BIM for Highway Infrastructure: A Systems Thinking Insight into the Impeding Factors

Abstract

Purpose – While Building Information Modeling (BIM) adoption has received considerable attention in buildings, its implementation in highway infrastructure projects remains limited. This study aims to identify and contextualize the critical factors impeding BIM adoption in highways and to examine their causal interrelationships.

Design/methodology/approach – A four-stage mixed-method research framework was employed. First, a systematic literature review identified twenty factors and quantified their relative importance using normalized literature scores. Second, a cross-country industry survey generated corresponding normalized empirical scores. Third, these datasets were integrated to rank and categorize the factors and to identify critical impediments using Pareto analysis. Finally, causal interrelationships among the critical factors were examined through causal loop diagram developed using systems thinking–based modelling.

Findings – Thirteen key impediments, classified into five categories (financial, technical, management, environmental, and legal) were found to impede BIM adoption in highway infrastructure projects. Nineteen causal interrelationships and seven feedback loops were identified. The findings provide quantitative evidence that BIM implementation in highways is hindered not by fundamentally new barriers, but by the intensification and interaction of well-documented challenges observed in building projects within the linear infrastructure context.

Originality/value – This study extends BIM adoption research by identifying impediments specific to highway infrastructure. By uncovering underlying causal interrelationships and feedback structures through systems thinking and causal loop modeling as a methodological novelty, it provides a system-level understanding of BIM adoption dynamics. It also offers strategic insights for policymakers and industry stakeholders to design targeted, system-aware interventions aimed at improving BIM adoption in highway infrastructure projects.

Keywords Building Information Modelling; Technology; Construction

Paper type Research Paper

1. Introduction

Building Information Modelling (BIM) has predominantly been used in the vertical Architecture, Engineering, and Construction (AEC) industry (Biancardo, Viscione, et al., 2020), where it has exhibited a wide array of benefits by virtue of visualization and coordination (3D), scheduling (4D), automated quantity takeoff (5D), life cycle performance analysis (6D), facility management (7D), and safety management (8D) (Charef, 2022; Rehman et al., 2025; Ullah et al., 2019). However, BIM is underutilized in horizontal infrastructure (Costin et al., 2018; Tang et al., 2020), and infrastructures projects often suffer from a lack of strategies for utilization of BIM. This underutilization deprives highway infrastructure projects of numerous potential benefits.

Although highways represent one of the largest and wide-spread components of transportation infrastructure and one of the most valuable assets for any country (Mushtaq et al., 2026), BIM adoption in highway projects remains limited due to various hinderances (Castañeda et al., 2024). Highways generally extend over kilometers and interact with numerous environmental interferences, making BIM adoption in highway projects particularly challenging (Nielsen et al., 2024; Vignali et al., 2021; Vitásek & Matějka, 2017).

While many studies have attempted to explore the factors affecting BIM adoption and implementation in buildings, highway infrastructure has received comparatively less attention, often neglecting causal interrelationships and complex system created by interconnections of factors. Therefore, it is crucial to bridge this gap and to analyze the factors impeding adoption and implementation of BIM in highway infrastructure projects and their interrelationships. A Systems Thinking approach to analyzing such factors can offer a deeper understanding of the complex interactions between these factors and help facilitate more effective solutions for improving BIM adoption in highway infrastructure.

The aim and originality of this study is to gain a holistic understanding of the factors impeding BIM adoption and implementation in highway infrastructure and deciphering the complex system created by their causal interrelationships. The study provides guidance for policymakers and industry stakeholders in formulating targeted, system-aware strategies to enhance BIM adoption in highway infrastructure projects. This can lead to development of better highway infrastructure which can ultimately result in better economy as well as improved quality-of-life of general public (Zhao et al., 2019).

The remainder of this paper is structured as follows. Section 2 reviews the relevant literature, followed by a detailed step-by-step explanation of the research methodology in Section 3. Section 4 then presents the results along with an in-depth discussion of the findings. The study's significance and implications are outlined in Section 5, while the conclusions and limitations are provided in Section 6.

2. Literature background

This section reviews previous studies in two subsections. The first subsection presents a broad overview of BIM adoption and utilization in highway projects. The second subsection reviews studies on impediments to BIM adoption in buildings, linear infrastructure, and general AEC or mixed contexts, highlighting their scope limitations and linking these limitations to the research gap addressed in this study. To provide a broader perspective, some earlier studies are also discussed to contextualize the evolution of BIM adoption research and to show how the examination of barriers has evolved in more recent work.

2.1 BIM adoption and utilization in highway projects

Previous BIM studies have primarily focused on buildings, while adoption and utilization of BIM in highway infrastructure remains relatively underexplored (Belcher & Abraham, 2023; Castañeda et al., 2024; Chong et al., 2016). Some studies related to BIM utilization in pre-construction, construction, and post-construction phases of highways are outlined in **Table 1.**

Table 1. Examples of BIM adoption and utilization in highway infrastructure. Source(s): Authors own work

The transportation sector is recognizing the importance of BIM in improving the project delivery besides enhancing competitive market advantage (Ammar et al., 2022; Barberi et al., 2022; Liu et al., 2024). As infrastructure assets are becoming bigger and more complex, there is an increased need for applying BIM (Kalajian et al., 2023; Park et al., 2014). Application of BIM in transportation infrastructure has been given a variety of names i.e. Infrastructure Building Information Modelling (i-BIM), Bridge Information Modeling (BrIM), Civil Integrated Management (CIM), Construction Information Modelling (CiM), Civil Integrated Management (CIM), Virtual Design and Construction (VDC) etc. (Costin et al., 2018; Del Savio et al., 2022; Panagiotis et al., 2024; Sankaran et al., 2016). Adopting and integrating BIM with other advanced digital technologies can improve the planning, execution, and management of highways, delivering significant improvements in efficiency, accuracy, and cost-effectiveness (Aziz et al., 2017; Zakaria et al., 2024). Utilization of BIM can increase collaboration and decrease fragmentation thereby leading to performance improvement as well as reduction in infrastructure costs (Alsofiani, 2024; Azhar, 2011; Mahadewi et al., 2025; Samimpay & Saghatforoush, 2020). While these studies show the growing use of BIM in highway projects, challenges in adoption remain, motivating the need to examine barriers in more detail.

