

Article

BIM Uses for Mitigating Deficiencies in Road Scheduling Planning

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Abstract: Efficient scheduling is essential for successful and sustainable road construction projects. However, conventional planning approaches often lack adaptability, visualization, and integration with modern technologies, leading to schedule deficiencies and cost overruns. Therefore, this paper studies the influence of BIM uses in mitigating planning deficiencies in road construction scheduling. A four-stage research method was employed: (1) identification of BIM uses relevant to road projects, (2) determination of principal causes contributing to scheduling deficiencies, (3) cross-impact analysis to quantify BIM's influence on these deficiencies, and (4) expert interviews to characterize key BIM uses. Results highlight that 4D construction planning, quantity take-off and cost estimation, and traffic management planning positively impact road scheduling, reducing errors in work breakdown structures, resource allocation, and coordination between project stakeholders. BIM streamlines communication, supports proactive risk management, and enables real-time schedule adjustments by providing an integrated digital environment. This research shows the advantages of applying BIM in road construction to improve project planning, curtail scheduling setbacks, and encourage adopting innovative practices. The results provide information that planners can utilize to enhance the use of BIM in scheduling road construction projects.

Keywords: BIM; scheduling; construction planning; road infrastructure; deficiencies; cross impact matrix



Academic Editors: Larysa Neduzha and Iryna Bondarenko

Received: 31 January 2025

Revised: 9 March 2025

Accepted: 18 March 2025

Published: 19 March 2025

Citation: Castañeda, K.; Sánchez, O.; Peña, C.A.; Herrera, R.F.; Mejía, G. BIM Uses for Mitigating Deficiencies in Road Scheduling Planning.

Sustainability **2025**, *17*, 2729. <https://doi.org/10.3390/su17062729>

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1. Introduction

Road infrastructure is essential for the development and progress of any country [1]. However, this industry faces several obstacles, such as managing limited resources, meeting tight deadlines, and dealing with environmental and social impacts. Planning the road construction schedules is crucial to ensuring these projects' efficient and timely completion [2]. However, the methods for preparing such schedules face significant challenges, compromising accuracy and efficiency [3]. Furthermore, the growing need for sustainable road networks has prompted the industry to seek innovative procedures to transform this field [4]. The process's complexity is compounded by the coordination of various teams and tasks, uncertainty in the availability of materials, and variable weather conditions, among

others [5]. Considering these challenges, it is essential to implement methodologies and technologies that support the scheduling planning process and ensure the timely delivery of road projects while meeting budget, quality, and sustainability goals [6].

Scheduling road projects involves various traditional methods that depend on the project's complexity, available resources, and specific characteristics of each construction site. The most common methods include Gantt charts for visual planning, the Critical Path Method (CPM), and the Project Evaluation and Review Method (PERT) for time management [7–9]. These methods are essential in project management as they provide visibility of activities, optimize resources, and help identify the critical path. However, traditional approaches have limitations like the need for constant updates due to changes in requirements, their rigidity, which makes them less adaptable for dynamic projects, and lack of integration with 3D models, which can limit the visualization of the physical development of the project and make it challenging to identify potential problems during construction [9]. Therefore, traditional methods require technological and methodological adaptations to overcome limitations and maximize their usefulness in project management.

Technological advancements, such as augmented reality, geographic information systems, the Internet of Things, artificial intelligence, digital twins, 3D printing, and Building Information Modeling (BIM), are transforming the planning and management of construction projects [10]. Among these, BIM has shown remarkable benefits in complementing traditional scheduling methods in construction projects. BIM enables the creation of three-dimensional digital models of a project's physical and functional characteristics, offering a detailed visualization of the construction process before its commencement [11]. This significantly improves planning and schedule management by integrating time and cost data with the 3D model, providing real-time construction simulations and work sequence analysis [12]. Visualizing the project's development over time helps identify potential conflicts, cost overruns, or delays before they occur, improving decision-making and coordination between teams. Furthermore, BIM can support resource optimization and risk management by providing a deeper understanding of the project, facilitating more accurate and efficient planning [13].

Research in the construction sector's adoption of BIM for schedule planning has made significant progress [14], particularly in the field of buildings. Predictive models based on BIM have been developed to enable more integrated and collaborative project management, leading to more informed and efficient decision-making [15]. These studies have utilized advanced technologies such as genetic algorithms and multi-objective optimization systems to address scheduling challenges and optimize the balance between time and cost [16,17]. Implementing these models has improved the accuracy and efficiency of schedule generation, with several case studies demonstrating reduced planning time and improved cost management. Additionally, hybrid systems that integrate BIM with multi-objective-based techniques (MOFBI) and multi-criteria decision-making (MCDM) to balance resources in project scheduling have been explored, showing results with uniform distributions of solutions [18]. Other studies highlight using BIM to facilitate communication and collaboration, implement decision support systems, and improve the accuracy of cost and schedule estimates. Further research demonstrates the effectiveness of BIM in coding and breaking down construction activities, managing progress through three-dimensional and PDCA models, and automating the sequence of construction activities [19]. This has led to reduced planning times and improved accuracy. These studies highlight how BIM can significantly contribute to solving construction project management challenges by optimizing schedule, cost, and collaboration between participants.

Despite significant progress in schedule planning in the construction industry, notable challenges remain, such as project delays and cost overruns [20–22]. These challenges are

mainly related to the deficiencies observed during the planning phase of road projects, where managing a vast amount of information to create work breakdown structures is critical to planning and controlling the construction process effectively. Several shortcomings have been identified that directly impact schedules, including those related to the quantification of materials, integration with traffic management plans, overestimation of equipment and personnel productivity, and problems in assigning precedence relationships, among others [23]. BIM has been proven to offer considerable benefits in schedule management, highlighting its ability to mitigate many deficiencies in road project planning [24,25]. Despite this, the adoption of BIM in this sector is still limited, underscoring the need for focused research into how this technology could mitigate various factors that negatively affect schedules.

The integration of emerging technologies in the planning of road construction schedules has been little explored. This presents an opportunity for further research to adapt and expand advanced technologies to address the unique challenges involved in road infrastructure construction. BIM can be used to plan and manage schedules and has the potential to help mitigate some of the issues that influence the planning of construction schedules for road projects [10,11,23]. Therefore, this study aims to (1) estimate the influence of using BIM to mitigate road project scheduling deficiencies and (2) characterize the BIM uses required to mitigate road project scheduling deficiencies. Thus, the development of this research provides an understanding of effective BIM integration and how it can lead to significant improvements in schedule planning, directly contributing to schedule deficiencies that affect road construction. The results provide a valuable perspective for improving road infrastructure while highlighting the need to adopt innovative practices in project planning and execution.

The innovation of this study lies in the systematic methodological approach that directly connects specific deficiencies in road schedule planning with the most suitable use of BIM to address those deficiencies. Unlike previous research, which has primarily focused on buildings or partial scheduling methods, this study explores the use of BIM in road infrastructure. Using a cross-impact matrix, it quantifies how each BIM use contributes to alleviating the identified planning deficiencies. Additionally, semi-structured interviews are conducted to complement the quantitative analysis and better understand the practical implementation of these BIM uses in real-world contexts. This combination of methods (expert questionnaires, assessments of deficiencies in road construction projects, and qualitative interviews) creates a framework that researchers could adopt in other contexts. It identifies the most impactful BIM uses and provides concrete guidelines for improving scheduling accuracy and efficiency in road projects. Therefore, this study contributes to the field of civil engineering by providing empirical evidence and practical strategies for enhancing road construction planning through BIM adoption.

