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Minimizing Cost Overrun in Rail Projects through 5D-BIM: A Conceptual Governance Framework

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Abstract: Integration of 5D Building Information Modelling (BIM) into large rail projects has the potential to significantly enhance cost management and control. Nevertheless, 5D-BIM implementation has encountered difficulties stemming from technical, functional, and governance-related factors. This paper builds a conceptual framework to support financial decision-making, enhances project management, and promotes efficient project delivery. The framework encompasses a set of interrelated elements that include project governance, BIM policies and standards, digital platforms, BIM LOD, cost estimation classification, and continuous improvement. The proposed framework acknowledges the significance of project governance in guiding and organising the implementation of 5D-BIM. Additionally, BIM policies and standards ensure the adherence to quality standards for the produced BIM models. Digital platforms serve as the basis for multiple users to generate, access, share, and exchange project information. BIM LOD promotes collaboration and coordination among all project stakeholders. Cost estimation classification aligns the estimation process with the development of project scope and financial decision-making. Continuous improvement plays a vital role in optimizing processes, enhancing efficiency, and achieving higher-quality outcomes. Moreover, it fosters stakeholder satisfaction, improves project performance, and nurtures a conducive environment for innovation and learning. The study analyses the framework utilization in the Victorian rail projects and identifies key implementation challenges. The main technical hurdles encountered were the lack of current horizontal infrastructure standards for data exchange and the lack of compatibility with current cost management standards. Increased project complexity and the absence of clear project governance strategies and processes also posed organizational challenges. A further validation of the framework in real-world rail projects was recommended to achieve the implementation goals.

Keywords: Project governance; 5D-BIM; Mega-projects; Cost Overrun; Rail Projects; Conceptual Framework

1. Introduction

Navigating the mega rail projects requires an in-depth understanding of their expansive and complex nature [1]. Successful project delivery is not just about managing a multitude of complex activities within strict timeframes and budgets [2]. It also involves an extensive array of stakeholders and communication dynamics [3]; as a result, coordination and collaboration between various stakeholders play a vital role [4]. The success of mega rail projects hinges on the robustness of project governance. Poor project governance in mega projects can lead to delays, scope creep, and inadequate resource allocation, all of which contribute to a snowball effect on costs and eventually lead to a budget blowout and cost overrun[5]. While the debate continues between academics on cost overrun definition, causes, magnitude, and reference point of measurement, they all agree on the detrimental consequences of this phenomenon [5–11]. The governance of mega projects is a complex and dynamic field, that requires a multidisciplinary approach and collaborative efforts across sectors and borders. Effective Building Information Modeling (BIM) is regarded as vital to the success of these projects

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[12]. BIM implementation heavily relies on policies and standards to ensure consistency, interoperability, and quality [13]. However, the gap between the rapidly evolving technological landscape and the slower pace of policy and standard development poses significant challenges. It creates a scenario where the full potential of technological advancements cannot be realised due to regulatory limitations or a lack of guidance [14]. To effectively connect the realms of BIM and construction management, it is important to adopt a flexible approach to policy and standard development that is consistently updated. A collaborative effort between technologists, practitioners, and policymakers is thus essential to establish practical and realistic standards that can effectively utilise the latest technological advancements.

The State of Victoria, Australia is embarking on its most ambitious rail endeavor to ensure these projects adhere to both global standards and local regulations by adopting a 5D-BIM framework [15]. This framework incorporates successful strategies employed by other major rail projects worldwide, while also remaining adaptable to the unique policy context of the region.

This paper presents a conceptual governance framework for implementing 5D - BIM to support financial decision-making, enhanced project management, and promote efficient project delivery of railway projects. The study builds upon an earlier Systematic Literature Review (SLR) on the role of 5D BIM in minimizing cost overruns in rail projects [1]. The SLR aggregated 4,342 publications and analyzed 1,888 papers to identify and discuss cost overruns in rail projects and 5D-BIM applications and trends over the last 23 years [1], and identified key clusters influencing the success of 5D BIM implementation.

Motivated by the clusters identified in the SLR, the present framework introduces a process of continuous improvement with the goal of providing a flexible and adaptive environment for 5D-BIM adoption.

This research begins by examining 5D-BIM across various global contexts. Following this global overview, the study methodically narrows its focus to the state of Victoria. This shift from a broad, international perspective to a more concentrated regional analysis allows for the creation of a 5D-BIM framework that is not only informed by global best practices but is also meticulously customized to the specific needs and challenges unique to Victoria. The transition from a wide-ranging analysis to a focused, region-specific application forms the core of the research methodology. This approach ensures that the framework is both globally informed and locally applicable.

The framework looks into 5D-BIM in the context of governing projects, it provides a comprehensive approach to incorporating 5D BIM into railway projects while following the Victorian Digital Asset Strategy. To demonstrate the practical implications of this conceptual framework, a case was conducted in Victoria. The study included a thorough investigation of the delivery mechanisms used in mega rail projects in Victoria, as well as an analysis of government-verified documents such as policies, standards, and guidelines. We then identified various conceptual framework elements in the context of Victoria and carefully examined how these elements integrate. The framework's versatility in adapting to different global contexts makes it an invaluable resource. The framework was formulated from previous 5D-BIM implementation experiences and a thorough examination of literature and policies. It delineates crucial aspects of BIM implementation in rail projects, emphasizing governance and adherence to policies and standards in both the international and Victorian/Australian spheres.

The first section of this paper discusses the significance of project governance in the context of mega rail projects and explores the potential contributions of 5D-BIM to effective project management and successful project delivery. The next section presents a theoretical background essential for further comprehension of the research. Next previous studies are discussed and a contextual background to the current study is provided, as well as the approach for developing the 5D-BIM framework. Critical analysis of 5D-BIM implementation in various geopolitical contexts are then presented, focusing on two case studies from the UK and India, after which the 5D-BIM framework is described, detailing its different elements and elaborating on the structure and dynamics of the framework. Finally, the Victorian perspective of the 5D-BIM framework is presented, followed by the discussion and conclusion.

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2. BIM-based Governance management frameworks

Previous studies have endeavoured to establish a 5D-BIM framework to manage costs, but they have certain limitations [16]. These studies fail to consider project governance, BIM policies, and stakeholder involvement [17]. To enhance project management and support financial decision-making, a conceptual framework is necessary. The framework comprises several subsections, including a literature review, theoretical foundations, and essential concepts.

2.1. Management frameworks

Effective project management in public sector megaprojects relies heavily on governance frameworks [18]. These frameworks serve as a vital tool in ensuring transparency, accountability, and compliance with legal and ethical standards [19]. Examples of such frameworks include corporate governance [20], IT governance [21], and BIM governance [22]. They help guide the decision-making process, establish authority and accountability structures, and prioritize regulatory compliance, ethical standards, stakeholder engagement, and strategic decision-making. Governance frameworks are designed to optimize resources, streamline processes, and achieve project objectives in mega projects [23]. They are a highly effective communication tool for involving stakeholders [24].

The rise of digital technology has significantly impacted mega projects governance and delivery strategies. Many government agencies and organizations are undergoing digital transformation, integrating technology into all aspects of their operations. This shift has given rise to the integration of BIM and digital tools in their frameworks [25]. This has led to improvement in the delivery experience of these projects [26]. Governance frameworks that incorporate digital technologies tend to have a flatter and more agile structure, facilitating faster decision-making and greater adaptability to changing market conditions or technological advancements [27]. Incorporating BIM and digital technologies enables decentralized and data-driven decision-making through the Common Data Environment (CDE). The Norwegian Quality Assurance Scheme serves as an example. This framework involves a two-stage external quality assurance process, applied before key decision points as shown in **Figure 1**.

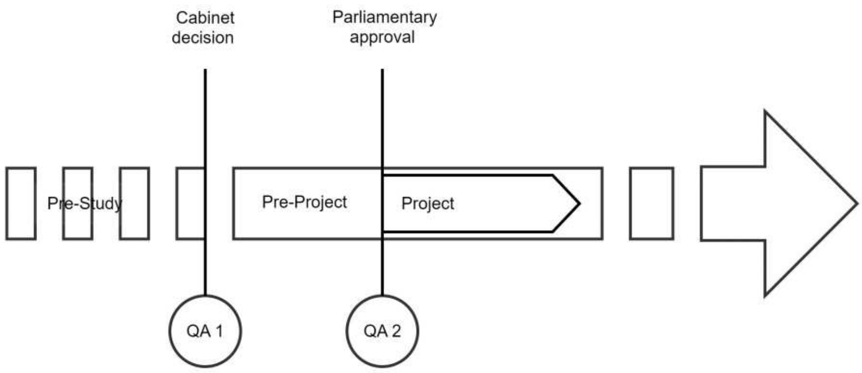

Figure 1. The Norwegian scheme for quality assurance of major public investments (the QA scheme) adopted from [19].

The Norwegian Quality Assurance Scheme offers key advantages for megaprojects governance, including thorough evaluation of project viability, risks, and benefits, ensuring informed decision-making. It also emphasizes stakeholder involvement for balanced perspectives and prioritizes early risk identification and management. However, there are challenges such as adapting to rapid technological and economic changes and managing the complexities and interdependencies of megaprojects. This highlights the need for continuous adaptation and improvement to maintain its effectiveness in a dynamic megaprojects environment [19].

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Mandates for BIM compliance are often accompanied by supportive measures to facilitate the industry's transition. These measures may include financial and technical assistance. For example, in anticipation of the 2016 BIM mandate, the UK government partnered with industry organizations to offer technical support. This support included initiatives to enhance the skills and capabilities of clients and supply chain actors, develop standards, and establish knowledge-sharing platforms and BIM-based governance frameworks [28]. An example of a governance framework based on BIM and CDE is the UK BIM Framework, which represents a comprehensive approach to BIM implementation and information management in megaprojects. The framework aligns with the guidelines of The Construction Playbook [29], which sets out key policies and guidance for the assessment, procurement, and delivery of public works projects and programs in the UK. It emphasizes the transformation of approaches to both the delivery and operation of assets and is particularly focused on guiding organisations towards the successful implementation of BIM information management practices [22].

The UK BIM Framework requires precise information requirements to support strategic objectives and ensure the security and relevance of information. It also emphasizes the importance of timely and accurate information for effective decision-making. Additionally, a value-based approach to tendering is emphasized, which involves considering both cost and quality, often requiring a BIM Execution Plan and assessing the capability of involved organizations [22].