2.2 Impediments to BIM adoption

An overview of the literature on BIM adoption impediments reveals some notable limitations. First, numerous studies have explored BIM adoption challenges in building projects, whereas relatively limited attention has been given to these challenges in the specific context of highway infrastructure projects. This gap aligns with the observations of Castañeda et al. (2024), (Nielsen et al., 2024), (Panagiotis et al., 2024), and Biancardo, Viscione, et al. (2020), that BIM remains an emerging concept in road infrastructure, with a lower maturity level compared with building projects. Second, an overview of the studies that do examine BIM adoption in infrastructure projects suggests that the challenges are largely similar to those identified in the building sector e.g. Alsofiani (2024), (Halim et al., 2022), Dolaček-Alduk et al. (2022), Guo et al. (2021), and Belay et al. (2021); however, this observation requires empirical confirmation, which the present study addresses. Third, a significant body of the literature discusses BIM adoption challenges in general AEC context without clearly delineating the application domain (i.e., buildings versus linear infrastructure) e.g. Agwa and Celik (2025), Hatami and Rashidi (2025), Ikediashi et al. (2025), Lourenço et al. (2025), El Hajj et al. (2023), Durdyev et al. (2022), and Babatunde et al. (2021).

Given the limitations discussed above, this study identifies twenty key factors impeding BIM adoption **(Table 2)**, synthesized from an in-depth review of the literature covering studies on building projects, infrastructure projects, and research that examines BIM adoption challenges without any domain differentiation. This study subsequently examines these factors to assess their relevance within the specific context of highway infrastructure projects, rank their relative importance based on combined literature and industry input, and investigate their causal relationships.

Table 2. Detailed list of factors impeding BIM adoption. Source(s): Authors own work

2.2.1 *Vertical (buildings) construction*

Liu et al. (2010) examined factors affecting BIM adoption in the vertical AEC industry, providing foundational insights into adoption barriers. Stanley and Thurnell (2014) analyzed barriers to BIM implementation in New Zealand, also focusing on building projects. Chan et al. (2019) carried out a quantitative survey to identify and rank barriers in Hong Kong's vertical AEC sector. Similarly, Farooq et al. (2020) and Saka and Chan (2020) applied Interpretive Structural Modelling (ISM) and Cross-Impact Matrix Multiplication Applied to Classification (MICMAC) to examine barrier interrelationships, contributing a systems perspective, though their focus was limited to non-horizontal sectors. (Kineber et al., 2023) investigated the key barriers hindering BIM adoption in building construction projects in developing countries using a survey of industry professionals combined with exploratory factor analysis (EFA) and partial least squares-based structural equation modelling (PLS-SEM). Similarly, (Al Aamri et al., 2025) evaluated the current level of BIM adoption in Oman's construction industry, identifying key technological, organizational, and cost-related barriers through a survey of industry professionals from public and private sectors. Overall, these representative studies highlight efforts to identify and prioritize barriers to BIM adoption in buildings, including studies dating back to 2010, which demonstrate the depth and maturity of research in buildings domain.

2.2.2 *Linear infrastructure*

Costin et al. (2018) examined factors affecting BIM adoption in transportation infrastructure, providing insights into key barriers, though the study did not examine the interrelationships among these factors. Eadie and Johnston (2020) investigated barriers to BIM adoption in highway projects, offering empirical evidence in the infrastructure domain. Halim et al. (2022) studied barriers from consultants' perspectives in highway projects, while Nielsen et al.

(2024) analyzed global initiatives related to BIM in road infrastructure. Alsofiani (2024) conducted a systematic review of infrastructure BIM barriers across multiple countries. Dolaček-Alduk et al. (2022) examined the barriers to BIM adoption in infrastructure projects and provided guidelines for the Croatian Chamber of Civil Engineers. Guo et al. (2021) conducted a study to identify challenges and solutions for BIM in infrastructure projects based on interviews with industry professionals; however, the study did not include literature-based insights or analysis of causal relationships. Similarly, Belay et al. (2021) carried out a study which was limited to identification and ranking of barriers to BIM adoption in Ethiopian infrastructure projects. Collectively, these selected studies reflect advancement in understanding BIM adoption challenges in highways, yet broader causal interactions among barriers remain underexplored, highlighting the need for more systemic analysis in linear infrastructure contexts.

2.2.3 General AEC / mixed contexts

Babatunde et al. (2021) identified and ranked BIM barriers in Nigerian AEC firms using statistical and factor analysis, capturing general industry patterns. Durdyev et al. (2022) prioritized BIM barriers during the facilities management phase using fuzzy multi-criteria decision-making methods. El Hajj et al. (2023) studied BIM adoption barriers across Middle East and North Africa (MENA) developing countries using statistical and principal component analysis, while Agwa and Celik (2025) and Hatami and Rashidi (2025) explored barriers in broader AEC contexts using multi-criteria and Delphi-based methods. Ikediashi et al. (2025) examined BIM adoption barriers for facilities management, linking them to stakeholders' attributes through regression analysis. Lourenço et al. (2025) prioritized BIM implementation barriers in Portugal and examined hierarchical and causal relationships using ISM and MICMAC. This body of literature highlights studies in general AEC or mixed contexts that do not explicitly distinguish between building and infrastructure domains and use a range of analytical approaches.

The preceding literature review highlights a notable gap, specifically, the limited attention to examination of BIM adoption challenges in linear infrastructure, particularly highways, and the causal interactions among these challenges. Addressing this gap, this study identifies impediments to BIM adoption in highway infrastructure projects and examines their systemic interactions, providing insights to support policymakers and industry stakeholders in designing system-aware interventions to enhance BIM adoption.

3. Research methodology

The first step in this study was a critical review of publications on BIM which not only provided an impetus for undertaking the study but also helped in identification of the research gap. The research framework adopted to bridge the research gap is shown in **Figure 1** wherein main stages, key techniques, and research flow are indicated. The research methodology was based on a structured four-stage approach which is elaborated upon in the following sub-sections.

Figure 1. Research methodology. Source(s): Authors own work

3.1 Stage 1: Literature-based factor identification and scoring

Stage 1 focused on identifying BIM adoption impediment factors from the existing literature and quantifying their relative importance. This process entailed three main steps viz. collection of literature, identification of factors and computation of their literature scores, and normalization of literature scores. These steps are explained in the following subsections.