2. Literature Review

BIM implementation in construction projects has remarkably improved schedule planning [11,12,24]. Through BIM, the creation of detailed digital replicas of projects is facilitated, allowing the execution of simulations of the construction process before the physical start of construction. This anticipation capability substantially improves decision-making processes by enabling the analysis and comparison of alternative construction procedures [14]. In this way, project managers can select the option that maximizes efficiency and profit based on a thorough and detailed analysis facilitated by BIM [26]. The benefits of BIM in planning construction project schedules have led to several studies in the field. Nguyen et al. [18] developed a hybrid system that integrates BIM, multi-objective forensics (MOFBI), and multi-criteria decision-making (MCDM) to facilitate resource balanc-

ing in project scheduling. To demonstrate the efficiency and effectiveness of the proposed framework, they applied it to three building project scheduling problems. The study found that the framework can generate result curves with highly uniform resource distribution of solutions and provide visual analysis to aid decision-making. Guo et al. [27] have created a system for coding and breaking down construction activities, which can be used for automated scheduling with BIM implementation. The system helps calculate each construction activity's duration, allowing for the automatic generation of component-level schedules for the most commonly used hybrid concrete structures in building projects. This provides a time sequence for construction simulation and automation for intelligent construction equipment.

Rehman et al. [28] conducted a literature review to investigate the main factors that generate delays in construction projects and how BIM can help address these issues. They supplemented their research with primary data collection and a case study to evaluate the effectiveness of the aspects studied. The authors concluded that BIM substantially impacts construction projects by providing an effective solution for schedule management and mitigating delay risks. In schedule control, Zhang et al. [19] presented a study to improve the use of technology in engineering projects by focusing on construction progress management. They used a parametric modeling technique to create a three-dimensional BIM model, which was integrated into the Glodon BIM5D platform to develop a four-dimensional model. The PDCA (plan-implement-check-act) cycle theory was then applied to the project. Through a case study, the proposed methodology was tested, and it was found that integrating BIM and PDCA clarified schedule control objectives and optimized the management process. This resulted in a 60% reduction in scheduled simulations and a 3.5% advancement in the construction period. Roa'a et al. [15] examined the valuable contributions of project management in managing the cost and schedule of construction projects by providing higher levels of precision and reliability. Online surveys and interviews were implemented to determine the importance of BIM technology in managing the cost and schedule of construction projects. A study case of a building is used to compare in terms of accuracy, effort, and quantity budgeting between manual results and REVIT software (<https://www.autodesk.com/products/revit/overview>, accessed on 30 January 2025) estimates. The findings indicate that applying project management theories significantly reduces budget, time, and effort in construction projects and is essential to prevent financial losses and problems with cost overruns or delays. They also show that using modern methods such as BIM improves the accuracy of cost and schedule estimates, helping to avoid errors.

Singh et al. [17] proposed a method to automate the installation of pipes and optimize the schedule using 4D BIM technology. The technique extracts information from 3D models and facilitates time planning. The method establishes specific rules for automatically matching piping components with installation activities and uses constraint analysis with sequential rules to coordinate piping systems efficiently. A case study was conducted, which demonstrated that this approach could generate optimal installation sequences and schedules, reducing planning time by 96% to 97% and significantly improving accuracy compared to traditional methods. ElMenshawey and Marzouk [16] have developed a model that automatically creates schedules for construction projects using BIM. The model primarily focuses on solving the time-cost dilemma by providing user-variable scenarios. The model exports quantities from BIM and generates construction activities and their durations, applying logical sequences to connect them. The study uses the NSGA-II genetic algorithm for multi-objective optimization, aiming to balance project duration and costs by selecting the most appropriate scenario and exporting it to Primavera. This approach allows the schedule to be adjusted based on different performance parameters, such as the number

of crews or construction methods, offering various solutions for different combinations of duration and cost.

Furthermore, the implementation of BIM in road projects has developments that enable 3D modeling combined with time and cost analysis [29–32]. By integrating new technologies such as UAV equipment, LIDAR, and remote sensing, it has been possible to obtain models of road projects for monitoring and project management [33–36]. However, there are challenges to implementing BIM in highway projects, where researchers report studies about improving interoperability between different cost and schedule software or avoiding data loss when using data interchange formats [37,38]. The development of BIM tools for highways is lower with respect to buildings. Therefore, BIM adoption on highways is limited [39–41]. Significant progress has been made in generating new entities and property sets for roadway elements in the Industry Foundation Classes (IFC) standard [42–46]. Studies have developed methodologies and tools for BIM integration and scheduling, but they need to be adopted at the industrial level to improve project management [47–51]. Recent studies have focused on machine learning that allows the integration of computer data analysis for generating or evaluating automated models [52–56]. This enables the integration of BIM models and artificial intelligence (AI), finding recent applications for the different stages of a construction project life cycle [57–61]. Similarly, research related to BIM has been developed for road infrastructure projects [62,63]. Although there has been progress in the use of BIM in construction schedule planning, most studies have only focused on building projects. This lack of attention to BIM in road project planning highlights a research gap. It is essential to assess the potential of BIM to improve schedule planning in road infrastructure projects. Additionally, there is a weakness in studies investigating how BIM can help mitigate factors that adversely affect construction schedules. This observation emphasizes the need for more targeted and in-depth research in these critical areas to expand understandings of BIM and its functional application in the construction industry.

3. Research Method

This study examined how BIM uses can help reduce deficiencies in road schedule planning. The research method used four steps (See Figure 1). First, a questionnaire was created to identify the main BIM uses that can mitigate schedule planning problems. It was sent to construction planning experts knowledgeable in BIM technology and road engineering. Second, the critical deficiencies affecting road construction scheduling were selected from previous research [64]. Third, a second questionnaire was designed to estimate the effect of BIM uses on the improvement of the schedule planning deficiencies groups, according to the experience and knowledge of the professionals. Fourth, a cross-impact matrix was created to visualize and quantify the interactions between the different variables. This helped identify the BIM uses with the most relevant potential effect on mitigating specific schedule problems. Fifth, semi-structured meetings were conducted with professionals with expertise in road construction process planning and BIM. These interviews focused on obtaining information on how BIM helps mitigate the deficiencies that affect schedule planning. Finally, the results are reported in chapter four.