Collaborative working is a crucial aspect of the framework. It encourages investments in processes, IT infrastructure, and procedures that promote collaborative efforts [30]. This, in turn, ensures that the information produced is consistent, and the specified methods are effective before being put into production. The delivery and acceptance of information are crucial stages in the framework, requiring thorough verification against established requirements, standards, and production methods. The primary framework standards are the ISO 19650 series, which provide essential guidance on managing, delivering, and verifying information, ensuring consistency and compliance across projects [22]. An important implicit aspect of the UK BIM Framework is the Common Data Environment (CDE).

2.2. Project governance

Project governance is crucial for successful project delivery and benefits realization [31]. However, the literature on it remains fragmented, lacking consensus on its definition and elements [32]. Governance involves monitoring and controlling transactions between parties, ensuring efficient value sharing [33]. In the context of a project, governance is multifaceted, involving the parent organization, contractors, suppliers, and project dynamics [34]. A well-defined regulatory framework is essential for successful project governance, ensuring quality, adherence to objectives, effective management of issues, and rigorous evaluation of key documents [35]. Project governance involves aligning project objectives with organizational strategy to benefit stakeholders.[34].

As project management has evolved into its own distinct field, governance schools of thought have emerged to analyze the purpose of projects and identify suitable governing mechanisms [36]. There are two main schools of thought on governance in the academic literature. The first school examines governance from the standpoint of the organization at a macro level, while the second school takes a more granular approach and looks at governance from a sub-organizational level [37].

Corporate governance is the responsibility of directors and is the system used to direct and control a corporation [38]. It is led by professional bodies and institutions such as the Australian Institute of Company Directors [39], the Institute of Directors in Southern Africa [40], and the Organisation for Economic Co-operation and Development [41].

Project management standards define change as a variation within project boundaries [42]. However, every project functions as an agent of change. Senior management must ensure adequate support for projects to achieve outcomes aligned with organizational objectives [43]. Project governance involves principles, structures, and procedures to manage projects effectively. Projects are subject to oversight by their owners [44]. It is imperative to highlight the inherent conflict between the development or exercise of project governance and the provision of supporting projects to achieve

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their objectives [37]. This tension arises because one of the primary functions of governance is to establish accountability [45, 46]. To address this conflict and manage the risk exposure of individual projects, Turner and Keegan [47] suggest introducing two key roles in organizational governance: the broker and the steward. Central to their proposal is the "single truth" concept, emphasizing a unified information source within an organization to guide decision-making across various teams. The broker role focuses on managing external relationships, ensuring alignment between external demands and internal capabilities. Conversely, the steward role focuses on internal coordination, aligning team actions with the organization's policies. Together, these roles create a balance, fostering consistent policy implementation and informed decision-making based on a shared understanding of facts [48].

Project governance challenges often stem from a lack of transparency, which can create a breeding ground for mismanagement, inefficiencies, and even corruption. The absence of transparency can fuel scepticism and mistrust between the government and the public and ultimately undermine the project's credibility and the stakeholders' integrity [49]. In mega rail projects where the sheer magnitude of these projects often amplifies the risks and consequences associated with the absence of transparency [50].

Achieving transparency in project management can be riddled with obstacles, creating a need for robust strategies to combat these challenges [51]. The main challenges in ensuring transparency in project governance include:

- Strategic misrepresentation, political pressures, and the influence of vested interests by manipulating the flow of information and suppression of unfavorable project cost and progress data to serve specific political agendas [52, 53]
- Excessive bureaucracy and complexity of decision-making structures and processes. This includes the presence of hierarchical power dynamics within government agencies, which can impede the free flow of information [54].
- Absence of data management systems and using outdated or incompatible technology platforms to track and monitor project progress [55].
- Poor stakeholder engagement and inadequate communication of project goals, strategies, and performance to the right stakeholders, can create an environment conducive to political maneuvering and corruption [56].

Integrating technology-driven solutions such as data analytics and digital platforms can enhance transparency and facilitate real-time monitoring of project progress. These tools enable stakeholders to access accurate and up-to-date information, promoting accountability and informed decision-making throughout the project lifecycle [57].

2.3. Five-Dimensional Building Information Modelling (5D-BIM)

Originally developed for vertical construction projects like buildings [58], BIM is now finding its way into horizontal assets such as roads and railways [59]. This global trend toward increasing BIM implementation in the development and management of horizontal assets is bringing about a multitude of benefits that enhance efficiency, sustainability, and overall project outcomes [60] . The benefits of BIM in horizontal projects like roads and rail include improved accuracy, cost savings, sustainability, and data-driven decision-making [61]. 5D-BIM, in particular, provides continuous benefits throughout the project lifecycle in terms of cost estimation, cost budgeting, cost control, quantity take-off, and lifecycle cost analysis [1].

Li & Cao [62] define BIM as a digital representation of an engineering project's entity and functional characteristics. BIM, in essence, is much more than just software; it is a set of data sources and software tools that support various disciplines and build a multidimensional built environment [63]. It is a collaborative approach for storing, sharing, exchanging, and managing multidisciplinary information across the full building project lifecycle, including planning, design, construction, operation, maintenance, and demolition [64, 65].

The foundation of the BIM concept lies in the creation of a centralised model that consolidates all information related to the building. The term "nD" in BIM refers to any views linked to the virtual

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building model [66]. The 4D links the construction activities represented in time schedules with 3D models to generate a real-time graphical simulation of construction progress versus time. Furthermore, linking 'cost' to the BIM model generates the 5D model, which enables the instant generation of cost budgets and financial representations of the model versus time [67]. **Table 1** shows the different BIM dimensions[1].

Table 1. BIM dimensions.

BIM Dimension	Descriptions	Characteristics	Popular software / solutions
3D	3D-BIM is the foundational level, it represents the geometry dimensions.	3D building data and information, field layout and civil data, reinforcement and structure analysis, existing model data.	AutoCAD, Revit, Bentley MicroStation, ArchiCAD, Allplan, and Tekla[68].
4D	4D-BIM adds the element of time to the 3D model.	Project schedule and phasing, just-in-time schedule, installation schedule, payment visual approval, last planner schedule, critical point.	Synchro PRO, Navisworks, Trimble Vico Office, Fuzor, Asta Power Project, and C3D interactive[69][70].
5D	5D-BIM extends the capabilities of the model by incorporating cost estimation and quantity take-off data.	Conceptual cost planning, quantity extraction to cost estimation, trade verification, value engineering, prefabrication.	RIB CostX[17] , Bexel Manager[71], PriMus[72], Cubicost[73], and Contruent (Ares prism) [74].
6D	6D-BIM focuses on sustainability and environmental aspects.	Energy analysis, green building element, green building certification tracking, green building point tracking.	Autodesk BIM 360 Ops[75], FM: Systems[76], and EcoDomus[77].
7D	7D-BIM integrates the facility management, operation & maintenance data into the model.	Building life cycles, BIM as built data, BIM cost operation and maintenance, BIM digital lend lease planning.	IBM TRIRIGA[78], ARCHIBUS[79], IBM Maximo[80], and FM: Systems[76].

A typical 5D-BIM model in the rail industry is a comprehensive digital representation of a railway infrastructure project, including the physical and functional characteristics of the railway system. It includes detailed elements tailored to the specific needs and complexities of rail projects[81–83]Railway Geometry: Detailed geometric information about tracks, alignments, gradients, turnouts, and crossings, as well as the relationships and clearances between these elements.

- Rail-Specific Components: This includes the design and specification of rails, sleepers (ties), ballast, signaling equipment, electrification systems (like catenaries or third rails), and communication systems.
- Stations and Facilities: Detailed models of station buildings, platforms, canopies, ticketing areas, and other passenger-related facilities.
- Structural Elements: Bridges, tunnels, retaining walls, culverts, and other structural components that support the rail infrastructure.
- Interoperability and Systems Integration: This pertains to integrating various subsystems within the railway infrastructure, such as signaling systems, train control systems, and power supply systems.
- Material Specifications and Libraries:

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- Product Libraries: Manufacturer-specific components that are used within the railway industry, such as specific types of rail or signaling equipment.
- Standard Libraries: Commonly used elements and symbols within the rail industry, often adhering to national and international rail standards
- Quantities and Shared Properties: Data for material quantities, lengths of track, numbers of components, and other quantifiable aspects of the railway, which are vital for cost estimation and procurement.
- Non-geometric Data: Information such as maintenance schedules for track and equipment, operation manuals for signaling systems, and warranty information for installed components.
- Analytical Models: These models are used for various types of analysis, including structural analysis of bridges and tunnels, dynamic analysis of track under loading from trains, and capacity analysis for signaling systems.
- Environmental and Contextual Data: Information about the terrain, surrounding environment, and interface with existing infrastructure, which are crucial for planning and environmental impact assessments.
- Construction Sequencing (4D): Integration of the construction schedule to visualize the construction process over time, optimize the sequence of works, and reduce conflicts during the construction phase.
- Cost Estimation (5D): Embedding cost information for budgeting, cost management, and financial tracking throughout the lifecycle of the railway project.

2.4. Common Data Environment (CDE)

The Common Data Environment (CDE) is a tool that offers several benefits to project management. The International Organization for Standardization's ISO 19650 sets the framework for a Common Data Environment (CDE), defining it as an agreed source of project/asset information for the collection, management, and sharing of information containers through a managed process [84]. The central element is the data repository, which is the primary storage space for all data. Additionally, the structure of stored information, crucial for CDE, must be predefined and regularly updated, often as a contractual requirement. The system also involves managing property and access rights to secure data and control access [85]. For BIM-based collaboration, it mandates exclusive data exchange through the CDE at specific times, as per the contract. Lastly, it uses planning statuses (work in progress, shared, published, archived) to coordinate cooperation and track the usability of data sets [86]. It promotes collaboration among various project stakeholders, reduces miscommunication and errors, and maintains accountability [87]. The CDE includes robust version control, access control, and documentation of all changes and activities related to project data. This was demonstrated effectively in a case study by Ye et al. [88], where BIM, CDE, and smart contracts were used for managing claims. It also has predefined storage structures, exclusive data exchange, and planning statuses that track the usability of data sets [89].

However, implementing CDEs is challenging due to a lack of strategy, high costs, inadequate training, and incomplete setup. Better implementation strategies, training, and protocols are needed for efficient CDE utilization [90]. The importance of CDE in managing collaborative work is emphasized, and strategies to overcome barriers in CDE adoption are proposed.