3.1.1 Literature collection

After conducting a structured literature search, studies on impediments to BIM adoption were systematically collected from multiple academic databases, including Emerald Insight, ScienceDirect, Scopus, and Web of Science. The search was performed using predefined keywords and combinations such as *"barriers", "challenges", impediments", "Building Information Modeling", "BIM", "highway infrastructure", "road infrastructure", "transportation infrastructure", "infrastructure projects", "linear infrastructure".* Inclusion and exclusion criteria regarding publication relevance, focus on BIM adoption and implementation, peer-reviewed status, and publication within the last two decades were then applied during the screening process. This time bracket was selected keeping in view the general trend of the number of BIM-related scholarly publications. As a result, sixty-one pertinent scholarly articles were retained for further analysis. The selected studies were not limited to a single sector but included BIM adoption studies related to highway infrastructure, buildings, and studies with no explicit domain identification.

3.1.2 Factor identification and scoring

Following the literature collection, a systematic content analysis was conducted to identify the factors influencing BIM adoption and implementation and to determine the corresponding Literature Score (LS) for each factor (see **Table 2** for the list of identified factors). The LS reflects the relative frequency with which each factor is discussed in prior studies. Microsoft Excel was used as a data management tool to record the extracted factors, tabulate their frequency of occurrence, and calculate the LS for each factor. As not all reviewed articles examined the same set of factors, a structured scoring procedure was applied, consisting of five steps:

(1) For each article, the influence of the factors explicitly examined in that study on BIM adoption and implementation was recorded. When an article explicitly classified a factor's influence (e.g., *very low*, *low*, *medium*, *high*, *very high*), that classification was recorded directly. If no explicit classification was provided, the influence level was systematically inferred through a structured qualitative assessment of the authors' descriptions. To ensure consistency, the inference followed predefined criteria based on the intensity of emphasis (e.g., extent of discussion and prioritization), causal framing (whether the authors explicitly link the factor to BIM adoption or simply mention it without indicating influence), and strength of language (e.g., use of qualifiers indicating magnitude or importance) used by the authors.

(2) For each factor, frequency of occurrence i.e. the total number of articles in which it was discussed, was recorded.

(3) Each identified influence level was assigned a numerical score using the scale adopted by Gündüz et al. (2013) and Jahan et al. (2022) where *very low* = 1, *low* = 2, *medium* = 3, *high* = 4, *very high* = 5. These values represented literature-derived impact scores assigned to each factor across the reviewed studies.

(4) For each factor, scores were aggregated, and their arithmetic mean was calculated to represent its average impact. The mean impact score reflected the average perceived influence of each factor across studies, while the Relative Importance Index (RII) in Step 5 integrated both frequency and impact to derive the final LS.

(5) Finally, the LS was computed for each factor using the RII method (**Equation 1)**, consistent with prior applications in the literature (Ghufran et al. (2022); Jin, Hancock, Tang, Chen, et al. (2017); Sambasivan and Soon (2007).

3.1.3 Normalized literature scoring

Determination of LS was followed by computation of Normalized Literature Score (NLS) for each factor using **Equation (2)**. Normalization is a data rescaling technique that converts values measured on different scales to a common theoretical scale. The NLS provided a normalized measure that allowed direct comparison of the relative importance of the factors.

$$RII = \frac{\sum W}{A \times N} \tag{1}$$

$$NLS = \frac{LS}{\sum LS} \tag{2}$$

where '*W'* is the product of factor's mean impact score and the corresponding frequency of occurrence, '*A*' is the maximum impact score, '*N*' is the total number of articles, '*LS*' is the literature score of each factor, and '*ΣLS'* represents the total literature score.

3.2 Stage 2: Industry-based survey and factor scoring

While Stage 1 involved literature-based identification and scoring of factors affecting BIM adoption across buildings, linear infrastructure, and general AEC contexts, Stage 2 focused on analyzing the identified factors specifically in the context of highways through quantitative data collection via a comprehensive online questionnaire survey (see **Appendix**) of industry professionals and subsequent analysis. The industry survey was intended to obtain a focused overview of practitioners' perception of the impact of these factors on BIM adoption in the specific context of highway infrastructure. Based on survey results, the survey score (SS) and normalized survey score (NSS) were computed which represented the practical relevance of each factor from an industry perspective, complementing the initial literature-based findings.

3.2.1 Participation criteria and survey design

Survey participation was limited to individuals meeting a predefined professional profile. Respondents with direct professional involvement in highway infrastructure projects and experience or familiarity with BIM were invited to participate. The target population comprised professionals such as engineers and architects within client organizations, as well as professionals from engineering consultancy firms, contractors, and academic institutions engaged in highway infrastructure delivery or BIM-related research and education.

The survey form comprised two major sections. In the first section, demographic details pertaining to educational and professional profile, and the level of understanding of BIM and highway infrastructure were sought from respondents. The second section requested the respondents to score each factor's impact on BIM adoption in highway infrastructure projects on a five-point Likert scale (1 = very low impact, 2 = low impact, 3 = medium impact, 4 = high impact, 5 = very high impact).

3.2.2 Respondents' profile

The survey obtained 124 valid responses from professionals belonging to seven countries viz. China (15%), Germany (5%), Saudi Arabia (10%), Malaysia (17%), Pakistan (37%), South Korea (8%), and the UAE (7%). The survey captured practitioners' judgment on the relative importance of the identified impediments in the context of highway projects. These countries collectively represent a broad perspective encompassing developed as well as developing countries (Akram et al., 2022). The readiness for adopting and implementing BIM varies across different countries (Al-Mohammad et al., 2023), and both developed as well as developing countries face problems in BIM adoption (Ullah et al., 2019). Germany, USA, Canada, UK, China, South Korea etc. have higher BIM adoption percentage and higher BIM maturity level as compared to the developing countries (Bhatti et al., 2018; Farooq et al., 2020). Stringent measures were taken to securely manage and store the collected data. All data were anonymized, and access was restricted to the authors to ensure participant confidentiality.