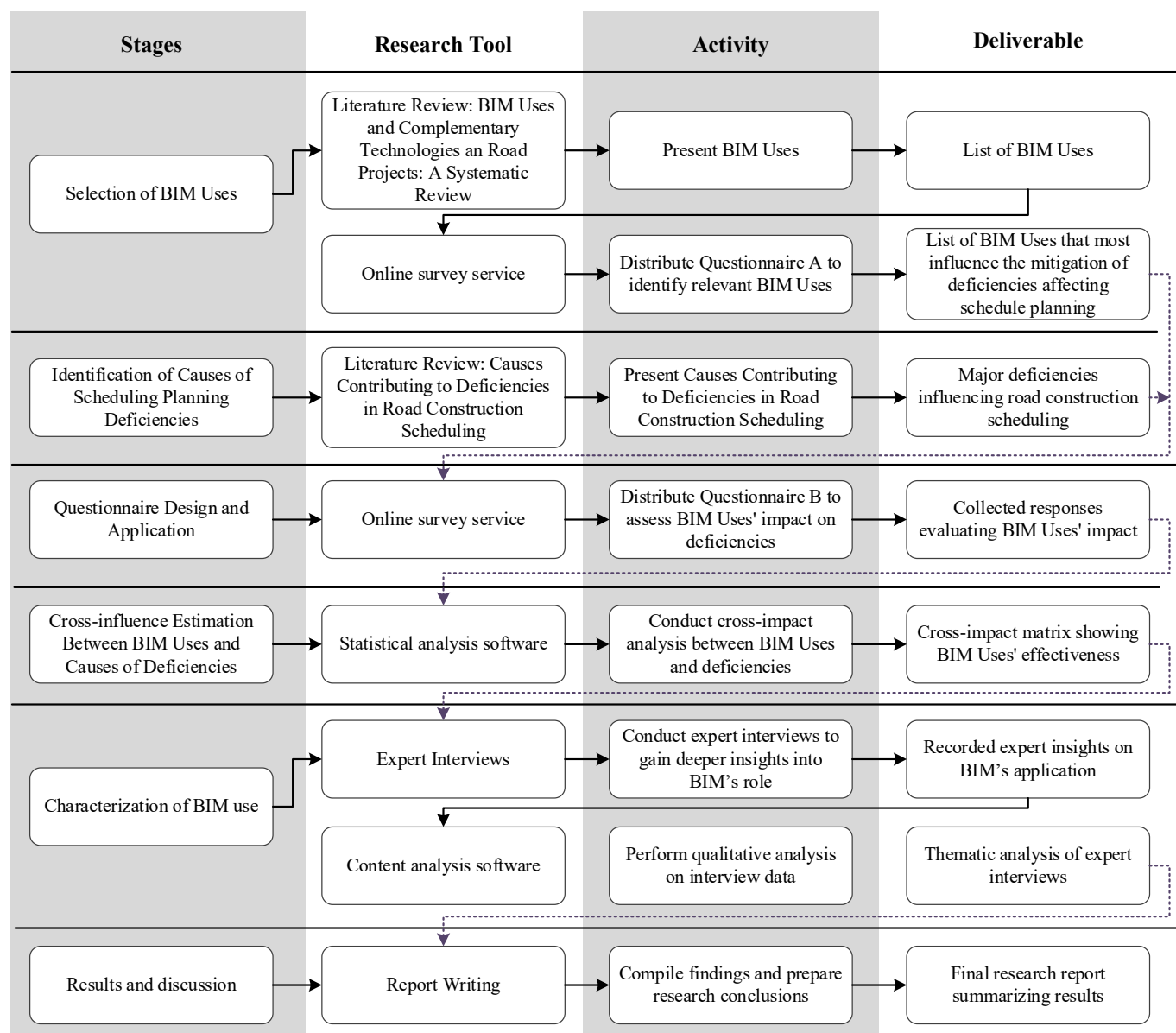


Figure 1. Methodological framework.

3.1. Selection of BIM Uses

This study is grounded in the work of Castañeda et al. [64], which presents a recent (2024) systematic review of BIM uses in road infrastructure projects, offering a comprehensive and up-to-date foundation for the research. From the 39 BIM uses identified by Castañeda et al. [64], (see Table 1), it was proposed to conduct a questionnaire to detect the main BIM uses aligned to the mitigation of shortcomings in planning construction processes of road projects (see Supplementary Material S1). The questionnaire gathered opinions from an expert group with experience in road project construction process planning and BIM adoption. The questionnaire consisted of two parts. The first part was oriented to collect information on five categorical variables: (1) profession, (2) academic degree, (3) country of experience, (4) role in the construction sector, and (5) years of experience. The second part identifies the BIM uses aligned with mitigating deficiencies in planning construction processes for roadway projects. Each BIM use was evaluated using a scale with three options for ranking: (1) Yes = 2, in case the BIM use contributes to schedule deficiency mitigation; (2) Indirectly = 1, in case the BIM use indirectly contributes to schedule deficiency mitigation; and (3) No = 0, in case the BIM use does not contribute

to schedule deficiency mitigation. The questionnaire was hosted on the Survey Monkey platform, facilitating its distribution to practitioners through a URL link.

Table 1. BIM uses for road projects.

Category	BIM Uses
Road design	3D Existing Conditions Modeling, Alignment Optimization, Clash Analysis, Design and Evaluation of Roadside Facilities, Design Documentation, Design Review, Geometric Design, Modularization for Prefabrication.
Traffic analysis	Traffic Management Plan, Traffic Monitoring, and Traffic Analysis in Design.
Soil aspects	Analyzing Earthmoving Operations, Geological and Geotechnical Analysis.
Road safety	Construction Safety Analysis, Driving Simulation, Road Lighting Analysis, Road Safety Analysis.
Environmental issues	Environmental Impact, Solar Radiation Analysis, Sustainability Analysis.
Other engineering analysis	Drainage Analysis, Pavement Analysis, Road Acoustic Analysis, Structural Analysis, Transmission Lines Analysis, Underground Utility Analysis, Vulnerability Analysis.
Construction planning and analysis	Equipment and Material Planning, Space Use Planning on the Site, Workforce/Labor Planning and Training, 4D Construction Process Impact Analysis, 4D Construction Planning, Constructability Analysis, Maintenance Plan, and Schedule Estimation.
Cost analysis	5D Cost Analysis, Quantity Take-Off, and Cost Estimation.
Construction monitoring and control	4D and 5D as-built—as Planned Comparison and Monitoring, Tracking Onsite Construction Progress.

A preliminary survey was sent to five professionals with over five years of experience in road projects and BIM adoption. The objective was to evaluate the clarity of the content. After analyzing the answers and observations obtained, the authors adjusted the questionnaire. A revised version was submitted to the same group of experts for a final validation process. This concluded with the approval of the questionnaire's final version for use in the study. Questionnaire A was sent to 20 professionals with experience in road construction process planning and BIM adoption in the architecture, engineering, and construction (AEC) industry (see Supplementary Material S1). The purpose of Questionnaire A was to identify the most relevant BIM uses for mitigating scheduling deficiencies in road construction projects by gathering expert evaluations and calculating a Relative Influence Index (RII) to rank the 39 BIM uses based on their perceived impact. Out of the 20 responses, 12 were analyzed for the final sample (see Appendix A).

The data collected was used to conduct a Relative Influence Index (RII) analysis to identify BIM uses that have the most impact on mitigating road infrastructure project scheduling deficiencies. This analysis was centered on a questionnaire by sector professionals, who assigned weights to each of the three classification options allowed for each BIM use. Thus, the RII was calculated using Equation (1).

$$RII = \left(\frac{\sum_{i=1}^N w_i}{N * w_{max}} \right) \quad (1)$$

where w_i is the classification weights, assigned by the evaluator i ; N is the total number of valid questionnaires ($N = 12$); and w_{max} is the maximum possible weights for classification ($w_{max} = 2$), based on the evaluation scale in the questionnaire (0, 1, 2).

The BIM uses were evaluated based on their RII, sorted from highest to lowest. This helped identify the uses that have the most impact in mitigating the causes of deficiencies in schedule planning. After analyzing the results, seven BIM uses were selected with the most significant influence in mitigating such deficiencies.

3.2. Identification of Causes of Scheduling Planning Deficiencies

Identifying deficiencies in road construction scheduling was based on a systematic literature review to consolidate the causes most frequently identified in previous studies. The study by Castañeda et al. [65] served as a key reference, as it synthesized findings from multiple sources and structured them into a comprehensive set of 34 deficiencies. Thus, the selected deficiencies came from a single study and represented a broader consensus within the existing literature. In addition, Castañeda et al. [65] applied exploratory factor analysis to classify these deficiencies into seven components (see Table 2), which were subsequently used to assess the impact of the selected BIM uses in the first phase of the analysis. These seven components were used to determine the impact of each of the seven BIM uses selected in the first stage of the analysis.

Table 2. Causes and components contributing to schedule planning deficiencies.