2.5. BIM Policies and Standards

Different regions have varying approaches to the implementation of Building Information Modelling (BIM) policies. The differences in policy adoption can be explained by the policy diffusion theory, which suggests that a government's decision to adopt a policy is influenced by the decisions of other governments [91]. Peters et al. (2012) [92] expand on this idea by introducing policy-induced innovation, which emphasizes how policy mechanisms can act as incentives for innovation. Filippopoulos and Fotopoulos (2022) [93] contribute to this discussion by highlighting the importance of factors such as regional economic development and openness in determining policy effectiveness.

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Building Information Modelling (BIM) is being implemented at different paces around the world, with countries taking various approaches. While the U.S. [94] and UK [95] have made progress with both market-driven and government-mandated methods, China and Australia [96] are still developing their BIM frameworks [97, 98]. Singapore [99] has a clear strategy centered around Integrated Digital Delivery (IDD), while Japan's unique design-build system has made BIM adoption slower [100, 101]. Germany has created a plan with phases for BIM implementation, including standards, pilot projects, and new project applications [13]. Each country's approach to BIM implementation is shaped by its specific regulatory landscape. To advance BIM globally, it's important to harmonize these diverse approaches, set international standards, and address obstacles. **Table 2** offers a summarized comparison of the various policies and standards for BIM from multiple countries.

Table 2. A comparison of various BIM policies and standards from different countries.

Country	BIM Policy	Approach	Challenges/Support	References
China	Outline of Development of Construction Industry Informatisation (2016-2020) Railway BIM Data Standard[102]	Strong government involvement.	Policy development lags behind practical application	[14, 103]
USA	National BIM Standard – United States® (NBIMS-US™)[104]	Market-driven, less government enforcement.	Barriers to BIM adoption include size and scale of the project, high training and migration costs, general resistance and reluctance, and the Computer Aided Design (CAD) vs BIM debate	[95, 105]
UK	Government Construction Strategy (2016-2020)[106]	Government-mandated BIM in public projects.	Setting standards and protocols for collaborative work	[105, 107]
Singapore	Singapore BIM Guide[99]	Government-led with strategic technology adoption.	Training, standards development, and incentives	[100, 108]
Japan	- Guidelines for BIM Standard Workflows (MLIT, 2020)[109] -Vision for the Future and Roadmap to BIM[110]	Combination of government initiative and private sector involvement.	Challenges include difficulty in immediate promotion according to international standards, lack of mandatory BIM use, and reliance on government-led projects	[100, 101]
Germany	German BIM Implementation Strategy for Federal Buildings[111]	Emphasis on standardisation and industry-driven initiatives.	National BIM standards and guidelines focused on interoperability	[112, 113]
Australia	- National BIM Guide[96]	Market-driven with some government influence.	Barriers in Small and Medium-sized Enterprises (SMEs) include ROI concerns and resource limitations	[97, 98]

2.6. 5D-BIM software and tools

In the context of organizational governance, BIM software and tools align seamlessly with the roles of the broker and the steward. BIM's centralized data repository ensures a single source of truth, facilitating the broker's management of external relationships by aligning project data with current client expectations. The steward leverages BIM for internal coordination, aligning project execution with organizational policies and goals. This integration of BIM into the functions of both roles

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promotes a coherent, transparent, and unified approach to project management, ensuring consistent policy implementation and informed decision-making across all levels of the organization.

A variety of software solutions have been developed to facilitate the integration of 5D-BIM into horizontal projects such as roads and railways. However, it is important to note the absence of a universally applicable solution or a 'one-size-fits-all' approach. Typically, a combination of software solutions is required for successful implementation. 5D-BIM can be developed through two main approaches: one by establishing a live connection to the estimation software tools and the second one is using integrated 5D cost management solutions [114–116]

In the second approach, 5D BIM-based cost management applications are employed to manage and analyse the cost within the BIM model itself. This approach facilitates both manual and smart quantity take-off, the development of cost reports, and the visualization of cost information. It also assists in the management of project costs throughout the entire project cycle, from the initial phase to the closeout phase. **Table 3** shows popular 5D-BIM software packages.

Table 3. Popular 5D-BIM software packages.

Software/solution	Competitive advantage	Key Features	Training Availability	Additional Notes	Cost (Approx.)	References
RIB- Cost-X[117]	Cost-X excels at enabling users to conduct thorough quantity take-offs and cost estimations directly from the BIM model. This functionality automates the generation of quantities and cost data based on the elements within the BIM model, while also facilitating comprehensive cost analysis and reporting.	Construction estimating, takeoff, BIM file support	Online self-paced, day sessions, private training	Integrates with Microsoft Excel	Flexible pricing based on project type/size/No of users.	[17, 118, 119]
Bexel Manager[120]	Bexel Manager stands out by having advanced visualization tools that integrate with the 3D model to represent cost data in intuitive charts, graphs, and dashboards, helping stakeholders to understand complex cost information more easily.	3D, 4D, 5D, 6D BIM uses, digital construction management	Online, trainer-led, self-paced	Advanced open BIM technologies	Varies, $ 985 /user/year for Bexel Manager Teamworks, 250+ user.	[71, 121, 122]
ARES PRISM (rebranded as Contruent)[123]	ARES PRISM is highly regarded for supporting Earned Value Management (EVM) allowing for better project control, also for its high scalability and customizability.	Integrated cost and scheduling, project management	Instructor-led and online, fundamental to advanced	Executive dashboards	Flexible pricing based on project type/size/No of users.	[74]
Cubicost[124]	Cubicost is known for its strong integration capabilities with various BIM platforms, allowing users to leverage 3D models for accurate quantity take-off and cost estimation.	BIM for quantity surveying, 5D BIM cost management	Workshops, online courses, interactive sessions	Supports different modeling and estimation modules TAS, TRB, TBQ, TME modules	Not specified	[73, 125]
PriMus[126]	PriMus is often praised for its user-friendly interface, making it accessible and intuitive for both seasoned professionals and those new to cost estimation software. It seamlessly integrates with various price books and databases,	Drag-and-drop interface, integrates with CAD	Online resources and support	Manages quantity surveying, cost estimating, BOQ	Starts at $31.57/month	[74, 127]

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Software/solution	Competitive advantage	Key Features	Training Availability	Additional Notes	Cost (Approx.)	References
	enabling users to access up-to-date pricing information for materials and resources.					

The comparative analysis of 5D-BIM software reveals several key trends in the industry. Increasingly, BIM software products are moving towards cloud-based solutions, reflecting a broader technological shift towards more accessible and collaborative platforms. Additionally, there's a noticeable trend towards flexible pricing models among software providers. This flexibility often includes scaling costs based on project size, type, or the number of users, making 5D-BIM tools more accessible to a wider range of projects and companies. The adoption of these trends can be attributed to advancements in internet and web technologies, which enable more scalable, versatile, and user-friendly software solutions.

2.7. Digital platforms

Due to the need to improve the performance of infrastructure megaprojects, there has been a shift away from using traditional project delivery methods to collaborative forms of project delivery [128].

Digital platforms encompassing online systems and applications, establish the basis for multiple users to generate, access, distribute, or exchange project information[129, 130]. Digital platforms enable interoperability and transactions in a secure, confidential, and discrete manner, eliminating the need for users from different parties to have simultaneous access to each other [131]. Employing digital platforms in megaprojects offers a multitude of inherent benefits and possesses the potential to enhance the decision-making process and project governance [132]. Relative to traditional bespoke or 'big one-off' strategies, platforms exhibit the capacity to significantly minimise cost overruns in megaprojects [133].

However, a digital platform doesn't function in a governance vacuum; it inherently replicates a governance framework that establishes protocols, oversees, and facilitates and regulates interactions between participants, as well as the exchange of data and data services[134].

2.8. 5D-BIM implementation challenges/barriers

Mega rail projects are typically managed as programs, comprising various packages, executed at different times, in different geographical locations, and often by different contractors [135]. This complexity leads to the use of a wide array of software packages across the project. The diversity of software used by each entity poses a significant challenge. High levels of collaboration and data sharing are crucial for successful project delivery, requiring a strong focus on harmonization and software compatibility. Additionally, the field of BIM faces a skills gap, complicating the effective implementation and integration of these technologies [136].

BIM challenges in mega rail projects fall into three categories: Governance (People) addresses leadership and skills gaps; Governance (Policy) focuses on quality control and legal aspects; and Communication Processes and Workflow emphasize effective coordination protocols. Technology involves data security, software selection, and hardware management. The rapid advancement of technology compared to policy updates poses significant challenges in compliance and aligning BIM practices with current capabilities. **Table 4** shows the key 5D-BIM implementation challenges/barriers along with their associated fields and categories.

Table 4. 5D-BIM implementation challenges & barriers.

Category	BIM field	5D-BIM key implementation challenges/barriers	Reference
Governance	People	Lack of Leadership and commitment from the project team.	[137, 138]
		Ambiguity in Project Roles and Responsibilities	[137, 138]
			[137–140]
		Lake of Training and Skill Gaps	
		Resistance to Change	[137–140]
	Policy	Challenges with quality control	[98, 137]
		Legal Challenges in Data Ownership and Sharing	[98, 137, 138, 141]
		Need for success measurement and KPIs	[137, 138]
		Risk management issues	[137]
Policy and standards	Policy	Lack of Consistency	[98, 137, 138, 141]
		Uncertainty in compliance with industry and government requirements	[98, 137, 138]
Communication, Processes, and workflow	People	Need for communication Protocols	[98, 137–140]
	Technology	Data Security and Privacy Risks	[137, 138]
Tools and software	Technology	Selecting the right software	[98, 137–139, 141]
		Data management challenges	[137, 138]
Integration and compatibility	Technology	Difficulties in data migration and integration	[137, 138]
		Hardware requirements and cost	[137, 140, 141]

3. Previous studies

Many researchers have attempted to develop a 5D-BIM framework for cost management and control. For example, Boton et al. [142]conducted an extensive systematic literature review of 5D-BIM, analyzing eighteen different software and web solutions. This analysis focused on five key areas of cost management practices. Based on this study, they developed a 5D-BIM framework, aimed at facilitating informed decision-making about the most effective 5D-BIM solutions across different stages of a project's lifecycle. Moses et al. [143] conducted interviews with 21 participants from UK-wide construction organizations and consequently developed a 5D-BIM conceptual framework to facilitate costing in contractor-led projects. Lu et al. [144] developed a framework for accurate cash flow analysis by considering various payment patterns, thereby enhancing cash flow analysis and aiding contractors in making financial decisions. Ranjbar et al. [145] extends this by incorporating risk analysis into cash flow management, acknowledging the uncertainties inherent in construction projects.