The respondents belonged to four major categories viz. client (10%), engineering consultant (48%), contractor (27%) and academia (15%). As per educational profile, 23% had bachelor's degrees, while 77% were postgraduates encompassing Masters, MPhil., and PhD. Other salient demographics of survey respondents are presented in **Table 3.**

Table 3. Salient demographics of survey respondents (n = 124). Source(s): Authors own work

This diverse and experienced group of participants ensured robustness of survey data quality indicating widespread relevance across varied geographical contexts. The Cronbach's coefficient alpha was adopted as statistical tool for measuring reliability and internal consistency of valid survey responses (Jin, Hancock, Tang, & Wanatowski, 2017). A value exceeding 0.70 indicates good internal consistency of dataset (Taber, 2017; Won et al., 2013).

3.2.3 Survey-based factor scoring

The SS for each factor was computed using the concept of RII as already shown in **Equation (1)**, followed by computation of NSS using **Equation (3).**

$$NSS = \frac{SS}{\sum SS} \tag{3}$$

where *'NSS'* represents the normalized survey score, 'S*S*' is the survey score of each factor, while '*ΣSS'* is the total survey score. Normalization ensured that all factor scores were scaled on a common basis for comparison.

3.3 Stage 3: Combined scoring and factor shortlisting

3.3.1 Combined factor scoring

Building on NLS and NSS, normalized combined score (NCS) was computed for each factor to integrate both literature evidence and practitioners' insights. The NCS was calculated using **Equation (4)** (Amin et al., 2022; Jahan et al., 2022).

$$NCS = (0.40 \times NLS) + (0.60 \times NSS) \tag{4}$$

where *'NLS'* is the normalized literature score and *'NSS'* represents the normalized survey score.

3.3.2 Factor shortlisting

Following the computation of NCS, all the factors were ranked in descending order according to their NCS values. The cumulative NCS was then calculated for the ranked factors. The Pareto principle (80/20 rule) was applied to the cumulative NCS for factor shortlisting, as it helps distinguish the significant aspects of a problem from the trivial ones (Ahmad et al., 2018). Factors contributing cumulatively up to 80% of the total NCS were retained. This shortlisting step enabled the contextual refinement of the initial set of BIM adoption factors and produced a subset applicable exclusively to the highway infrastructure context based on combined literature and survey inputs.

The shortlisted factors were subsequently categorized on the basis of their nature (Deng et al., 2020) and a factor category matrix (FCM) was developed to depict these categories. Although the categorization was not directly used in subsequent analyses, it helped in understanding the overall structure of the factors and provided context for interpreting their nature and causal relationships.

3.4 Stage 4: Causal relationship modelling and analysis

Stage 4 obtained the expert opinion to produce a factor relationship matrix (FRM) and subsequently employed the Systems Thinking approach to model and analyze the causal relationships among the shortlisted factors i.e. impediments to BIM adoption and implementation in highway infrastructure. Systems Thinking approach is derived from Systems Theory and is based on the principle that the constituent parts of any given system cannot be best understood in isolation; instead, they should be studied within the context of their interactions and relationships with one another as well as with other systems. *"Systems thinking is, literally, a system of thinking about systems."* (Arnold & Wade, 2015).

The tools and techniques provided by Systems Theory for understanding complex systems are better than analytical network process (ANP) and ISM etc. The ANP does not show complete dependencies (Wu, 2008), and similar is the case with ISM despite the fact that it authorizes intuition into interrelationships among different elements (Attri et al., 2013). Systems theory provides a robust interdisciplinary framework for understanding complex phenomena by emphasizing relationships, interactions, and interdependencies rather than isolated components. Its key strengths include transdisciplinary applicability, holistic perspective, complexity reduction, and practical problem-solving (Adams et al., 2014; Mele et al., 2010). Modeling under the Systems Thinking approach involves, inter alia, development of causal loop diagram (CLD) which are used for visualizing and analyzing the structure and behavior of a system.

3.4.1 Factor relationship matrix

The polarities and interrelationships among the shortlisted factors were identified through expert consultation. Among the survey respondents who had assessed the impact of each factor on BIM adoption in highway infrastructure projects using a five-point Likert scale, one professional per country with the highest relevant experience in highway infrastructure and BIM implementation was selected. A total of seven professionals participated, representing China, Germany, Saudi Arabia, Malaysia, Pakistan, South Korea, and the UAE. They were asked to evaluate pairwise relationships among the shortlisted factors, indicating the presence, direction, and polarity of influence. These assessments were compiled into an FRM.

3.4.2 Modelling and analysis

The FRM served as the basis for causal relationship modeling and analysis. According to Jahan et al. (2022), researchers consider *AnyLogic*, *iThink*, *Stella Professional*, and *Vensim* as some famous software tools for development of CLDs. The authors employed *Vensim* for development of CLD which led to identification of causal loops, and the factors having maximum causal relationships with the other factors.

4. Results and discussion

4.1 Literature-based factor scores

The NLS results (**Figure 2**) indicate concentration of the literature around certain dominant impediments. *High initial investment costs* emerged as the most frequently cited barrier, achieving the highest NLS (0.1392). This finding highlights the persistent financial concern, e.g. software acquisition, hardware upgrades, training expenses, and other implementation costs associated with BIM. The second and third most prominent impediments are *integration, incompatibility, and interoperability challenges* (NLS = 0.1083) and the *lack or absence of BIM standards, policies, and regulations* (NLS = 0.1074).

Figure 2. Normalized scores of factors. Source(s): Authors own work

A second tier of BIM impediments reported in the literature is related to the *lack of BIM-supportive organizational culture, vision, and structure* (NLS = 0.0895), *lack of technical resources in form of BIM specialists and training* (NLS = 0.0825), and *lack of client-driven demand and top management commitment* (NLS = 0.0785). The relatively high literature scores of these factors suggest that literature does not consider BIM adoption solely a technical issue but is strongly influenced by organizational readiness, resources, and leadership. Legal, contractual, and behavior-related barriers occupy the mid-range of the ranking, which include the *lack of legal and contractual frameworks for BIM-based workflows* (NLS = 0.0666), *resistance to shifting from traditional working practices* (NLS = 0.0547), and *lack of BIM knowledge and related workflows* (NLS = 0.0537).