Principal Components	Causes Contributing to Deficiencies in the Scheduling
Project Preparation and Contextual Conditions	Inadequate planning of the articulation with neighboring areas Inadequate exploration of existing site conditions Inadequate estimation of permit acquisition durations Deficient project location Poor understanding of the project by the planner Lack of political/social considerations in planning Deficient estimation of material supply (stocks)
	Inadequate selection of construction methods
Scope and Schedule Planning	Failures in the definition of successor and predecessor relationships between activities Failures in the configuration of the work schedule (working days, holidays, working hours, seasons of the year) Omission or deficiency in the definition of work packages (WBS) Inadequacy of planning software adopted
	Omission of road markings in planning Poor zoning of the construction process based on traffic conditions Failures in on-site traffic estimation Poor planning of machinery routes
Traffic Management Planning	Poor estimation of workforce performance Deficient coordination with public utilities (water, sanitary, electrical, and other surface or subway networks) High complex access to the project area
Project Complexity	Lack of planning of storage and parking sites Deficient estimation of material quantities Poor estimation of workforce quantity
Resource Estimation	Inadequate estimation of construction document approval times Poor identification of project stakeholders Request for project start time extensions (applies in cases of rescheduling requests)
Considering External Factors	Lack of verification during the schedule preparation Inadequate estimation and consideration of waiting times (setting time or other waiting times between activities) High complexity of construction work
Planning Accuracy and Operational Complexity	

3.3. Questionnaire Design and Application

The quantitative estimation of the influence of BIM uses in mitigating deficiencies in road schedule planning was carried out for the seven main components of deficiencies in road schedule planning, which were identified in the study by Castañeda et al. [65], and the seven BIM uses selected in the first stage from the RII. A questionnaire was created to collect the data, which was carried out by gathering opinions from a group of experts with experience in road construction planning and BIM implementation (see Supplementary Material S2). The questionnaire consisted of two parts. The first part was oriented to collect information on five categorical variables: (1) profession, (2) academic degree, (3) country of experience, (4) role in the construction sector, and (5) years of experience. The second part is centered on collecting the impact of BIM uses on each of the seven significant causes affecting schedule planning on road projects. Each effect of BIM uses on the components was determined using a five-point Likert-type scale, where 1 = very low, 3 = medium, and 5 = very high. Questionnaire B was conducted on the Survey Monkey platform, facilitating its distribution to practitioners via a URL link.

The same group of professionals used in the first validation of Section 3.1 was used again to validate the draft version of the questionnaire. The purpose of this validation was to assess the clarity of the content. After analyzing the obtained answers and comments, the authors adjusted the questionnaire. This process was iterative and concluded with the approval of the questionnaire's final version for use in the study. The final version of Questionnaire B was then sent to 42 architecture, engineering, and construction (AEC) professionals with experience in road construction planning and BIM implementation (see Supplementary Material S2). The purpose of Questionnaire B was to quantitatively assess the influence of the BIM uses (selected in Section 3.1) on mitigating seven key components of scheduling deficiencies in road construction projects (presented in Section 3.2) by collecting expert evaluations through a five-point Likert scale and applying a cross-impact analysis to identify the main BIM uses. After a thorough review, 12 incomplete responses were discarded, and 30 were included in the final analysis (see Appendix B).

To ensure the validity of the research instrument, a Cronbach's alpha analysis was conducted to assess the internal consistency of the responses obtained in the impact section of the questionnaire (see Equation (2)). In quantitative research utilizing questionnaires as a data collection tool, Cronbach's alpha serves as a key metric for evaluating the reliability of measurement scales. This coefficient ranges from 0 to 1, where $\alpha \geq 0.9$ indicates excellent internal consistency, $0.8 \leq \alpha < 0.9$ is considered good, $0.7 \leq \alpha < 0.8$ is acceptable, $0.6 \leq \alpha < 0.7$ is questionable, $0.5 \leq \alpha < 0.6$ is poor, and $\alpha < 0.5$ is deemed unacceptable. The coefficient is computed using the following equation:

$$\alpha = \frac{K}{K-1} \left(1 - \frac{\sum_{i=1}^k S_i}{S_t} \right) \quad (2)$$

where K is the number of combinations between causes of deficiencies of scheduling planning and BIM uses ($K = 49$), S_i is the variance of the scores assigned to the influence of each combination, and S_t is the total variance of the influence.

Cronbach's alpha analysis for responses concerning the impact of BIM uses on the identified causes yielded a coefficient of 0.92, indicating excellent internal reliability. This result suggests a high level of consistency in responses, reinforcing the validity of the research instrument employed in this study.

3.4. Cross-Influence Estimation Between BIM Uses and Causes of Deficiencies

After expert consultation, a cross-impact analysis was conducted to evaluate the influence of BIM uses in mitigating deficiencies in road construction scheduling. This

method systematically quantifies the effect of BIM uses on scheduling deficiencies, allowing for a structured evaluation of interactions between variables, highlighting key cause–effect relationships, and guiding decision-making based on their potential impact. Three main steps were identified for the analysis. Firstly, the cross-impact matrix was structured, with seven main components of causes of deficiencies in road construction scheduling arranged in the rows, and selected BIM uses placed in the columns. Secondly, the collected survey data were used to calculate the arithmetic mean (see Equation (3)) and a measure of central tendency such as the median (see Equation (4)). This measure of central tendency provides a better representation of the perceived “typical impact” without being distorted by extremely low or high responses. It also provides a clear picture of the trend or tilt of respondents’ overall opinions. Thus, a matrix of seven columns and seven rows was prepared to analyze the impact of BIM uses and deficiencies in schedule planning for road projects.

$$\bar{X} = \frac{1}{n} \times \sum_{i=1}^n x_i = \left(\frac{x_1 + x_2 + \dots + x_n}{n} \right) \quad (3)$$

where n is the total number of valid questionnaires ($n = 30$); and x_i is the score assigned by the experts consulted (very low = 1 to very high = 5).

$$M_e = \frac{x_{\frac{n}{2}} + x_{\frac{n}{2}+1}}{2} \quad (4)$$

where n is the total number of valid questionnaires ($n = 30$), $x_{\frac{n}{2}}$ is the score found at position $\frac{n}{2}$, and $x_{\frac{n}{2}+1}$ is the score found at position $\frac{n}{2} + 1$.

From the cross-impact analysis scores, a color scale was used to visually identify the influence of interactions between BIM uses and causes of deficiencies. The matrix obtained helped to identify its application limitations and propose solutions oriented towards best practices based on the experiences, perceptions, and opinions of those with deep knowledge in the field.

Therefore, the selection of the main BIM uses followed a two-stage process combining expert evaluation and cross-impact analysis. First, an initial list of 39 BIM uses, identified by Castañeda et al. [30], was evaluated through a questionnaire distributed to 20 professionals with experience in road project planning and BIM adoption, of which 12 responses were validated and analyzed. Each professional assessed the contribution of each BIM use to mitigate scheduling deficiencies using a three-point scale (2 = contributes directly, 1 = contributes indirectly, 0 = does not contribute). Using these responses, a Relative Influence Index (RII) was calculated to rank the BIM uses from highest to lowest relevance. The BIM uses were identified based on their RII scores (top five rank). In the second stage, these BIM uses were further evaluated through a cross-impact analysis, conducted using a second questionnaire distributed to 42 professionals, with 30 valid responses included in the analysis. These professionals rated the influence of each BIM use on the mitigation of seven key components of scheduling deficiencies identified in previous research by Castañeda et al. [31], using a five-point Likert scale (1 = very low to 5 = very high). From these ratings, both the arithmetic mean and the median were calculated, forming a cross-impact matrix that visually illustrates the relative influence of each BIM use on each deficiency component. Based on this matrix, the three main BIM uses were selected.