While these frameworks offer significant advantages at the project level, their implementation could be limited in the case of mega projects, which are often delivered as a portfolio/program with various types of packages. In addition, these studies exhibit certain limitations, notably overlooking the influence of project governance and BIM policies on the efficacy of 5D-BIM solutions and implementation.

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This limitation supports the need for a conceptual framework that can be used by different stakeholders to support financial decision-making and enhance project management and delivery. This study, grounded in a thorough systematic literature review on the use of 5D-BIM for minimizing cost overruns in mega rail projects[1], acknowledges the unique challenges and organizational complexities of mega rail projects; it has a more overarching goal and highlights the importance of a holistic governance framework that encompasses not just financial and risk management but also broader project governance and stakeholder management, ensuring integrated implementation of 5D-BIM throughout the project lifecycle.

4. Contextual background and research method

This study, which is an integral part of a broader research on minimising cost overrun in rail projects through 5D-BIM, analyses the literature on successful governance frameworks, concentrating on mega projects in the rail industry. It compares the policies and standards from various international governance frameworks and analyses and conceptualizes dimensions to the context of Victoria, Australia, as a practical conceptual framework. After analyzing the findings from the literature review, the study conducts a detailed policy and document analysis to explore the various governance dimensions involved in the implementation of 5D-BIM, as well as the factors contributing to challenges and successes with a focus on notable rail projects like Crossrail [146] [147] and Nagpur Metro Rail [148].

To develop the 5D-BIM conceptual framework, the initial stage involved a detailed analysis of the SLR results to construct a concept map that identifies the elements of the 5D-BIM framework and illustrates the processes both within and among these elements. Following this, we thoroughly examined, analysed, and categorized the 5D-BIM implementation challenges and barriers. Finally, we proceeded to investigate the diverse 5D-BIM policies on a global scale and assess their application in real-world projects, extracting valuable lessons from these case studies.

Figure 2 presents the keyword cluster map for the 5D-BIM framework development using Leximancer[149] as a powerful text analysis tool. The map helps to dissect and understand the functionality of each cluster element and their relation within the system.

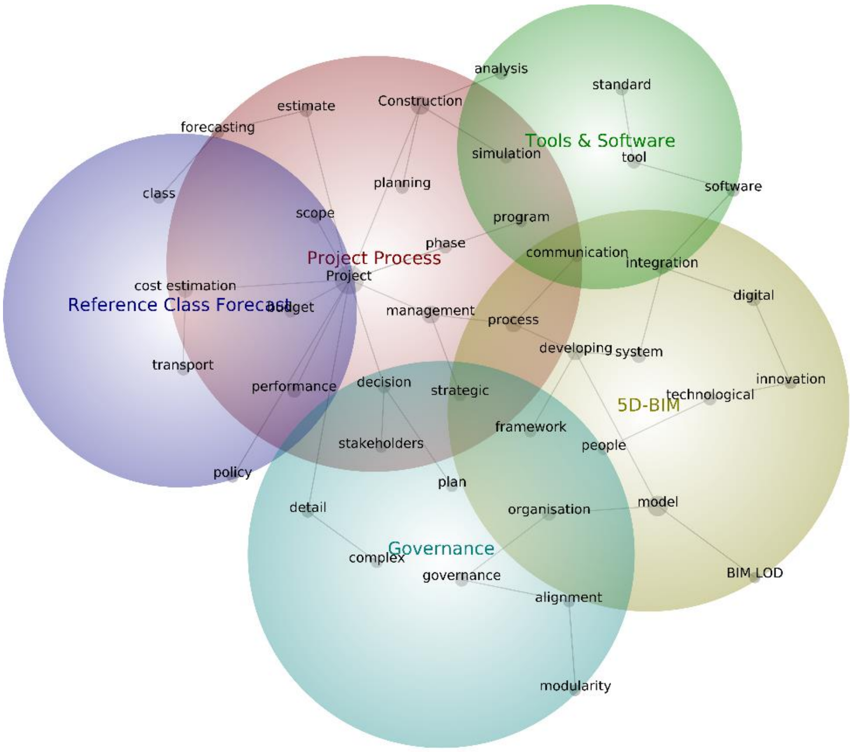

Figure 2. The concept keyword cluster map for the 5D-BIM framework.

5. Critical analysis of 5D-BIM implementation in various geopolitical contexts

Figure 3. Map of mega rail projects employing BIM.

Figure 3 presents a worldwide map displaying mega rail projects across the globe that employ BIM throughout their project lifecycle. The comparison of these projects in terms of their BIM maturity reveals a diverse landscape of technological integration and standards, as shown in

Table 5 This overview highlights a global trend towards more sophisticated BIM practices. However, the degree of implementation and standardization varies significantly, depending on the regional policy context and project-specific factors.

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Table 5. comparison of mega rail projects employing BIM.

Project	Location	BIM Standards and Policy	BIM Maturity Level
California High-Speed Rail	USA	NBIMS-US	Advanced: Full collaboration with a shared model, real-time data sharing, and highly integrated processes.
Maryland Purple Line	USA	NBIMS-US	
HS2	United Kingdom	BS1192/ISO 19650	
Crossrail	United Kingdom	BS 1192	
Riyadh Metro	Saudi Arabia	Emerging BIM adoption, no standardized framework or BIM policy	Moderate: Greater collaboration, shared data through common formats, and more advanced BIM software.
Qatar Rail	Qatar		
Etihad Rail	United Arab Emirates		
MTR Northern Link	Hong Kong	HKIBIM, Advanced BIM adoption	
Rail Baltica	Baltic States (EU)	Varies by country, moving towards ISO 19650	
Stuttgart-Ulm	Germany	ISO 19650, Moderate BIM adoption	
City Rail Link	New Zealand	NZ BIM Handbook, Moderate BIM adoption	
Melbourne Airport Rail	Australia	NATSPEC BIM Guide, Moderate to Advanced BIM adoption	
Suburban Rail Loop			
Sydney Metro			
Nagpur Metro Rail Project	India	BS 1192:2007+A2:2016, Emerging BIM adoption	
Metro Istanbul	Turkey	Emerging BIM adoption, no standardized framework	Developing: Isolated or early-stage BIM usage, limited collaboration, basic BIM tools.

We'll analyze the experiences of the UK and India in delivering mega rail projects using BIM, including implementation challenges and benefits. Certain principles in delivering mega projects have broad applicability, as shown by global mega rail ventures that use BIM.

5.1.1. Mega Rail Projects Governance and Delivery in the United Kingdom (UK)

Rail project delivery and governance in the UK are interpreted as complex and multi-faceted systems/structures involving multiple government agencies and stakeholders. This system/structure is designed to ensure efficient and effective planning, execution, and oversight of rail infrastructure development, maintenance, and operations [150].

Within this system/structure, the Department for Transport (DfT) [151] holds the primary responsibility for the country's transport policies, including the oversight of the railway network. It sets the overall strategic direction for the development and maintenance of the rail infrastructure. The DfT is responsible for setting policy objectives, determining funding allocations, and establishing regulatory frameworks for the operation of the railways.

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However, the actual delivery of railway projects often involves collaboration between multiple agencies. Network Rail [152], for example, is responsible for the maintenance, renewal, and development of the rail infrastructure. It manages the tracks, signals, and stations, and oversees major enhancement projects. Network Rail works closely with the DfT to ensure that the railway network meets the required safety standards and performance targets set by the government.

Moreover, the Office of Rail and Road (ORR) [153] serves as the independent regulator for the rail industry in the UK. It monitors the performance and safety of the rail network, ensures that operators adhere to established standards, and promotes competition and efficiency within the industry. The ORR also plays a crucial role in overseeing the implementation of government policies and regulations related to the rail sector.

In addition to these key agencies, local government bodies, such as Transport for London (TfL) [154] and Transport for the North [155], have jurisdiction over specific regional rail services and infrastructure projects. They work in partnership with the central government and other relevant agencies to address the specific transport needs of their respective areas.

The UK government has been at the forefront of integrating cutting-edge technologies, such as digital engineering and BIM, into the governance and delivery of mega rail projects [156]. These technologies play a pivotal role in transforming the planning, design, construction, and management of infrastructure, enabling government agencies to streamline processes, improve decision-making, and ensure efficient cost management and control throughout the lifecycle of mega rail projects [157]. The UK government's decision to make BIM a mandatory requirement for public sector projects has catalyzed a paradigm shift in the way infrastructure development is planned, executed, and maintained, resulting in a remarkable surge in the awareness and adoption of BIM within the construction industry over the past decade from 3% in 2011 to 73% in 2020 [158].

The governance of mega rail projects within the UK is inevitably influenced by the prevailing political context. The UK's political environment is characterized by a parliamentary democracy, where the government's policies, decisions, and actions significantly impact the delivery of various projects[159]. Political shifts, changes in leadership, policy reforms, and governmental priorities can all have profound implications for project governance as well [160]. Although, the United Kingdom is widely recognized for its relatively transparent government system, it is not immune to the risks of corruption [161]. The complex nature of mega rail projects often makes them susceptible to political maneuvering, with stakeholders frequently seeking to align project outcomes with their political agendas, regional interests, or electoral considerations. To mitigate this issue and enhance transparency, the government relies on governance frameworks supported by various mechanisms, including the Freedom of Information Act, public consultations providing independent expertise, and parliamentary scrutiny, which aim to ensure that decision-making processes are accessible and accountable to the public.

The UK government has recently launched a roadmap as an umbrella for the governance of infrastructure projects [162]. Beneath this general framework, the rail project governance formerly adhered to the Guide to Railway Investment Projects (GRIP), subsequently replaced by the Project Acceleration in a Controlled Environment (PACE) [163] which was developed as part of the Programme and Portfolio Management (P3M) framework policy, **Figure 4** shows the mega rail projects governance system in the UK.

The cost estimation and control for mega rail projects is guided by the Cost Estimating Guidance from the Infrastructure and Project Authority [164]. Moreover, the adoption of ISO 19650 Building Information Modelling (BIM), which succeeded BS 1192, serves as the principal reference for BIM integration and information flow within the rail sector [165], collectively forming the foundational framework for 5D-BIM implementation throughout the lifecycle of mega rail projects.