Lower-tier impediments, for example, *data ownership and copyright concerns*, *steep learning curve*, and *low willingness to collaborate in BIM-based workflows*, exhibit comparatively smaller NLS values, indicating less frequent emphasis in literature. The least cited factors include *limitations in BIM processes and software tools*, *difficulties in measuring expected BIM benefits*, *complexity of highway infrastructure projects*, and *increased workload due to BIM model development*. Although these issues receive relatively less attention individually in literature, their cumulative effect can still influence BIM adoption outcomes in practice.

4.2 Reliability, consistency, and descriptive statistics of survey responses

The Cronbach's coefficient alpha emerged to be 0.830, which indicated good reliability and internal consistency of survey responses. Summary statistics for the impact score of each of the twenty factors based on the survey responses are presented in **Table 4**.

Table 4. Summary statistics of survey responses. Source(s): Authors own work

The descriptive statistics for the factor *lack of client-driven demand and top management commitment* indicate that respondents, on average, rated this factor at 3.5081, with a median value of four (4) and a mode of five (5), suggesting a tendency toward higher ratings. The standard deviation of 1.2461 reflects moderate variability in responses. The negative kurtosis (-0.9427) indicates a relatively flat distribution, while the slight negative skewness (-0.3262) suggests that responses are slightly skewed toward higher ratings. Overall, this factor appears to be perceived as significant, with a distribution that leans toward stronger agreement among respondents. The remaining factors in Table 4 are interpreted in the same manner.

4.3 Survey-based factor scores

The NSS results **(Figure 2)** indicate the relative importance of BIM adoption impediments from the perspective of industry practitioners, with higher values reflecting a greater perceived impact on highway infrastructure projects. The findings show that *lack of client-driven demand and top management commitment* represents the most critical barrier, achieving the highest NSS value (0.0623). This highlights the perceived importance of leadership support and client mandates in enabling BIM adoption in highway projects. The next most influential impediments are the *lack of a BIM-supportive organizational culture, vision, and structure* (NSS = 0.0619) and the *lack or absence of BIM standards, policies, and regulations* (NSS = 0.0597), underscoring the high perceived importance of organizational readiness and highway-specific BIM standards.

Technical and resource-related challenges also feature prominently in the NSS results. The *lack of technical resources* (NSS = 0.0587) and *integration, incompatibility, and interoperability challenges* (NSS = 0.0520) reflect industry concerns regarding the availability of skilled human capital and the ability to effectively integrate BIM technologies. In contrast, *high initial investment costs*, while still relevant, achieved a comparatively lower score (NSS = 0.0497), indicating that practitioners perceive financial barriers as less restrictive than organizational and managerial constraints.

Impediments occupying the mid-range of the NSS results include the *lack of legal and contractual frameworks for BIM-based workflows* (NSS = 0.0554), *resistance to shifting from traditional working practices and tools* (NSS = 0.0592), and *lack of BIM knowledge and related workflows* (NSS = 0.0565). These findings suggest that contractual uncertainty and behavioral resistance continue to influence BIM adoption, albeit to a lesser extent than leadership and organizational factors.

Impediments, such as *data ownership and copyright concerns, steep learning curve,* and *low willingness to collaborate in BIM-based workflows*, exhibit relatively smaller NSS values, indicating limited perceived influence. The least influential barriers identified by practitioners include the *lack of specialized insurance policies* (NSS = 0.0399) and *increased workload due to BIM model development* (NSS = 0.0396). Additionally, *challenges related to BIM model and drawing scale* (NSS = 0.0408) received lower scores, suggesting a comparatively minor perceived impact on BIM implementation in highway infrastructure projects.

In comparison with the literature-based scores, the industry survey reveals a partial realignment. While both data sources consistently highlight the importance of standards, interoperability, and skills-related barriers in BIM adoption, the industry survey places greater emphasis on client demand, top management commitment, and organizational culture for BIM adoption in specific context of highway infrastructure. Conversely, cost-related barriers, which dominate literature, appear less critical in highway projects from the practitioners' opinions.

4.4 Combined factor scores

By synthesizing evidence from both the literature-based analysis (NLS) and the industry survey (NSS), the NCS **(Figure 2)** offers an integrated assessment of factors' impact by jointly reflecting their prominence in literature and their perceived importance in highway infrastructure perspective. Higher NCS values indicate a greater overall influence of a factor on BIM adoption.

The results indicate that *high initial investment costs* represent the most critical barrier, achieving the highest NCS value (0.0855). This highlights the dominant role of financial constraints in limiting BIM adoption. The *lack or absence of BIM standards, policies, and regulations* ranked second (NCS = 0.0788), emerges as the second most critical impediment. The third-ranked factor, *integration, incompatibility, and interoperability challenges* (NCS = 0.0746), reflects persistent technical difficulties in integrating BIM tools and workflows. This is followed by the *lack of a BIM-supportive organizational culture, vision, and structure* (NCS = 0.0729), underscoring the importance of organizational readiness and strategic alignment for effective BIM adoption.

Factors with moderate influence include *lack of client-driven demand and top management commitment* (NCS = 0.0688) and *lack of technical resources in the form of BIM specialists and training* (NCS = 0.0682). In addition, the *absence of a legal and contractual framework for BIM-based workflows* (NCS = 0.0599) indicates that legal and contractual uncertainties continue to impede BIM use.

Highway-specific challenges are also evident in the NCS results; however, they exhibit comparatively low NCS values, indicating a lower impact relative to other identified impediments. The *lack of BIM data formats and schemas for horizontal construction* (NCS = 0.0354) highlights limitations in adopting BIM to the needs of linear infrastructure. Similarly, the *complexity of highway infrastructure projects* (NCS = 0.0306), such as extensive spatial scales, multidisciplinary coordination, and long project lifecycles, presents additional challenges for effective BIM implementation. Overall, the NCS-based analysis shows that financial, regulatory, and organizational barriers exert the greatest influence on BIM adoption.

4.5 Shortlisted factors

Pareto analysis of NCS led to shortlisting of thirteen factors which are presented in **Table 5** along with their respective IDs, NLS, NSS, NCS, and rankings. These factors represent the impediments to BIM adoption in highway infrastructure projects, as identified through combined literature–industry insight.