3.5. Characterization of BIM Use

An interview was conducted to synthesize the main BIM uses (selected in the previous stage) in road projects to manage the lack of uses in the scheduling planning of construction processes. The researchers conducted semi-structured interviews with eight experts with more than five years of experience in road project planning, management, and

BIM adoption. The eight experts were interviewed and selected based on their extensive experience in the construction of road infrastructure projects and specialized knowledge of BIM adoption in road infrastructure projects (see Appendix C). The purpose of the interviews was to gain deeper insights into the practical application of BIM in addressing the root causes of scheduling deficiencies in construction projects. The semi-structured interview had three parts, which are detailed in Supplementary Material S3. Firstly, informed consent was obtained from the experts to conduct and record the interview, and their training and experience were assessed. Secondly, the experts gave a presentation to contextualize the research stages that led to the interview. Thirdly, the experts were asked how each of the main BIM uses can mitigate the causes of shortcomings in the scheduling of construction procedures. Each session lasted between 15 and 30 min and aimed to collect information about existing processes, implementation deficiencies, opportunities for improvement, and required resources, among others. These interviews provided valuable information centered on the professionals' experience and in-depth comprehension of the field of interest, forming the basis for describing BIM uses required to mitigate road project scheduling deficiencies.

Finally, a qualitative analysis was conducted based on the transcripts of the interview recordings. This type of analysis began with a detailed reading of the responses to identify common themes, patterns, and trends. In addition, it was complemented with the use of NVIVO software (<https://lumivero.com/products/nvivo/>, accessed on 30 January 2025), which allowed for the categorizing of responses, identification of patterns, drawing of key conclusions, and understanding of how BIM can contribute to mitigating deficiencies in the planning of construction schedules. Therefore, the analysis was structured in six main steps: (1) transcribing the recordings, (2) cleaning up the text, (3) breaking the text into smaller units, (4) eliminating conjunctions, (5) categorizing the text, and (6) content analysis. This approach sought to capture the complexity and multidimensionality of BIM implementation in road infrastructure construction directly from the professionals' perspective. In addition, the combination of qualitative analysis with NVIVO allowed a more detailed interpretation of the information collected, thus, facilitating the development of practical solutions to the challenges identified.

4. Results and Discussion

4.1. BIM Uses to Mitigate Schedule Deficiencies

Table 3 presents the main BIM uses that address issues with schedule planning based on Questionnaire A responses of 12 experts in road infrastructure construction. An analysis was conducted using a Relative Influence Index (RII) to establish a ranking of the BIM uses that professionals identified as having the most significant influence in mitigating the causes of deficiencies. The seven main BIM uses that contribute to the mitigation of planning deficiencies are the following: (1) Quantity Take-Off and Cost Estimation: This has the highest contribution in relationships of cost and time estimation and its variation during the project lifecycle, allowing the determination of possible cost and schedule overruns due to changes in the project [66]. (2) Equipment and Material Planning: This refers to project planning, availability, and supply of equipment and materials, which has been identified as one of the most critical factors in previous studies related to BIM [67]. (3) 4D Construction Planning: Integrating time data into a 3D BIM model is essential, enabling risk reduction and resource optimization [68]. (4) Schedule Estimation: Integrating the time dimension in BIM facilitates change management and project version control [69]. (5) Traffic Management Plan: This is relevant in road projects as is associated with coordination, risk management, construction processes, and user interaction [70]. (6) Space Use Planning on the Site: BIM allows visualization, analysis, and simulation of conditions and scenarios that

may occur before construction, coordinating the design with equipment and personnel [71].
 (7) 5D Cost Analysis: This improves the project’s financial planning and contributes to decision-making throughout the life cycle [72].

Table 3. Relative influence index of BIM uses that contribute to mitigating road schedule deficiencies.

Id	BIM Use	RII	Rank
U ₃₇	Quantity Take-Off and Cost Estimation	1.00	1
U ₂₈	Equipment and Material Planning	0.96	2
U ₃₂	4D Construction Planning	0.92	3
U ₃₅	Schedule Estimation	0.92	3
U ₉	Traffic Management Plan	0.79	5
U ₂₉	Space Use Planning on the Site	0.79	5
U ₃₆	5D Cost Analysis	0.79	5
U ₃₀	Workforce/Labor Planning and Training	0.75	8
U ₃₃	Constructability Analysis	0.75	8
U ₃₄	Maintenance Plan	0.75	8
U ₁	3D Existing Conditions Modeling	0.71	11
U ₃	Clash Analysis	0.71	11
U ₈	Modularisation for Prefabrication	0.71	11
U ₃₁	4D Construction Process Impact Analysis	0.71	11
U ₃₉	Tracking Onsite Construction Progress	0.71	11
U ₁₂	Analyzing Earthmoving Operations	0.67	16
U ₃₈	4D and 5D as-built—as Planned Comparison and Monitoring	0.63	17
U ₄	Design and Evaluation of Roadside Facilities	0.58	18
U ₅	Design Documentation	0.58	18
U ₁₄	Construction Safety Analysis	0.58	18
U ₁₅	Driving Simulation	0.58	18
U ₁₇	Road Safety Analysis	0.58	18
U ₂₆	Underground Utility Analysis	0.58	18

4.2. Impact Between BIM Uses and Schedule Planning Deficiencies

Table 4 displays the cross-impact matrix, where the columns present the top seven BIM uses that help mitigate schedule planning issues identified in Section 4.1. The rows contain the main components and related deficiencies in planning the road construction schedule. Based on expert opinion, a color-coding scheme has been implemented to determine the most influential uses. Dark green represents very high values; light green corresponds to high, yellow to medium, orange to low, and red to very low. The values obtained, as mentioned in Section 3.4, are the mean and median for each cross. According to Questionnaire B responses conducted with experts in road infrastructure construction, a new ranking was established based on the total score obtained. It was determined that the top three most influential BIM uses in mitigating the causes of deficiencies analyzed are (1) 4D Construction Planning, (2) Traffic Management Plan, and (3) Schedule Estimation, out of the seven analyzed. Similarly, the components most relevant by BIM for their mitigation were organized, and it was observed that the components of the causes of deficiencies most influenced by BIM for their mitigation, according to the total score, are (1) Scope and Schedule Planning, (2) Resource Estimation, and (3) Traffic Management Planning.

Table 4. The cross-impact matrix between BIM uses and causes of deficiency in road schedule planning.

Id	Main Components	BIM Uses X (Me)							Total Score	Rank
		4D Construction Planning	Traffic Management Plan	Schedule Estimation	Space Use Planning on the Site	Equipment and Material Planning	Quantity Take-Off and Cost Estimation	5D Cost Analysis		
C ₁	Scope and Schedule Planning	4.5 (5.0)	4.0 (4.0)	4.4 (5.0)	3.8 (4.0)	4.1 (4.0)	4.3 (5.0)	3.8 (4.0)	28.97	1
C ₂	Resource Estimation	4.2 (4.0)	3.9 (4.0)	3.9 (4.0)	3.9 (4.0)	4.0 (4.5)	4.4 (5)	3.4 (3.5)	27.73	2
C ₃	Traffic Management Planning	4.3 (5.0)	4.4 (5.0)	3.9 (4.0)	4.1 (4.0)	4.0 (4.0)	3.5 (3.5)	3.1 (3.0)	27.47	3
C ₄	Planning Accuracy and Operational Complexity	4.2 (4.5)	4.0 (4.0)	4.1 (4.0)	3.7 (4.0)	3.8 (4.0)	3.9 (4.0)	3.5 (3.0)	27.27	4
C ₅	Project Complexity	4.0 (4.0)	3.4 (3.5)	3.2 (3.0)	3.7 (4.0)	3.4 (3.0)	3.4 (3.0)	3.3 (3.00)	24.53	5
C ₆	Considering External Factors	3.5 (3.5)	3.45 (3.5)	3.7 (3.0)	3.1 (3.0)	3.0 (3.0)	2.8 (3.0)	3.1 (3.0)	22.7	6
C ₇	Project Preparation and Contextual Conditions	3.0 (3.0)	3.3 (3.0)	3.0 (3.0)	3.4 (3.0)	2.9 (3.0)	2.5 (2.0)	2.7 (3.0)	20.83	7
Total score X		27.77	26.73	26.17	25.8	25.23	24.9	22.9	179.5	
Rank		1	2	3	4	5	6	7		

