelling and Analysis for MEP Services," *Int. J. Res. Anal. Rev. (IJRAR), (E-ISSN 2348-1269, P- ISSN 2349-5138)*, vol. 5, no. 3, pp. 913–922, 2018, doi: 10.1007/978-3-031-32309- 6_3.
[5] S. Hauer, J. Murschetz, A. Bres, A. Sporr, and M. Monsberger, "Metatga: A Chance for BIM in the Field of MEP," *BauSIM 2020, Online Conf.*, vol. 1, no. 1, pp. 1–6, 2020, doi: 10.3217/978-3-85125-786-1-60.
[6] Q. Wu, L. Chen, P. Shi, W. Wang, and S. Xu, "Identifying Impact Factors of MEP Installation Productivity: An Empirical Study," *Buildings*, vol. 12, no. 5, pp. 1–18, 2022, doi: 10.3390/buildings12050565.
[7] M. W. Khan, M. F. Shaari, and S. Hussain, "MEP System Installation Related Rework Causes and Impact on Project Performance ; A Case Study of Riyadh Metro Project Saudi Arabian," *Eur. Chem. Bull.*, vol. 12, no. S2, pp. 2554–2570, 2023, doi: 10.31838/ecb/2023.12.s2.400.
[8] S. Akbari, M. Sheikhkhoshkar, F. Pour Rahimian, H. B. El Haouzi, M. Najafi, and S. Talebi, "Sustainability and building information modelling: Integration, research gaps, and future directions," *Autom. Constr.*, vol. 163, no. April, p. 105420, 2024, doi: 10.1016/j.autcon.2024.105420.
[9] S. Goswami, S. James, R. Shukla, and B. N. Gourav, "Challenges in MEPF Services in Retail Store Setup: A Case Study Approach," *Converging Horizons Constr. Built Environ. Digit. Sustain. Strateg. Perspect.*, vol. 1, no. 1, pp. 337–345, 2025, doi: 10.17492/jpi/nicmar/2507032.
[10] Y. Hong and F. Guo, "A framework of BIM-IoT application in construction projects through multiple case study approach," *J. Build. Des. Environ.*, vol. 3, no. 202438, pp. 1–14, 2025, doi: 10.70401/jbde.2025.0004.
[11] D. R. Riley, P. Varadan, J. S. James, and H. R. Thomas, "Benefit-Cost Metrics for Design Coordination of Mechanical, Electrical, and Plumbing Systems in Multistory Buildings," *J. Constr. Eng. Manag.*, vol. 131, no. 8, pp. 877–889, 2005, doi: 10.1061/(asce)0733-9364(2005)131:8(877).
[12] P. H. Raol and J. R. Pitroda, "Integration of BIM with Lean Principles in Construction: A Review," *Stud. Indian Place Names, ISSN 2394-3114*, vol. 40, no. 60, pp. 4771– 4780, 2020.
[13] D. Parmar, J. R. Pitroda, and S. Malek, "Use of BIM (Building Information Modelling) as an integrated tool to plan, design and manage critical construction projects," *Int. J. Adv. Res. Innov. Ideas Educ.*, vol. 3, no. 1, pp. 1145–1153, 2017.
[14] A. Khanzode, M. Fischer, and D. Reed, "Benefits and lessons learned of implementing Building Virtual Design and Construction (VDC) technologies for coordination of Mechanical, Electrical, and Plumbing (MEP) systems on a large Healthcare project," *Electron. J. Inf. Technol. Constr.*, vol. 13, no. September 2007, pp. 324–342, 2008.
[15] A. M. Hathiwala and J. R. Pitroda, "Application of 5D Building Information Modeling for Construction Management," *Solid State Technol.*, vol. 64, no. 2, pp. 2156–2163, 2021.
[16] D. Gor, R. L. Patel, J. Pitroda, and C. G. Patel, "A Critical Literature Review of BIM Cloud Score : Building Information Model and Modeling Performance Benchmarking," *J. Emerg. Technol. Innov. Res.*, vol. 5, no. 11, pp. 861–866, 2018.
[17] P. H. Raol, S. Deshmukh, and J. R. Pitroda, "Integration of BIM with Lean Principles in Indian Construction Industry," *Int. Res. J. Eng. Technol.*, vol. 07, no. 07, pp. 968– 973, 2020, [Online]. Available: www.irjet.net
[18] A. Khanzode, "An Integrated, Virtual Design and Construction and Lean (IVL) Method for Coordination of MEP, CIFE Technical Report #TR187," *CIFE Tech. Rep. #TR187*, no. February, pp. 1–34, 2010, [Online]. Available: cife.stanford.edu/sites/default/files/TR187.pdf
[19] K. Shah, "Using Digital Twin Technology to Overcome Challenges in Civil Engineering and Construction: A Review," *Int. J. Eng. Adv. Technol.*, vol. 13, no. 1, pp. 49–57, 2023, doi: 10.35940/ijeat.a4305.1013123.