Table 5. Shortlisted factors impeding BIM adoption in highway infrastructure projects. Source(s): Authors own work

The analysis of factor scores reveals that the factor *high initial investment costs related to BIM* (ID: F01) holds the top rank (Rank 1), with NCS = 0.0855. Highest NCS value emphasizes the most notable influence of this factor on BIM adoption in highway infrastructure. The factor *lack/absence of BIM standards, policies, and regulations* (ID: F02) is ranked second, with NCS = 0.0788. Although it is also a crucial barrier, it is slightly less impactful than the *high initial investment costs*. Similarly, the factor *integration, incompatibility, and interoperability challenges* (ID: F03) is ranked third, showing NCS = 0.0746.

The shortlisted factors broadly fall into five major categories **(**see **Table 6)** viz. financial, technical, management, enterprise environment, and legal (Deng et al., 2020). The financial category (F01) involves *high initial investment costs*. The technical category (F03, F09, F11) covers *interoperability issues*, *lack of BIM knowledge*, and a *steep learning curve*. The management category (F02, F06) includes the *lack or absence of BIM standards and insufficient technical resources*. The enterprise environment category (F04, F05, F08, F10, F13) encompasses the *lack of supportive culture, low client demand, resistance to change, poor collaboration, and limited contractor expertise*. The legal category (F07, F12) highlights the *absence of legal frameworks* and *data ownership concerns*. This classification emphasizes the comprehensive nature of challenges impacting BIM adoption in highway infrastructure projects.

Table 6. Factor category matrix. Source(s): Authors own work

The following subsections examine the shortlisted impediments by distinguishing between impediments that are common and transferable from vertical construction, and those specific to highway infrastructure. The implications arising from this combined perspective are elaborated upon in the *Significance and implications* section.

4.5.1 Common factors in buildings and highways

The results show a notable commonality between the shortlisted factors influencing BIM adoption in highway infrastructure and those documented in vertical (buildings) construction. These include *high initial investment costs*, *interoperability challenges*, *organizational culture*, *client-driven demand and top management commitment*, *lack of technical resources in form of BIM specialists and training*, *lack of legal and contractual frameworks*, *lack or absence of BIM standards, resistance to change*, *lack of BIM knowledge*, *low willingness to collaborate in BIM-based* *workflow*, *steep learning curve*, and *data ownership and copyright concerns*. Regarding *lack or absence of BIM standards*, the issue is not that the standards do not exist for buildings, but rather that the existing standards are predominantly building-centric and primarily developed around vertical construction processes, object libraries, and information delivery requirements, and are therefore not fully transferable to linear assets.

The prominence of these factors confirms earlier findings from building-sector BIM research where financial constraints, organizational readiness, collaboration challenges, and other factors consistently dominate adoption barriers. More importantly, these results empirically confirm the transferability of these impediments from vertical to linear infrastructure, addressing a gap that has often been implied in the literature but is explicitly validated in this study through a combined literature–industry analysis. While these factors are found to be common across both sectors, their manifestation and severity in highway infrastructure projects are shaped by the operational environment, which typically involve larger spatial extents, longer lifecycles, and complex interfaces with existing assets. Hence, their implications in highway infrastructure warrant context-specific investigation.

4.5.2 Intensification of factors in highways context

Within the shortlisted challenges, certain challenges assume heightened significance in the specific context of highway infrastructure projects. The *integration, incompatibility, and interoperability challenges* are exacerbated in highway projects because of the need to integrate BIM with extensive geospatial data and civil infrastructure design tools. The *lack or absence of BIM standards, policies, and regulations* further intensifies this challenge, as many existing standards remain predominantly building-oriented and are insufficient for linear infrastructure requirements.

Similarly, *lack of contractors and subcontractors capable of working with BIM* is a particularly relevant barrier in highway projects. Highway delivery often involves a fragmented supply chain with specialized contractors for earthworks, pavements, and structures. This constraint is less pronounced in vertical construction, where BIM adoption has reached relatively higher maturity levels across the supply chain. Organizational and managerial factors e.g. *client-driven demand, top management commitment, and BIM-supportive organizational culture* also carry distinct implications in highways, where public-sector clients frequently dominate and procurement frameworks are rigid. In such contexts, the absence of strong client mandates can significantly affect BIM adoption across projects and organizations, reinforcing traditional practices.

4.5.3 Highway-specific factors

The Pareto-based shortlisting reveals that some factors presumed to be exclusive to highway infrastructure did not meet the cumulative NCS threshold and were therefore excluded from the final set of impediments. Notably, factors such as the *lack of BIM data formats and schemas for horizontal construction* and *complexity of highway infrastructure projects*, which are explicitly linked to the linear nature of highway projects, exhibited comparatively lower NCS. This finding suggests that, despite their contextual relevance, highway-specific technical complexities do not directly impede BIM adoption when compared with other factors. Instead, their influence appears complementary and secondary, operating primarily through their direct impact on interoperability challenges. Consequently, this influence is overshadowed by more systemic and fundamental issues, such as leadership commitment and organizational readiness, that are broadly shared across both buildings and linear infrastructure.

4.6 Factor relationship matrix

More than thirty causal relationships were initially identified among the shortlisted thirteen factors. Through careful and progressive shortlisting based on expert opinion, the relationships were condensed to nineteen. The FRM, showing the relationships between factors, is presented in **Table 7**, where the rows and columns correspond to the thirteen shortlisted factors (F01 to F13).

Table 7. Factor relationship matrix. Source(s): Authors own work

The diagonal entries marked as "—" in Table 7 indicate that no factor is connected to itself. The entries indicate whether a relationship exists (1) or not (0) between pairs of factors. For instance, the cell at the intersection of row F01 and column F03 has a value of "1" which indicates that F01 *(high initial investment costs)* has direct influence on F03 *(interoperability challenges)*. Similarly, the cell corresponding to row F01 and column F08 has a value of "1" which indicates that F01 directly influences F08 *(resistance to shift to BIM)*. Conversely, the cell at the junction of row F01 and column F02 has a value of “0” which indicates that F01 does not influence F02 *(lack/absence of BIM standards)*.

4.7 Causal loop diagram

The consolidated CLD developed using Vensim is shown in **Figure 3**, while the individual causal tree of each of the thirteen factors extracted from Vensim is shown in **Figure 4**. CLD comprises seven constituent causal loops. The loops are labelled on the CLD and discussed in the following sections.