Table 4 indicates that some BIM uses are more closely related to the main components of schedule deficiencies than others. Some BIM uses share a relationship with other uses, while others do not. BIM uses such as 4D Construction Planning, Traffic Management Planning, and Schedule Estimation have a high relationship with the first four main components: Scope and Schedule Planning, Resource Estimation, Traffic Management Planning, and Planning Accuracy and Operational Complexity. These BIM uses in the road domain are aligned with the corresponding deficiencies in planning. Previous studies have shown that BIM uses can mitigate scheduling deficiencies [73–75]. BIM could have a high impact on mitigating deficiencies such as a lack in the definition of work packages (WBS), failures in setting the work schedule, shortcomings defining successor and predecessor relationships between activities, lack of planning of storage and parking locations, and deficient zoning of the construction process according to traffic conditions.

The BIM Space Use Planning on the Site significantly influences mitigating deficiencies related to Traffic Management Planning, Resource Estimation, and Scope and Scheduling Planning. Therefore, some of the causes of deficiencies where the BIM use Space Use Planning on the Site shows high influence are poor planning of machinery routes, shortcomings in storage planning and parking sites, and inadequacy of planning software adopted. Previous research has shown that BIM adoption can provide valuable contributions in these aspects within the construction sector [76,77]. Similarly, this research confirms its applicability and relevance in road project planning. In addition, the adoption of advanced technologies for spatial analysis [78] has enhanced detailed data-driven road planning using tools such as a Geographic Information System (GIS) [79] and temporal elements by integrating spatial planning with BIM 4D [80,81]. This synergy between 4D BIM and other technologies effectively addresses several of the shortcomings in planning previously mentioned, demonstrating how BIM can complement and enrich the process. Although the use of BIM for site spatial planning does not stand out as having the highest impact

compared to other BIM uses discussed in the study, its significant association with key components positions it as a relevant element in improving the planning and execution of roadway projects.

Equipment and Material Planning has a moderate relationship with some significant components. The three components with which it is most closely related are Scope and Schedule Planning, Resource Estimating, and Traffic Management Planning. Some of the shortcomings associated with this use of BIM include failures to establish successor and predecessor relationships between activities and deficient estimation of material quantities. Although it has been proven in other studies [82,83] that the use of Equipment and Material Planning shows good performance and can cover the deficiencies generated by these components [84], Equipment and Material Planning using BIM still faces challenges. This may be one of the reasons why experts have shown a slight preference for other uses of BIM on road projects. Specifically, the BIM use of 4D Construction Planning has effectively mitigated scheduling and resource management deficiencies. It provides smoother integration and advanced visualization that allows potential problems to be anticipated and resolved before they become significant obstacles in the construction process. Therefore, while equipment and materials planning with BIM are beneficial, its impact is less pronounced than other uses of BIM in road construction planning.

The Quantity Take-Off and Cost Estimation are closely related to Scope and Scheduling Planning, Resource Estimation, Planning Accuracy, and Operational Complexity. Some issues associated with using BIM in this context include a lack of definition of work packages (WBS), deficient estimation of material quantities, and lack of verification during the schedule preparation. Previous research in the construction industry has shown a direct link between the use of BIM and these factors [85–87], and this study expands on those findings in the context of roadway projects. While specific components are highly correlated with material quantity planning and cost estimating using BIM, others have a moderate or low relationship with this use of BIM. This indicates that while material quantity and cost estimation are crucial to certain aspects of road planning and management, their impact may be more limited in other phases of the construction process. The Quantity Take-Off and Cost Estimation enhances the accuracy and efficiency of project planning, providing a solid foundation for informed decision-making. BIM's capacity to integrate data and visualize potential scenarios enables professionals to identify and rectify deficiencies before they significantly impact project progress. Therefore, despite some components showing a weaker relationship with the use of BIM, its application remains vital for the overall optimization of road construction planning.

The 5D Cost Analysis has a medium to low relationship with most of the components analyzed, except Scope and Schedule Planning, with which it has a high relationship. Some of the deficiencies associated with this use of BIM include shortcomings in configuring the work Schedule and Omission or failures in the definition of work packages (WBS). 5D Cost Analysis through BIM integrates costs into the dimensional model, providing a powerful tool for project financial management [88]. This integration has improved the alignment between schedule and budget planning [89], ensuring that planning decisions are informed by full cost considerations and applied to infrastructure projects [90,91]. The ability of 5D BIM to provide a detailed view of costs throughout the project life cycle facilitates more effective management of financial resources, contributing to risk mitigation and greater predictability in project execution. However, applying this use of BIM has proven to be more significant in road projects' construction and operation phases [92]. During these phases, 5D cost analysis allows for the continuous and accurate assessment of actual versus planned costs, providing critical data that can influence strategic decision-making and

operational process optimization. This ability to monitor and adjust costs in real time is crucial to keeping projects within budget and maximizing financial efficiency.

4.3. Practical Experiences of Using BIM in the Mitigation of Road Schedule Deficiencies

The analysis of interviews with eight AECO industry professionals experienced in using BIM for road infrastructure projects provided valuable information on how BIM can help address construction process schedule planning deficiencies. The focus was on understanding the practical experiences of these professionals and gaining insight into the strategies and methods used to resolve schedule planning shortcomings in the context of road infrastructure construction (see Supplementary Material S4).

4.3.1. Four-Dimensional Construction Planning

Based on insights from professionals, it is clear that using the 4D Construction Plan has significant potential to reduce errors in defining the relationships between project activities. BIM allows for visualizing activities in a timeline relative to their physical space, combining the project's 3D model with the construction schedule. This visualization makes it easier to identify and rectify errors in activity sequences before they impact actual construction. Additionally, the preview feature provided by 4D simulation helps ensure that all activities are planned based on logical and physical dependencies, thus, preventing construction delays and errors. One of the professionals explains that during a 4D simulation, it is possible to observe whether the animation of an asphalt binder appears before the animation of the granular layers. This type of visualization allows the detection of problems in the definition of precedence relationships, making it possible to correct them and adjust activities to ensure they are executed in the correct order. Additionally, improving the accuracy of the sequence of activities contributes to increased safety on the construction site. Another professional mentioned that with 4D simulation, one could foresee and visualize earth movements and other activities that may compromise the safety of personnel and equipment. This way, 4D planning optimizes project efficiency and ensures a safer working environment. This BIM use also provides a clear and detailed visualization of the schedule and the 3D model, improving communication and coordination for more efficient and effective project execution.

The detailed, time-dependent visualization of the work schedule, including specific dates and times, makes it possible to identify problems that may be overlooked in a traditional schedule, such as incorrectly scheduled activities on holidays or at inappropriate times. One interviewee mentioned that integrating the work schedule into the simulation allows planners to ensure that all activities are scheduled at appropriate times, considering labor and seasonal constraints. This could improve schedule accuracy, optimize resource allocation, and prevent additional costs associated with out-of-hours work or adverse weather conditions. Four-dimensional simulation enables planners to identify activities not included in the WBS early on. An interviewed professional explains, "If an important activity, such as the construction of abutments, is forgotten in the planning of a bridge construction process, it will become evident during the simulation because the simulation of the abutments will not be visible. This allows us to correct the error before it affects the project". This early detection capability is crucial to ensure that all necessary activities are executed as planned.