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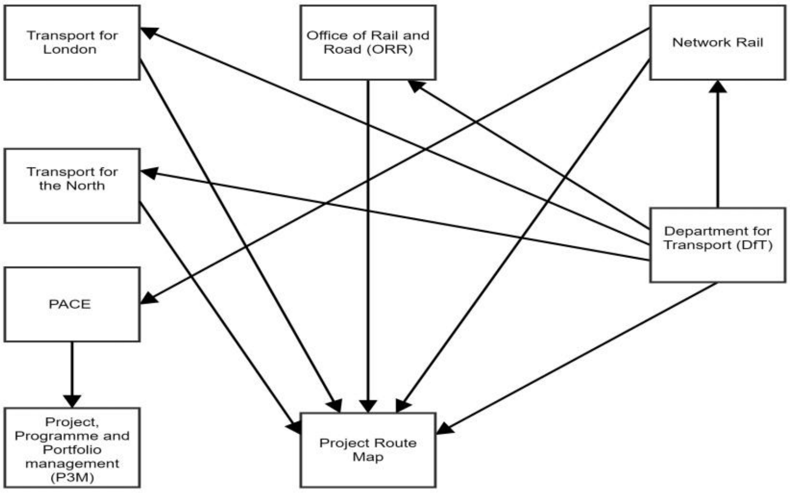

Figure 4. Maga rail governance system/structure in the UK.

Crossrail [166] , as one of the flagship mega rail projects, has significantly reaped the benefits of BIM implementation, serving as a trailblazer and paving the way for subsequent rail projects, like High Speed Two (HS2) [167].

The Crossrail is considered one of the significant mega rail projects in the UK and Europe. Initially budgeted at £14.8 billion in 2019, the project's total cost surged to £18.8 billion by 2022 [147, 168]. The project exhibited a high degree of complexity and a large number of stakeholders. To address this complexity and mitigate miscommunication risks, Crossrail employed BIM collaborative capabilities through appropriate contractual and governance mechanisms [166].

The system used comprised a Common Data Environment (CDE), a 3D model and a set of different software and tools such as Oracle Primavera (P6) [169] for schedule management. The system was also utilized to generate design drawings in the Industry Foundation Class format (IFC) for fabrication and manufacturing different components of the rail track [166].

The Crossrail strategy was centered on the following principles: Firstly, BIM is seen as more than just technology; it is primarily a framework of processes, standards, and methodologies to ensure the timely and cost-effective delivery of the project. Secondly, Crossrail involves the development of both a virtual and physical project, with the virtual component encompassing a 3D graphical model alongside informational models describing the physical environment. Thirdly, they emphasize the need for the 3D model to be intelligent while maintaining a lightweight profile by establishing connections to relevant databases. The emphasis is on creating an intelligent, yet lightweight 3D model that connects to relevant databases. Fourthly, effective information management is identified as the core of BIM; the data should be created and stored once, then reused throughout the project's lifecycle. Lastly, BIM can be used to enhance the management and delivery of different civil infrastructure elements like tunnels and portals in a similar manner to vertical projects [166].

Below, in **Table 6** are the different elements of the BIM adoption framework employed within the Crossrail project delivery system, along with the corresponding UK-wide standards that have evolved since their initial implementation in Crossrail.

Table 6. BIM adoption framework elements in Crossrail.

Dimension	CDE	Governance	5D-BIM software & Tools	BIM LOD	Cost management & Control standards	BIM Polices & standards	Digital Platforms
UK wide standard	ISO 19650 Building Information	PACE (Project Acceleration in a Controlled Environment) –	-	ISO 19650 Building Information Modelling BIM [165].	Cost Estimating Guidance – Infrastructure and Project Authority[164].	ISO 19650 Building Information Modelling (BIM) -	-

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	Modelling BIM [165].	replacement of GRIP)[163].				Replaced BS 1192[165].	
Crossrail	ProjectWise – based on Based on BS 1192[170]	Governance for Railway Investment Projects (GRIP)	Contruent (PRISM) [123]	AEC (UK) BIM Protocol[171]	Cost Estimating Guidance – Infrastructure and Project Authority[164].	BS 1192[170]	SAP – Axiom-SharePoint

Aside from the improved estimation, cost management, and control, the implementation of 5D-BIM in the Crossrail project had many benefits and challenges [172], including substantial direct saving of £70 million in expenses related to additional software and supporting staff, as well as an £8 million savings in risk contingency at Farringdon station.

5.1.2. Mega Rail Projects Governance and Delivery in India

The Indian railway network is one of the largest in the world [173]. In the Indian context, the delivery and management of mega rail projects involves a complex interplay of administrative, regulatory, and policy frameworks [174]. At the centre is the Ministry of Railways (MoR), serving as primary governing body responsible for the development and operation of the nation's railway network. The MoR manages various zones and divisions, each responsible for the administration and management of a specific geographic area [175].

Within MoR, the Railway Board takes on a pivotal role, responsible for the orchestration of policies, implementation strategies, and the overall management of the entire Indian Railways system. This complex organizational web extends further to include Railway Zones, dividing the country into distinct operational domains and divisions. Each of these zones shoulders the responsibility of managing and operating railway services within their designated geographical areas [174].

Additionally, the Indian government has increasingly adopted the use of Special Purpose Vehicles for the execution of specific railway projects. These SPVs are created with the involvement of both central and state governments, as well as private entities, to ensure efficient project delivery and management [176].

Beyond the Ministry of Railways and its subsidiaries, other government agencies play integral roles [177]. The Ministry of Finance emerges as a crucial player, providing vital financial support and allocating budgets for various railway projects. Simultaneously, the Ministry of Urban Development collaborates with the Ministry of Railways, with a particular focus on integrating railway projects into urban development plans, especially concerning metro rail systems and urban transit. Meanwhile, state governments are active participants in the governance of railway projects, particularly in areas such as land acquisition, the facilitation of necessary clearances, and coordination with the central government to ensure the successful implementation of railway projects within their respective states. **Figure 5** shows the rail project governance in India.

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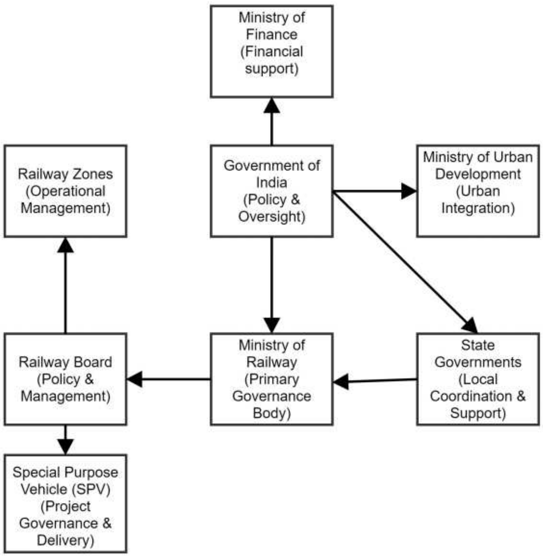


Figure 5. Rail Project Governance in India.

In 2012, the Indian government expanded the eligibility criteria for the metro rail system to include cities with populations exceeding 2 million. This policy change paved the way for Nagpur City to initiate its metro rail project [148], which was one of the first mega rail projects to adopt 5D-BIM in India.

The government founded Maha-metro (Maharashtra Metro Rail Corporation Limited) as a governing body responsible for the management and delivery of the project. The initial cost estimate for the first phase of the project was $1.1 billion, which was later revised to $1.2 billion in 2022. To enhance project management and ensure efficient project delivery, Maha-metro created a Digital Project Strategy Management platform tailored for the Owner Support Office (OSO). This platform incorporates the Enterprise Resource Planning system (ERP), BIM solution, and cost data, forming a cohesive 5D-BIM ecosystem to streamline project cost management and control [148].

The digital platform incorporates three key systems: Oracle Primavera (P6) [169], SAP[178], and Bentley software[179]. The results of this integrated system were presented through SAP-BI dashboards. The RIBiTWO software [180] facilitated the seamless integration of data from various sources, including the 3D model, scheduling information from P6, and cost data from SAP. This integration enabled enhanced schedule management (4D) and more effective cost management, control, and analysis (5D) [148].

The Nagpur Metro project has greatly benefited from BIM implementation throughout its lifecycle. During the design phase, BIM has ensured clear scope identification, maintained design consistency, facilitated clash detection and resolution, and automated quality assurance checks. In the site planning phase, BIM enhanced site visualization, streamlined logistic management, and optimized schedule management, ultimately reducing the overall project timeline. Throughout the construction stage, BIM played a critical role in project control, status reporting, and the tracking of contract variations and claims. Finally, BIM enabled a seamless project handover, with project data transitioning to the integrated asset management system, ensuring ongoing operational efficiency[148].

The implementation of BIM was fraught with various challenges. Initially, 5D-BIM implementation could not commence at the project's outset because the design consultants had submitted design documents in accordance with the contract requirements and standards. They subsequently requested a variation to update specifications and drawings. Furthermore, the initial contract stipulated the submission of 2D drawings, which necessitated a substantial amount of effort and time for conversion into a 3D environment. The absence of data standards and training requirements for all staff posed a significant challenge. Additionally, altering the working methods for contractors represented a fundamental change, particularly considering the varying levels of digital engineering maturity among different contractors [148].

Below, in **Table 7** are the different elements of the BIM adoption framework employed within the Nagpur Metro Rail Project delivery system, along with the corresponding India-wide standards that have evolved since their initial implementation in the project.

Table 7. BIM adoption framework elements in Nagpur Metro Rail Project.

Dimension	CDE	Governance	5D-BIM software & Tools	BIM LOD	Cost management & Control standards	BIM Polices & standards	Digital Platforms
India wide standard	ISO 19650 BIM [165].	Hybrid model State Administrative + SPV	-	ISO 19650 BIM [165].	Indian Railways – Estimation guideline[181]	ISO 19650 BIM [165].	-
Nagpur Metro Rail Project	ProjectWise[182] + Asset Wise CDE (eB)[183]	Hybrid model State Administrative + SPV	RIBiTWO [180] + Primavera P6	BS PAS 1199[184]	Indian Railways – Estimation guideline[181]	BS 1192:2007+A 2:2016[185]	SAP - ERP

5.1.3. Lessons learned from case studies in UK and India

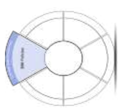
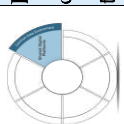
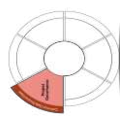
Introducing 5D-BIM in both the Crossrail and Nagpur Metro projects presented unique challenges, but both projects have substantially benefited from its implementation. Employing 5D-BIM proved to be a thoughtful/successful governance strategy [148, 166].

The key success implementation factors include adhering to the latest BIM policies, standards and mandates [148], developing a robust Common Data Environment (CDE) integrated with right BIM software and tools [148, 166] development of discipline-specific Level of Development (LOD) was important ensure that client requirements are fully understood and to ensure common understanding between different stakeholders[166]. The team and management's commitment to continuous improvement played a crucial role in achieving success and enhancing the implementation experience.