Figure 3. Consolidated causal loop diagram. Source(s): Authors own work

Figure 4. Causal tree of factors. Source(s): Authors own work

4.7.1 Causal loop R1

BIM has seen widespread adoption in the building sector; however, it is still an emerging topic in highway infrastructure (Castañeda et al., 2024). Although some organizations have developed consolidated BIM standards for infrastructure and buildings (e.g., ISO 19650 standards by International Organization for Standardization, and PAS 1192 framework by British Standards Institute), there is a lack of highway-specific BIM standards. Linear assets and vertical construction are primarily different in nature (Nielsen et al., 2024) which warrants development of dedicated BIM standards for highway infrastructure.

The causal loop R1 indicates that lack of BIM standards, policies, and regulations for highway infrastructure directly leads to lack of legal and contractual framework for BIM-based collaboration, which in turn leads to lack of BIM-conversant contractors. The experience of contractors in effective BIM implementation on highway infrastructure remains limited. This lack of BIM-conversant contractors exacerbates the lack of client-driven demand for BIM adoption in highway infrastructure. This, in turn, translates into resistance to shift to BIM and ultimately reinforces the lack of BIM standards, policies, and regulations.

This loop, inter alia, endorses and confirms the viewpoint of Chan et al. (2019) that the role of client's demand in advocating and implementing innovative technology is crucial to successful adoption of BIM for highways. This loop also shows that the benefits of BIM cannot be fully realized for highway infrastructure if there is lack of an appropriate project delivery system and suitable contract type.

4.7.2 Causal loop R2

From causal loop R2, it can be inferred that the lack of highway-specific BIM standards, policies, and regulations contributes to gaps in the legal and contractual framework for BIM-based collaboration, particularly given that BIM adoption in highway sector is still at an early stage. Adoption of BIM for highway infrastructure requires changes in the prevailing forms and formats of collaboration as well as the structure of contracts regulating the interaction between different stakeholders.

The lack of legal and contractual framework for BIM-based collaboration in highway infrastructure accentuates data ownership and copyright concerns within BIM ecosystem. These concerns have an adverse impact on the willingness to collaborate, which ultimately leads to resistance to BIM adoption. This resistance transmogrifies into lack of BIM standards.

This loop suggests that the organizations desirous of adopting and implementing BIM in highway infrastructure should, among other measures, pay attention to the development of highway-specific BIM standards, policies, and regulations. Furthermore, they should focus on formulation of highway-specific legal and contractual frameworks.

4.7.3 Causal loop R3

The loop R3 shows that higher initial investment costs for BIM software, licenses, training, and related expenses increase the resistance to adopting BIM. This resistance directly impacts the BIM learning curve for highway infrastructure, making it steep. Organizations already using BIM in building projects may also experience high initial costs and a more challenging learning curve when transitioning to highway infrastructure. This is due to the need to acquire infrastructure-specific software tools, associated licensing and subscription charges, training expenses, and hiring of BIM specialists with experience in infrastructure.

Application of BIM in highway infrastructure requires a different set of software tools as compared to those for buildings. Cost of new software tools may be impacted by the choice of BIM ecosystem i.e., open-BIM or closed-BIM. Moreover, expertise developed through BIM application in building projects may not directly translate to infrastructure projects, requiring additional training and industry-specific experience. These trainings may cause initial investment costs to be higher.

Measures taken for adopting and implementing BIM in highway infrastructure should not only appreciate the quantum of initial investment costs, but also the impact of these costs on BIM learning curve and the resistance to adopt BIM. BIM users may experience low return on investment costs in highway infrastructure owing to lower levels of experience and engagement (Ghaffarianhoseini et al., 2017).

4.7.4 Causal loop R4

This loop highlights that interoperability challenges among different BIM software tools in highway infrastructure projects result in a steep BIM learning curve, which in turn drives up initial BIM investment costs. This loop endorses the viewpoint of Zhao et al. (2019) that interoperability issues make the adoption of BIM challenging. Technology is a major facet of BIM, and utilization of technology in form of different software tools within either an open-BIM or closed-BIM ecosystem is inevitably accompanied by integration and data interoperability challenges, which are also referred as "*Islands of Automation*" (Kageyama, 2016).

Interoperability efforts related to BIM are mature in the building sector mainly due to well-established data exchange standards e.g., Industry Foundation Classes (IFC) that were originally developed with buildings in mind (Biancardo, Capano, et al., 2020; Drogemuller et al., 2021). In contrast, linear infrastructure assets have long faced more interoperability challenges, which may be attributable to unique geometric complexity, extensive geospatial dependencies, and corridor-based nature (Nielsen et al., 2024). This is evidenced by the limited support for such assets in IFC releases up to IFC4 (2013), which prompted buildingSMART International to initiate dedicated linear infrastructure programs around 2015. This resulted in progressive extensions, including IFC Alignment (IFC4.1), followed by expanded representations for corridors, pavements, and earthworks in IFC4.2 and IFC4.3. The IFC4.3 is specifically enhanced to improve infrastructure asset modeling and data exchange capabilities (El-Amraoui-Farssi et al., 2021; Jaud et al., 2021). In parallel, several other solutions, most notably LandXML and InfraGMLhave also sought to improve data exchange for linear assets. Despite these efforts, interoperability for linear infrastructure remains less mature than for buildings (Nielsen et al., 2024), indicating that development of data formats, standards, and schemas referring to horizontal elements in road infrastructure is still evolving. Addressing the data interoperability challenges with due consideration to their causal relationships with the learning curve and initial investment costs may be treated as an important prerequisite for effectively adopting and applying BIM in highways.

4.7.5 Causal loop R5

The loop R5 indicates that lack of BIM-supportive organizational culture, vision, structure, policies, processes, strategies, and initiatives reinforces the lack of BIM-related technical resources in highway infrastructure projects. This subsequently leads to a steep BIM learning curve, which ultimately contributes to a lack of BIM-supportive organizational structures.

This loop strengthens the findings of Ozorhon and Karahan (2017) that a BIM-conducive organization plays an important role in promoting and enhancing BIM adoption. This loop also shows the causal relationships among organizational structures, availability of BIM-related resources, and learning curve. This endorses the findings of Bosch-Sijtsema et al. (2019) that development and institutionalization of BIM profession is dependent upon structural and cultural systems in the organization.