BIM offers an integrated platform compatible with various tools and data formats. One practitioner explains that "by linking data to the BIM model, planners can identify format incompatibilities or missing information, which may indicate inappropriate software selection. For instance, if schedule data does not integrate correctly with the 3D model, it could be due to format incompatibilities, suggesting that the wrong software has been

chosen". Early detection of these problems enables planners to switch software or adjust data exchange formats to ensure seamless integration. Four-dimensional planning also allows for assessing whether the chosen software meets the specific project requirements. One interviewed professional mentioned that "4D planning can determine whether the software is capable of effectively handling time and cost data and whether it is compatible with other software used in the project". Compatibility with standards such as IFC is crucial for realizing the exchange of information between different platforms and ensuring the accuracy and availability of all project data. One of the professionals stresses the importance of choosing software compatible with the project's needs and capable of handling 4D planning. They emphasize that selecting the right software is vital to the project's success. In a complex road infrastructure project, such as constructing a new road with bridges and tunnels, choosing planning software that handles geometry and construction schedules and integrates seamlessly with other cost and human resource management systems is crucial. Working with standard data formats could help identify compatibility issues and avoid inadequate software selection early on.

4.3.2. Quantity Take-Off and Cost Estimation

This BIM use accurately calculates the materials required for each project phase. Knowing these quantities makes it possible to plan the volumes of material that will need to be stored at the construction site. One practitioner explains that "if a project requires a significant amount of granular subbase, BIM can help determine the space needed to store this material before its use, ensuring that there is sufficient space designated for it and avoiding congestion on the site". Additionally, BIM's ability to integrate logistics planning with site scheduling could support planning when and where certain materials and equipment would be needed. This allows for efficient storage and parking space management, as materials can be delivered and stored just before use, minimizing unnecessary space occupation and reducing the risk of damage or loss of materials due to prolonged storage. Furthermore, this BIM use facilitates communication and coordination between project stakeholders. Another professional emphasizes that the detailed and centralized information in the BIM model can be shared with suppliers and contractors, allowing for more accurate planning of material deliveries and machinery usage. This includes identifying suitable sites for unloading materials and organizing parking vehicles and equipment spaces, especially in urban areas or projects with limited space. The detailed digital replications of a project with a high level of development (LOD) allow for accurate estimates, reflecting changes in the BIM model due to design modifications. This can address poor material estimates, reducing the risk of under- or over-estimates that may impact on the project budget and schedule. Integrating job scheduling with resource management through BIM enables optimal labor planning and allocation. Professionals believe that using BIM methodology for calculating quantities and costs could ensure resource availability for each project phase, improve team coordination, and streamline scenario simulations, among other benefits.

4.3.3. Traffic Management Plan

This BIM use helps mitigate the omission of roadway markings by supporting the creation of digital twins, which make it possible to include the affected intersections and routes. These virtual models can represent in detail the operation and traffic flow in a road project, thus, providing a virtual replica of the environment that could help foresee and plan the construction phases, including road markings. One of the interviewees states that "digital traffic simulation, supported by BIM, makes it possible to identify the need and location of road signs with high accuracy. By visualizing traffic in a virtual environment, engineers can determine what type of signs are needed, how many are required, and

where they should be placed to maintain traffic safety and flow". To address issues related to poor zoning, planners can integrate traffic flow simulation with the work of other specialties. This will help identify optimal work areas that minimize traffic obstruction. For example, suppose a construction phase requires closing a section of road. In that case, BIM simulation can demonstrate how this closure will affect traffic flow and enable planners to adjust zoning to minimize delays and congestion. By combining these simulations, a zoning plan can be created that reduces traffic disruptions and optimizes the use of space. Additionally, this BIM use allows for vehicle flow simulations calibrated with actual site data, which helps to improve the accuracy of these estimates. Planners can analyze critical parameters such as operating speed, queue lengths at traffic lights, and travel times. These analyses allow the virtual models to be adjusted to accurately reflect actual traffic conditions in the project area. By calibrating these models with data observed at the site, it is possible to predict with greater certainty how traffic will behave during the different phases of construction. This improves the planning of machine routing activities, which is critical to avoid interference with traffic and ensure efficient operation. Planners can simulate and visualize machinery routes within the construction environment, allowing them to identify potential traffic conflicts and optimize routes to minimize disruptions during project execution. According to professionals, a BIM simulation can show the best route for transporting heavy materials, minimize traffic impact, and avoid congested areas. Adjusting machinery routes based on changing traffic conditions and project needs could improve more efficient coordination and reduce delays and additional costs.

4.3.4. Schedule Estimation

This BIM use supports the mitigation of verification gaps during schedule development by providing an integrated and consistent platform for the planning and scheduling of road infrastructure projects. Because it allows for creating a digital replica of the project, which facilitates simulation analysis and continuous data integration, this ensures that time estimates are more realistic and reliable, reducing the risk of unexpected deviations. One practitioner posits, "In bridge construction, BIM can break down the project into specific tasks such as foundation, pier, and deck construction, assigning precise times to each activity". This level of detail and accuracy in planning allows the schedule to be continuously verified and adjusted based on updated site data, which improves precision and confidence in the final schedule. In addition, the ability to perform automated checks of resources and activity durations through creating code schedules, according to the practitioners, could minimize human error and ensure that the schedule is more accurate to the construction plan.

BIM addresses the inadequate estimation and consideration of waiting times by precisely simulating construction sequences, which optimizes coordination between different teams and reduces times, which do not generate value for the project; one practitioner states, "On a road project, BIM can simulate the time a dump truck needs to wait while a backhoe loads material, or the waiting time due to traffic crossings on congested road corridors". Another professional noted, "BIM allows you to look at different scenarios and adjust activities as needed, which is crucial to mitigate risks and maintain planning throughout the project development and schedule". These simulations allow forecasting and planning of the impact of traffic and other disruptions on machine waiting time, ensuring that activities are coordinated efficiently. In addition, the ability to dynamically adjust waiting times according to actual project conditions and identify bottlenecks through the thorough decomposition of activities allows for more accurate and effective management of waiting times. This improves project performance, optimizes the use of resources, and minimizes costs associated with downtime. Finally, managing the high complexity of work

in road infrastructure projects is significantly enhanced with the use of BIM by allowing the decomposition of the project into manageable sub-activities and the creation of accurate models representing the elements involved “in the construction of a tunnel, BIM can model each phase of the process with a high LOD to understand the complexity of the elements and thus the project, which could be seen from excavation to lining and installation of ventilation and lighting systems”. This detailed modeling capability facilitates the identification and resolution of conflicts before they occur on-site, which improves the coordination and planning of construction activities. In addition, BIM enables the integration of multiple disciplines into a single model, ensuring that all teams manage the same up-to-date information, which is crucial on complex projects. The simulations and scenario analysis that BIM provides help to foresee the challenges associated with the complexity of the works and develop strategies to manage them. Continuous monitoring of project progress and the ability to update the model with real-time data ensures that planners can respond quickly to unforeseen changes and challenges, optimizing project execution and minimizing risks.

4.4. Discussion, Limitations, and Future Research

The findings of this study highlight the importance of implementing BIM uses to mitigate deficiencies in the scheduling of road construction projects. Four-dimensional Construction Planning, Quantity Take-Off and Cost Estimation, and Constructability Analysis were identified as the most influential ways to improve schedule planning in road projects. These results align with previous studies demonstrating that integrating BIM into construction planning enhances activity sequences’ visualization, analysis, and optimization, thereby reducing risks and improving schedule accuracy [12,19,24].