6. The 5D-BIM conceptual framework

The distinct elements/categories discussed in the preceding sections sets the stage for a deeper understanding of the anatomy, construction logic, and dynamics of a conceptual framework. **Table 8** below present the 5D-BIM conceptual framework and provide a brief overview of its various elements, their definitions, associated benefits, and relevant references.

Table 8. 5D-BIM conceptual framework.

	Framework	Definition	Key Benefits	Reference
 **5D-BIM Framework** The 5D-BIM framework provides a mechanism for project management/governance/ delivery. The continuous improvement lies in the heart of the framework to ensure the integration and efficiency of processes underlying the		BIM policy is a set of interconnected decisions or plans of action taken by the government (political group). BIM policy	BIM policy documents provide clear guidelines that assist organisations in achieving consistent input/output and	[13] [28] [186]
		Digital platforms are extensible technical codebase artefacts. Platform ecosystems typically include third-party modules that supplement this codebase [130].	Multiple users can use digital platforms to create, access, share, or exchange information, goods, or services [129, 130]. Digital platforms enable interoperability	[187] [188] [133]
		LOD is the degree to which the element' s geometry and related	BIM LOD allows models to become more accurate. It enables teams, including	[189][190]
		BIM software and tools are computer programmes that are used to create and manage BIM digital models, which include procedures, rules, and supporting	Using the right BIM software is a critical success factor for BIM implementation because it can significantly minimize the costs, time and risks	[191][192]
		Cost estimation classification is a categorization of cost estimates based on their degree of accuracy, reliability, and completeness. The most common	Cost estimation classification align the estimating process with project scope development and financial decision-making processes [192].	[193][194] [195]
		Project governance is defined as a collection of management systems, rules, protocols, relationships, and structures that provide the framework within which decisions for project development and	Project governance enables the organisation in aligning project objectives with its organisational strategy, achieving project goals, and monitoring performance. It also describes the methods	[34][32][196][37][197]
		Continuous improvement is a culture of ongoing improvement that aims to	Continuous improvement ensures the efficiency of project processes, it help	[198][199] [200][201]

The following subsections succinctly outline the 5D-BIM framework elements and its dynamics.

6.1. Project Governance:

In the 5D-BIM framework, project governance serves as the backbone, providing structure and direction for implementing 5D-BIM to achieve project goals while also upholding relevant policies, standards, and regulations. In turn, 5D-BIM supports project governance by acting as a centralised, coordinated, and integrated information source, facilitating informed financial decisions, progress tracking, and risk management throughout the project's lifecycle.

6.2. BIM policies and standards

While the role of process and technology is obvious, BIM polices, and standards plays crucial role in the successful BIM implementation. As the main client of mega projects, government's commitment to adopting BIM is pivotal for the construction industry, primarily because this industry is highly fragmented and subject to stringent regulations [13].

Policies and standards offer a roadmap for consistency, ensuring that BIM practices remain uniform within an organisation or across various projects. BIM policies and standards bolster quality assurance by outlining best practices, guaranteeing that BIM models and data are not only accurate but also reliable and perfectly suited for their intended purposes. Furthermore, they help in risk mitigation by identifying potential issues and guiding organisations in avoiding costly errors, delays, or disputes.

6.3. Digital platforms

Digital platforms exhibit a multitude of typologies, with no one-size-fits-all solution. Their suitability hinges upon the distinct characteristics of the project. Notable digital platforms in the field include Autodesk Cloud for design management[218], Oracle Primavera Cloud for project management[219], Bluebeam for document management[220], ARES PRISM (Contruent) for project control[221], and Bentley OpenRail for railways design and construction[222].

6.4. BIM LOD

BIM LOD fosters collaboration and coordination among all project stakeholders by establishing a shared understanding of what is required in the BIM models[203, 204].

BIM LOD signifies the progression of an element's geometry and its associated information during the BIM model development journey. The American Institute of Architects (AIA) has established a framework comprising five distinct levels of development: LOD 100, LOD 200, LOD 300, LOD 400, and LOD 500 [223].

LOD 100 (Generic) is limited to a generic representation of the project, it may include general railway alignment, cost per linear meter etc. LOD 200 (Approximate) is more precise than LOD100, but still uses generic elements to represent the geometry of the project. LOD300 (Specific) represent project geometry with additional information attached to it. LOD 400 (Installation) contain further details beyond the typical use of architect or engineer. LOD 500 represent the “As Built” status for the project[224]. **Figure 6** provides an illustrative example showcasing the five LOD in railway element design[225].

It is important to distinguish between level of development and level of detail, while level of details is more concerned with quantity, the level of development represent the degree to which BIM model was thought through.

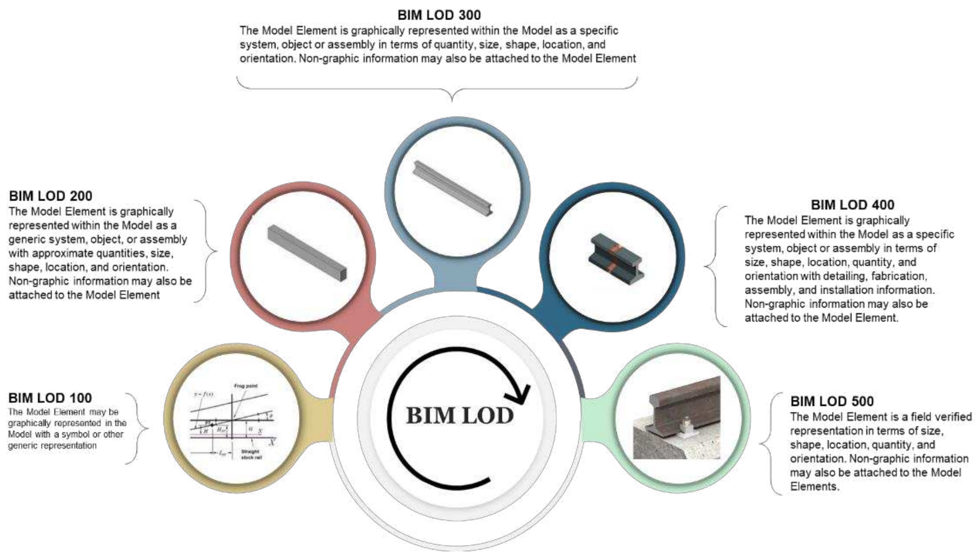


Figure 6. BIM LOD for Railway element.

6.5. Cost estimation classification

Cost estimation classification aligns the estimating process with the development of project scope and financial decision-making processes. It is used to categorize cost estimates based on the maturity level of the project. One of the key functions of project governance is to approve project budgets through different milestones (or gates) in the project lifecycle. The level of maturity of cost estimation is instrumental in obtaining budget approval. Usually, the gate reviews involve assessing the project's progress, risks, and alignment with strategic objectives. Cost estimation classification provides the metrics to ensure that sound cost data is used to support the project governance and decision-making process at each stage or gate.

6.6. BIM tools and software

Using the right BIM tools and software is essential for maximizing the advantages of implementation while preventing conflicts with other organisation systems.

The selected BIM software should align with the project's specific goals and objectives. In addition, different aspects have to be considered in the process, such as stakeholder engagement, involving the input of all relevant stakeholders, such as architects, engineers, contractors, and clients, ensuring that their needs and requirements are met. Furthermore, the chosen BIM software should enable comprehensive performance monitoring and reporting.

6.7. Common Data Environment (CDE)

Common Data Environment (CDE) plays a critical role in managing mega projects. CDE serves as a centralised platform for storing, managing, and sharing all project-related data, including designs, plans, specifications, schedules, and reports [86]. This ensures that all decision-makers and stakeholders have access to the most up-to-date and accurate information, thereby reducing the likelihood of errors or misinterpretations.

Access to a comprehensive and up-to-date data repository through a CDE enables decision-makers to make informed decisions quickly and accurately [226]. Real-time access to critical project data, such as cost estimates, progress reports, and risk assessments, helps in identifying potential issues early and implementing timely solutions and enhances the overall decision-making process and governance of mega rail projects [90].

While basic tools/platforms are widely used for team collaboration in projects such as SharePoint, Google Drive, or OneDrive, BIM implementation often requires more sophisticated, advanced platforms such as ProjectWise, Procore, or Aconex (Oracle) [227].The selection process

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should consider four key aspects: document management, BIM integration, security, and lifecycle functionality [228].

Finally, continuous improvement in mega rail projects is significantly important, as it helps to optimise processes and increase efficiency, resulting in higher quality outcomes, greater stakeholders' satisfaction, improved project performance, and fostering of an environment of innovation and learning [229]. Continuous improvement ensures ongoing adaptation and enhancement to meet evolving requirements and challenges, it plays a pivotal role in identifying bottlenecks, inefficiencies, and areas for enhancement within the interconnected components. It facilitates the streamlining of workflows, promotes synergy between various elements, and enables the integration of feedback and lessons learned into the framework's structure [217].

6.8. Global Adaptability of the 5D-BIM conceptual framework

Despite the variations in project governance systems and BIM standards and policies across different countries, the 5D-BIM implementation framework remains adaptable for deployment worldwide. The framework's versatility arises from its robust conceptual basis, allowing it to be tailored to the distinct requirements of diverse national contexts. As illustrated in **Table 9**, the framework seamlessly integrates with and conforms to the unique structures of transport and rail project governance and delivery ecosystems in various countries. This compatibility signifies the framework's potential to foster a standardized approach to 5D-BIM implementation while accommodating the specific intricacies of each nation's regulatory and operational landscapes.

Table 9. Alignment of 5D-BIM Implementation Framework with Global Transport and Rail Project Governance and Delivery Ecosystems.

Key Elements	**UK**	**USA**	**EU**	**Victoria (Australia)**
Project Governance	PACE (Project Acceleration in a Controlled Environment) – replacement of GRIP)[163].	Stage Gate process (differ by state) – California as an example [230]	Europe's Rail Joint Undertaking Governance and Process Handbook[231]	Gateway Review process[232]
Cost Estimation Classification	Cost Estimating Guidance – Infrastructure and Project Authority[164].	Cost Estimate Classification System - AACE[233]	ICMS: International Cost Management Standards [234]	Cost Estimate Classification System - AACE[233]
BIM policies and standards	ISO 19650 Building Information Modelling (BIM) -Replaced BS 1192[165].	National BIM Standard-United States® (NBIMS-US™)[235]	ISO 19650 Building Information Modelling (BIM) [165].	Victorian Digital Asset Strategy (VDAS) [236]

7. A Victorian perspective

In spite of sustained investments by the Australian government in infrastructure development, with a specific focus on rail networks, the present state of infrastructure development in Australia, particularly in the context of rail networks, confronts noteworthy hurdles, particularly concerning accurate cost estimation and robust financial decision-making processes. To surmount these

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obstacles. The implementation of the 5D-BIM framework, along with collaborative procurement methods and sound cost estimation methods, could help address these challenges [237]. The following section presents an analysis of mega rail project delivery in Victoria.