4.7.6 Causal loop R6

The loop R6 shows that a lack of BIM knowledge and workflows in highway infrastructure leads to a lack of BIM-related technical resources. The lack of technical resources leads to a steep learning curve, thereby making it more difficult to learn and adopt BIM. The steeper the learning curve, the more enhanced is the lack of BIM knowledge.

This loop supports the viewpoints of Al-Shalabi et al. (2015) that wrong, unclear, or insufficient understanding of BIM workflows inhibits BIM adoption. This loop also shows that adoption of BIM in highway infrastructure is affected by interaction and causal interrelationships among BIM knowledge, learning curve, and technical resources.

4.7.7 Causal loop R7

The loop R7 depicts the causal relationships among data interoperability challenges, learning curve, and lack of BIM knowledge. Higher the data interoperability and integration challenges in applying BIM in highway infrastructure, the steeper will be the BIM learning curve. The steepness of the learning curve will subsequently have adverse impact on BIM knowledge. This confirms the stance of Azhar (2011) that a steep learning curve is an important factor inhibiting BIM adoption and implementation.

5. Significance and implications

This study is grounded in literature and validated through empirical industry feedback, and is significant through its novel contribution to the body of knowledge. It identifies the critical factors that impede BIM adoption in highway infrastructure projects and offers a comprehensive overview of their interconnections. The utilization of the Systems Thinking approach has provided deeper understanding of the complex system created by causal interrelationships among different factors, which can help in development of robust BIM implementation strategies. Identification of causal loops and related polarities deciphers the complicated connections among factors supporting more informed decision-making on overcoming impediments. The findings are valuable for road infrastructure agencies and policymakers, especially in developing countries, for devising appropriate strategies to effectively address the BIM impediments with minimum policy resistance. Furthermore, these insights can help highway infrastructure agencies prioritize and streamline their organizational efforts to ensure successful BIM implementation, contributing to sustainable infrastructure development and delivering tangible benefits to the community.

The results provide quantitative evidence that many barriers previously identified in building sector, such as financial constraints, organizational readiness, and collaboration challenges, remain relevant and influential in highway infrastructure. The findings validate the applicability of existing BIM challenges while extending them to linear infrastructure contexts. BIM adoption in highway infrastructure is constrained less by entirely new challenges and more by the recontextualization and amplification of established impediments in the context of linear systems. Importantly, while many impediments are transferable, their manifestation and severity can be shaped by the operational environment of highway projects, which typically involve larger spatial extents, longer lifecycles, and complex interfaces with existing assets. By distinguishing between impediments that are common to both highways and buildings (transferable) and those unique to the highway context, this study advances BIM adoption research beyond sector-specific silos.

This study underscores the need for targeted industrial adaptations, such as developing highway-specific standards, improving interoperability, and tailoring implementation strategies to the unique geospatial and operational demands of linear projects. The findings suggest that addressing impediments to BIM adoption in highway infrastructure requires a coordinated set of financial, technical, management, legal, and other relevant measures that are tailored to the linear, corridor-based nature of road projects. To mitigate the high upfront costs associated with civil BIM platforms (e.g., OpenRoads Designer, Civil 3D, and InfraWorks), highway authorities may adopt a phased implementation strategy aligned with project stages, prioritizing early-stage applications particularly terrain modeling, horizontal and vertical alignment design, and quantity take-off for earthwork and pavement. Development of highway-specific BIM standards, aligned with established frameworks such as IFC 4.3 (Infrastructure), LandXML, and linear referencing systems, can reduce adoption uncertainty, promote consistent representation of linear geometric elements, and form a foundation for improved interoperability. Building on this foundation, interoperability challenges can be alleviated through clearly defined data-exchange workflows, particularly when integrating BIM models with complementary systems like geographic information system (GIS) platforms, traffic models, and pavement or bridge management systems.

In parallel, fostering a BIM-supportive organizational culture, reinforced through appropriate policies and strong top management commitment is also essential to enable BIM adoption across all stages of road projects. The provision of technical resources, including dedicated civil BIM specialists and tailored training programs, can help address knowledge gaps, reduce resistance to transitioning from traditional practices, and ease the learning curve associated with BIM. Finally, clarifying legal considerations related to data ownership, responsibilities for BIM model updates, and model handover at key milestones in the infrastructure lifecycle can also help improve collaboration among highway stakeholders. While the foregoing measures provide a broad strategic direction, further research is required to translate them into context-specific solutions for individual regions or highway authorities.

6. Conclusion and limitations

This study was aimed at identifying the critical factors affecting BIM adoption in highway infrastructure, finding the causal relationships among these factors, and subsequently modelling the causal relationships using a Systems Thinking approach to examine and understand complex interrelationships of these factors.

Thirteen critical factors spanning financial, technical, management, environment, and legal domains were identified, and nineteen causal relationships among these factors were uncovered. *Resistance in shifting from traditional working practices, tools, and processes to BIM-based collaboration*, and the *steep learning curve* have maximum causal relationships with other factors. The modelling of causal relationships evinced the presence of seven causal loops providing a novel insight into the systemic complexity.

It is important to acknowledge a few limitations. First, the analysis of temporal behavior of the complex system created by interaction of impeding factors was not covered in this study. Therefore, this study may be furthered through application of system dynamics modelling for exploring the temporal behavior of the system created by interactions and interrelationships of the factors. Second, given the swift pace and quantum of publication of scholarly studies in today’s digital world, the impeding factors identified herein may not be exhaustive and future studies may encompass any factor not covered herein. The factor categorization may accordingly be susceptible to change. Third, a further study entailing industry insights from a wider range of regions may also be considered. Fourth, it is worth noting that the international survey covered seven countries with varying levels of BIM maturity, cultural contexts, and national policies, which may limit the generalizability of the findings. Although the survey responses showed good reliability and internal consistency (Cronbach’s $\alpha = 0.830$), the results should be interpreted as broadly indicative rather than specific to any country. Further research is recommended within individual national contexts.

By integrating literature and empirical insights, this study offers both practical guidance for industry practitioners and theoretical understanding of BIM adoption dynamics, effectively bridging knowledge from vertical construction to linear infrastructure projects. Despite certain limitations, this study makes a significant contribution by bridging a critical research gap and providing valuable insights into the complex system of factors impeding BIM adoption in highway infrastructure projects.

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