7.1.1.1. Rail Projects governance in Victoria

In Victoria, several entities are entrusted with the delivery and governance of infrastructure rail projects. The pivotal agency in charge of planning, developing, and executing rail infrastructure projects across the state is the Victorian Department of Transport (DoT). Alongside DoT, there are additional organisations engaged in the oversight of rail infrastructure projects. These include Public Transport Victoria (PTV), Rail Projects Victoria (RPV), the Transport Infrastructure Council (TIC), and Infrastructure Victoria [238].

There are several different processes and mechanisms involved in the governance of Victoria's rail infrastructure projects, including public consultation, environmental assessments, project planning and design, procurement, project management, and operations and maintenance. The precise governance structure for individual projects is contingent upon multiple elements, such as scale, complexity, geographical location, and the spectrum of stakeholders engaged.

In late 2010, the Victorian government introduced the High Value High Risk (HVHR) framework as a strategy to mitigate cost overruns in mega projects. This framework applies to all public sector investments in infrastructure and information and communications technology. The framework uses different thresholds and assessment forms to classify projects [239].

While all projects covered by the framework undergo the project assurance process, HVHR are subject to more rigorous, scrutiny mandatory approval processes through the gate review process [239].

The gate review process involves six pivotal decision points (gates) throughout a project's lifecycle: Gate 1 for concept and feasibility; Gate 2 for the business case; Gate 3 for market readiness; Gate 4 for tender decision; Gate 5 for service readiness; and, ultimately, Gate 6 for benefits analysis.

Although the adoption of the HVHR framework has generally enhanced project governance in Victoria, subsequent audits have revealed certain gaps in its implementation. These gaps potentially expose the government to the risk of allocating substantial funds to projects without a clear understanding of the validity or attainability of projected benefits [240].

7.1.1.2. Victorian Digital Asset Strategy (VDAS)

In February 2019 the Victorian Government jointly with Office of Projects Victoria, announced the release of Victorian Digital Asset Strategy (VDAS). aims to ensure that all government projects, including rail projects, adopt and implement digital asset management principles and technologies to elevate asset performance, streamline maintenance processes, and enhance the overall efficiency of project delivery[236, 241]

VDAS is structured into three parts: strategic-level (Part A), organisational-level (Part B), and project-level (Part C). Together, these parts offer comprehensive guidance on planning, implementing, managing, and maintaining an efficient digital asset strategy across the asset lifecycle. The guidelines outline three levels of capabilities and 14 requirements throughout the asset lifecycle to ensure successful implementation. VDAS was developed in collaboration with the industry and is aligned with the international standard ISO 19650. While VDAS isn't mandatory, there is an increasing trend of its adoption in rail projects[242].

7.1.1.3. Cost estimation classification

The gate review process serves as a framework for evaluating the progress and quality of a project at different stages, including the accuracy and reliability of the cost estimates. By classifying cost estimation at each gate based on the available project information and level of detail, stakeholders can make informed decisions regarding project continuation, resource allocation, and

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risk management. It is crucial to conduct regular reviews and validations of cost estimates at each gate to ensure that the project stays on track and remains within the allocated budget.

The AACE International Cost Estimate Classification System serves as the basis for various estimation tools utilized by the Victorian government[243]. The system consists of 5 classes, which are as follows: Class 5 - Rough Order of Magnitude Estimate (ROM): prepared very early in the project life cycle; Class 4 - Preliminary Estimate: prepared during the project planning phase when the project scope is still being defined and preliminary data is available; Class 3 - Detailed Estimate: prepared during the early stages of project development when the project scope is defined to a certain extent; Class 2 - Study Estimate: prepared during the preliminary design phase when the project scope is partially defined and conceptual or preliminary engineering designs are available; Class 1 - Control Estimate: prepared for the control and monitoring of project costs during project execution.

Classes 5 and 4 of cost estimation could be applied during gate 1, the concept and feasibility stage. At this stage, the project idea is conceptualized and evaluated, and cost estimation is generally high-level and exploratory, focusing on providing a ROM estimate. This initial estimate helps in determining the feasibility and potential benefits of the project. Cost estimation classes 3 and 2 are more aligned with business case development, specifically at gate 2. The Class 1 estimate could be used for tender documents and when the project is market-ready in stage 3.

It's noteworthy that mega rail projects are typically organized as a program of several interconnected projects or packages, each with its own unique characteristics and delivery methods. Due to the diversity and complexity of these packages, it is common for the cost estimation classification to be applied differently to each one.

7.1.1.4. 5D-BIM software & tools, and Common Data Environment (CDE)

Key 5D-BIM software and solutions in Victoria include RIB-Cost-X [117], Bexel Manager[120] , ARES PRISM (now known as Contruent) [123], Cubicost[124], and PriMus[126]. Regarding Common Data Environment (CDE), government agencies in Victoria opt for an array of basic collaboration tools/platforms such as SharePoint, Google Drive, and OneDrive, as well as robust solutions like ProjectWise, Procore, and Aconex (Oracle) for projects employing BIM.

The selection of the 5D-BIM software and CDE platform is tailored to the unique requirements and complexity of each project.

8. Discussion

8.1. 5D-BIM framework development

The literature suggests that the challenges and key success factors associated with 5D-BIM implementation can be systematically categorized into five distinct domains: Project Governance, Policies and Standards, Communication Processes and Workflow, Tools and Software, and Integration and Compatibility, as outlined in **Table 8**. Moreover, **Figure 2**, the concept map, demonstrates the interconnection between 5D-BIM implementation and five main areas: Tools and Software, Project Processes, Digital Platforms, Governance, and Reference Class Forecasting. Furthermore, the analysis of policies and case studies discussed provided valuable insights and empirical evidence from the industry, highlighting the essential elements for successful 5D-BIM implementation, including sound project governance, the use of appropriate BIM tools and software, adherence to the latest BIM policies and standards, using a reliable Common Data Environment (CDE) for team collaboration, and information exchange. In light of these findings and the significant impact of governance on various complexities within mega rail projects, we have developed a conceptual 5D-BIM framework containing the following elements: project governance, BIM policies and standards, digital platforms, BIM LOD, cost estimation classification, alongside a Common Data Environment (CDE) as shown in **Figure 7** below.

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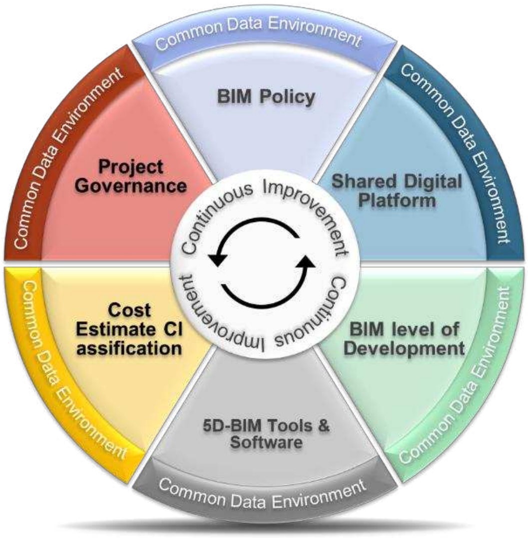

Figure 7. 5D-BIM Framework.

8.2. Implementing 5D-BIM Across Various Policy and Governance frameworks/Structures

The governance of mega rail projects in India and the UK reflects the differences in their political systems, policies, and regulatory environments, which subsequently impact the transparency and management of these projects. Effective project governance is crucial in ensuring transparency, mitigating risks, and preventing corruption. While both countries have made efforts to promote transparency in their respective rail projects, the varying regulatory frameworks, public participation, digital infrastructure, and anti-corruption measures contribute to different levels of transparency.

In the UK, the established regulatory framework and emphasis on public engagement contribute to a relatively higher degree of transparency in mega rail projects. The integration of advanced technologies, such as 5D-BIM, has significantly enhanced project planning, execution, and maintenance. The use of such technologies has streamlined processes, improved decision-making, and enabled efficient cost management throughout the lifecycle of these projects. Furthermore, the UK government has established mechanisms like the Freedom of Information Act, public consultations, and parliamentary scrutiny to ensure accountability and transparency, minimising the risks of corruption or inefficiencies.

Conversely, in India, the governance of mega rail projects is influenced by a different political and regulatory context. The complexities of the Indian bureaucratic system, along with varying levels of corruption, can pose challenges to maintaining transparency in project governance. However, the Indian government has been increasingly adopting digital infrastructure and technologies such as BIM to improve project management. While these efforts are underway, there is still a need for more robust institutional mechanisms and anti-corruption measures to enhance transparency and accountability in the governance of mega rail projects.

Despite the differences in policies, political systems, and environments between India and the UK, the implementation of 5D-BIM has demonstrated similar requirements and success factors in both countries.

The 5D-BIM framework builds on the key success implementation factors from the two projects, including compliance with the latest BIM policies, standards and mandates [148], developing a robust Common Data Environment (CDE) that is seamlessly integrated with appropriate BIM software and tools [148, 166], and development of discipline-specific Level of Development (LOD) [166].

In addition, the elements of the framework respond to the 5D-BIM implementation challenges: the digital Platforms facilitate efficient data sharing and management, addressing data synchronization issues similar to those encountered in the Nagpur project. The Cost Estimation Classification directly addresses cost overrun concerns by providing a more accurate and detailed estimation process, and the Continuous Improvement: emphasises the adaptability of the framework to ensure that it remains relevant as project demands and technologies evolve, addressing the need for continuous adaptation seen in both projects.

The use of 5D-BIM has proven instrumental in improving project efficiency, data management, and decision-making processes, leading to enhanced transparency and accountability. The successful integration of 5D-BIM in both countries serves as a testament to the universal benefits of adopting advanced technologies in project governance, irrespective of the political environment. By studying and learning from the experiences of the UK and India, other countries can draw valuable insights and best practices to enhance their own project governance frameworks, promote transparency, and mitigate the risks of corruption in mega rail projects.

8.3. Application to the Victorian Mega Rail Program Context

Victoria is undertaking an ambitious rail programme with a visionary outlook. The program's estimated budget is around $150 billion. Given the sheer scale and diversity of this large pipeline of infrastructure upgrades, there is a pressing need for enhanced governance efforts. These efforts are essential to foster a more structured project management and delivery environment, ensuring that each project is effectively managed and coordinated within this expansive program. Enhanced governance necessitates a policy change/transformation. Implementing governance frameworks such as the 5D-BIM framework and its integral elements could be the best response to this policy change and a starting point for further learning.

Outlined below are the various framework elements employed in Victoria. In project governance, the predominant tool is the gate review process. VDAS serves as the state's flagship policy for digital engineering and BIM implementation. Moreover, the state employs the AACE estimation classification for cost development. The following discussion provides a concise overview of these elements.

The governance of mega rail projects in Victoria aligns more closely with the UK's approach rather than India's, primarily in terms of its structured approach, regulatory mechanisms, and emphasis on transparent decision-making processes. Similar to the UK's governance framework, Victoria's infrastructure rail projects are overseen by various entities such as the Victorian Department of Transport (DoT), Public Transport Victoria (PTV), and Rail Projects Victoria (RPV). These agencies collaborate to ensure effective planning, execution, and oversight of rail infrastructure development, mirroring the multi-faceted governance structures seen in the UK's Department for Transport (DfT), Network Rail, and the Office of Rail and Road (ORR).

Furthermore, the implementation of the High Value High Risk (HVHR) framework and gate review process in Victoria, aimed at addressing potential cost overruns in mega projects, reflects the UK's emphasis on robust governance frameworks, such as the Guide to Railway Investment Projects (GRIP) and Project Acceleration in a Controlled Environment (PACE). Both governance models emphasize the importance of stringent gate review processes and clear decision points throughout the project lifecycle to ensure effective project management and minimize financial risks.

The Crossrail project in the UK stands as a prime example of successful project delivery and governance, showcasing the importance of effective coordination between various government entities, stakeholders, and industry partners. Similarly, the Nagpur Metro Rail Project in India highlights the significance of leveraging advanced technologies and strategic partnerships to ensure efficient project implementation and sustainable urban development. **Figure 8** provide a Victorian perspective of the 5D-BIM framework.

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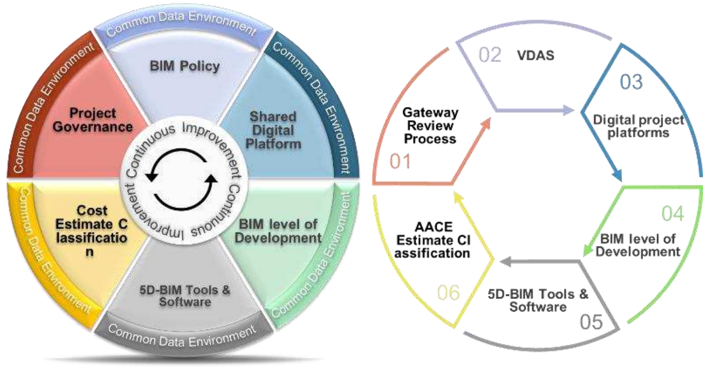

Figure 8. A Victorian perspective of the 5D-BIM framework.

The following subsections outlines key insights gained regarding various aspects of the 5D-BIM Framework:

8.3.1. Common Data Environment (CDE)

CDE is a critical component of the conceptual 5D-BIM framework. The importance of CDE as a centralised data repository lies in ensuring accurate, consistent, and real-time access to project information, thus enhancing transparency, efficiency, and cost management & control[89].

This approach is supported by literature and proven in practice through successful implementation in mega rail projects like Crossrail and Nagpur Metro Rail. The success of Crossrail, with its hybrid cloud-computing platform combining Microsoft Azure and Bentley's AssetWise software and Nagpur Metro's utilisation of iTWO and Bentley Systems' Open Rail CDE, underscore the practical advantages of a CDE. These include enhanced collaboration, process optimisation, and improved project [148, 166]. For Victoria, adopting a CDE as an integral component of the 5D-BIM framework aligns with literature and industry best practices, promising improved coordination, efficiency, and cost management in its mega rail projects.

8.3.2. Governance:

Incorporating governance into the 5D-BIM framework can facilitate better integration of technology and processes, ensuring that data-driven decisions are made efficiently and effectively.

Crossrail, noted for its vast scale and complex engineering requirements, encountered significant challenges in managing diverse stakeholders and aligning multiple project phases. Implemented a governance framework that prioritised clear communication, accountability, and regular monitoring. This approach was key in ensuring effective decision-making and risk management, keeping the project aligned with its goals. The Nagpur Metro, dealing with a wide network of contractors and consultants, adopted transparent operational protocols supported by BIM, and efficient communication strategies, emphasising stakeholder engagement.

For Victoria, incorporating project governance as part of the 5D-BIM conceptual framework can provide a guide for developing governance models that emphasise accountability and stakeholder engagement. This would involve restructuring the current gate review process and setting up clear governance roles, developing transparent communication channels, and implementing robust monitoring and reporting systems.

8.3.3. BIM policies and standards

BIM policies and standards are crucial for maintaining consistency and quality in mega rail projects, as evidenced by the Crossrail and Nagpur Metro projects. These standards provide a roadmap for uniform BIM practices, ensuring that models and data are accurate, reliable, and fit for purpose. For instance, Crossrail's adherence to the UK's BIM Level 2 standards ensured collaborative work and data accuracy, crucial for efficiently managing complex infrastructure.

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Victoria can benefit significantly from implementing a BIM mandate for mega rail projects similar to the UK's BIM Level 2 standards. Such a mandate would encourage the adoption of advanced digital technologies across the sector, leading to increased efficiency, cost savings, and improved project outcomes. By mandating BIM, Victoria can ensure that all mega rail projects follow a consistent framework for data management and collaboration, leading to better coordinated and more efficient project delivery. Furthermore, a BIM mandate can drive innovation and upskill the workforce in the latest digital construction techniques, positioning Victoria as a leader in modern, efficient, and sustainable infrastructure development.

8.3.4. BIM level of development (LOD)

Having a defined LOD as part of the 5D-BIM framework ensures that everyone involved in the project has a shared understanding of the model's precision and content at different stages of the project.

In the Crossrail project, the adoption of specific LOD standards, aligned with the UK's BIM Level 2 requirements, facilitated effective communication and coordination among the diverse teams involved. This approach ensured that the models developed were suitably detailed for various project phases, enhancing overall efficiency and reducing the likelihood of misunderstandings or information gaps.

In practice, the LOD framework doesn't align strictly with design phases but rather describes completion and deliverables in LOD terms, accommodating the varying progression rates of different building systems.

8.3.5. 5D-BIM Tools and software

Both academic literature and industry experience emphasise the importance of selecting appropriate BIM software for successful project delivery, particularly in complex mega rail projects like Crossrail and Nagpur Metro. The notion of a 'one size fits all' software solution is impractical; instead, a combination of specialised software is often required to address various project needs effectively, where each software contributes its unique capabilities, enhancing the overall project management process.

For mega rail projects in Victoria, adopting a similar strategy of using a mix of BIM software, tailored to the project's specific requirements, can enhance efficiency, collaboration, and project success.

8.3.6. Cost estimation classification

Cost estimation classification provides a structured approach to estimating costs at various stages of the project, enabling accurate budgeting and cost management & control. Despite implementing 5D-BIM, both the Crossrail and Nagpur Metro projects encountered cost overruns. Better cost estimation techniques, such as benchmarking and cost estimation classification, could have provided a more accurate and dynamic financial overview, allowing for early detection of potential budget deviations and enabling timely corrective actions.

Incorporating cost estimation classifications in 5D-BIM can significantly benefit mega rail projects in Victoria. It will allow the project team to have a more granular and accurate understanding of the project costs at each stage, leading to better budget management and reduced risk of cost overruns.

9. Conclusion

This research has developed a conceptual 5D-BIM framework in response to governance challenges in mega rail projects applied in the context of the state of Victoria- Australia. The findings significantly support the development of more adapted 5D-BIM solutions for both academia and industry. It has synchronized project governance and appropriate 5D-BIM solutions to minimize cost overruns in mega rail projects.

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The framework is unique in focusing on mega rail projects, comprised from a comprehensive review and analyses of literature and policies and standards in various geographical areas, each with its unique policy and governance ecosystem. Therefore, it aligns with the state-of-the-art research development and 5D-BIM consideration of best practices.

As discussed in this study, governments must adapt to the increasing complexities and challenges of mega rail projects. Such adaptation necessitates redefining the current governance frameworks and systems. It is recommended that the Victorian government adopts a strategic approach to 5D-BIM implementation. This approach should focus on establishing robust governance frameworks, investing in essential digital infrastructure, and fostering a culture of transparency, collaboration, and innovation within the rail sector. The 5D-BIM framework has the potential to provide significant value in mitigating cost overruns in the Victorian government state-wide mega rail projects.

The 5D-BIM conceptual framework is introduced as a foundational template to be empirically tested in future research. Potential directions for further research involve assessing the framework's practicality on real-life mega rail projects to evaluate, validate, and rigorously scrutinize the elements and dynamics of the framework, with the aim of establishing its universal applicability in different governance ecosystems.

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Abbreviations

The below abbreviations are used in this paper:

BIM	Building Information Modelling
5D-BIM	Five-Dimensional Building Information Modelling
VDAS	Victorian Digital Asset Strategy
CDE	Common Data Environment
BIM LOD	BIM Level of Development
SLR	Systematic Literature Review
IT	Information Technology
QA	Quality Assurance
ISO	International Organisation for Standardization
IDD	Integrated Digital Delivery
CAD	Computer Aided Design
EVM	Earned Value Management
DfT	Department for Transport
ORR	Office of Rail and Road
TfL	Transport for London

GRIP	Guide to Railway Investment Projects
PACE	Project Acceleration in a Controlled Environment
P3M	Programme and Portfolio management
HS2	High Speed Two
IFC	the Industry Foundation Class format
Maha-metro	Maharashtra Metro Rail Corporation Limited
OSO	Owner Support Office
ERP	Enterprise Resource Planning system
DoT	Department of Transport
PTV	Public Transport Victoria
RPV	Rail Projects Victoria
TIC	Transport Infrastructure Council
HVHR	High Value High Risk
SRL	Suburban Rail Loop
MAR	Melbourne Airport Rail
NBIMS	National BIM Standard

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