This study’s key contribution was identifying specific interactions between BIM uses and the principal components contributing to scheduling deficiencies. The cross-impact matrix enabled the mapping of these relationships, revealing that 4D Construction Planning has a significant impact on reducing deficiencies related to scope definition and activity sequencing, which is consistent with previous research highlighting the role of 4D planning in integrating activities and enabling early detection of conflicts [17,68]. Furthermore, the results confirmed the importance of the Traffic Management Plan in mitigating deficiencies associated with traffic control during construction, which is in line with prior studies demonstrating its effectiveness in optimizing site logistics and traffic flow management in road projects [70,75].

The strong relationship between Quantity Take-Off and Cost Estimation and the resource estimation component reinforces findings from previous research, which emphasizes BIM’s ability to improve accuracy in material and cost estimation, thereby reducing planning uncertainty and improving decision-making processes [85,90]. However, the study also revealed that the impact of BIM is not uniform across all components. For example, 5D Cost Analysis showed a lower influence on mitigating operational planning deficiencies, suggesting that its primary contribution relates to financial management rather than detailed activity sequencing, consistent with prior studies’ findings [88,89].

Despite these benefits, the literature also highlights important challenges associated with BIM adoption in road projects, several of which were confirmed in this study. First, high initial implementation costs remain a significant barrier, particularly for small and medium-sized firms with limited technology budgets [73]. Second, the learning curve and the need for specialized training to ensure effective BIM use are critical factors frequently reported as obstacles to widespread adoption [66,87]. Lastly, regulatory and legal barriers can constrain the implementation of BIM in road infrastructure projects, as some countries still lack comprehensive policies and regulations mandating or encouraging BIM use in public works contracts [19,22].

Another important aspect requiring further exploration is the empirical validation of BIM's impact on schedule performance in road projects. Although this study relied on expert opinions, no historical project data were used to quantify how BIM reduces scheduling errors or improves planning efficiency. Prior research underscores the importance of combining expert input with real-world data analysis to strengthen the empirical basis for BIM's benefits, providing quantifiable metrics on time and cost savings [28,83]. Moreover, recent studies have begun exploring the integration of emerging technologies that could amplify BIM's impact on schedule planning. For instance, combining BIM with artificial intelligence (AI) and machine learning (ML) has shown promise in improving schedule prediction accuracy and identifying potential delays in advance [14,18]. Similarly, real-time data from digital twins and IoT sensors is increasingly used to dynamically update project schedules, enhancing responsiveness and real-time decision-making during construction [78,80]. Future research should investigate how these advanced technologies can complement BIM, enabling more proactive and adaptive schedule management in road projects.

This study presents several limitations that should be considered when interpreting the findings. First, the analysis was based exclusively on the participation of professionals with expertise in road construction projects and prior experience using BIM. This sector-specific focus limits the generalizability of the results to other types of construction projects, such as building projects, urban infrastructure, or energy-related developments, where the nature of planning deficiencies and the effectiveness of BIM uses may differ. Second, the study concentrated exclusively on applying BIM technologies to mitigate scheduling deficiencies without incorporating complementary methodologies, such as Lean Construction, which could provide valuable process-focused strategies for improving schedule planning. By emphasizing BIM as the primary tool, the study potentially overlooks the synergistic benefits of integrating BIM with alternative process improvement approaches. Another limitation stems from the estimation of cross-impact relationships between BIM uses and causes of scheduling deficiencies based on expert perceptions rather than empirical project data. While expert input provides valuable insights, the absence of validation using historical data from real projects restricts the capacity to quantitatively assess the actual magnitude of BIM's contribution to mitigating planning deficiencies. Consequently, future research should complement expert-based assessments with longitudinal project data to enhance the robustness and external validity of the findings. Finally, the causes of scheduling deficiencies analyzed in this study were derived from prior research on road construction projects. As such, the identified deficiencies and their mitigation through BIM uses may not fully capture the challenges in other infrastructure projects. Expanding the analysis to include diverse project typologies would help refine the understanding of BIM's role across a broader spectrum of construction scenarios.

Future research should pursue several avenues to build on the findings of this study and address the identified limitations. One important direction involves empirically validating the cross-impact relationships identified between BIM uses and causes of scheduling deficiencies, considering the different realities around the world, i.e., including country, environment, and people, among other factors. Conducting case studies on real-world road projects, where BIM's influence on scheduling performance can be systematically measured and compared against projects using conventional planning approaches, would provide valuable quantitative evidence to support or refine the expert-based insights obtained in this research. Another promising avenue is the extension of the analysis to other construction sectors, such as building projects, transportation hubs, and large-scale urban developments. Examining how BIM uses interact with planning deficiencies in different project types would enhance the generalizability of the findings and reveal whether the

critical BIM uses identified in road projects hold similar importance in other contexts. This cross-sectoral comparison could also highlight sector-specific challenges and opportunities for BIM adoption. Additionally, future research could explore the integration of BIM with complementary methodologies, particularly Lean Construction, to develop a more holistic framework for mitigating scheduling deficiencies. Combining BIM's technological capabilities with Lean Construction's emphasis on process efficiency and waste reduction could yield innovative solutions for improving schedule reliability in road projects. Emerging technologies also represent a valuable research opportunity. Integrating BIM with artificial intelligence (AI) and machine learning (ML) could enable predictive analytics for schedule forecasting, risk identification, and adaptive rescheduling. Furthermore, using real-time data from sensors and digital twins could enhance the dynamic updating of schedules, improving responsiveness to on-site conditions and unforeseen events. Finally, future research should investigate the policy and regulatory environment necessary to foster wider BIM adoption in road infrastructure projects. Comparative studies across countries with differing regulatory frameworks could identify the best practices and effective incentives that promote the use of BIM in public sector projects. This policy-oriented research would provide valuable insights for governments and industry bodies aiming to accelerate BIM implementation in transportation infrastructure projects.

5. Conclusions

This study advances the theoretical understanding of how BIM can mitigate schedule deficiencies in road project planning by identifying and ranking the BIM uses with the greatest influence, based on input from 12 AEC professionals experienced in road projects and BIM implementation. Through the application of the Relative Influence Index (RII), the study highlights the seven most relevant BIM uses: (1) Quantity Take-Off and Cost Estimation, (2) Equipment and Material Planning, (3) 4D Construction Planning, (4) Schedule Estimation, (5) Traffic Management Plan, (6) Space Use Planning on the Site, and (7) 5D Cost Analysis.

The study also contributes by applying a cross-impact matrix to analyze and map the interactions between these BIM uses and the principal components of schedule deficiencies, providing a systematic framework for understanding the role of BIM in addressing specific planning vulnerabilities. This matrix-based approach offers theoretical insights into how the influence of BIM is distributed across different dimensions of project planning, from scope definition to operational complexity. Furthermore, the study enhances the theoretical framework by incorporating qualitative data from semi-structured interviews supported by NVIVO analysis. This mixed-method approach enriches theoretical understanding by capturing both quantitative relationships and qualitative insights, enabling a more comprehensive view of how BIM uses contribute to mitigating planning deficiencies in practice. Thus, this study offers practical guidance for road infrastructure project teams by identifying which BIM uses contribute most effectively to mitigating deficiencies in schedule planning. This allows decision-makers to prioritize specific BIM tools and processes, maximizing their benefits. BIM uses such as 4D Construction Planning and 5D Cost Analysis enhance project visualization, allowing real-time plan adjustments and better stakeholder coordination. These capabilities reduce the risk of delays and cost overruns by improving activity sequencing, resource management, and progress tracking.

Additionally, integrating BIM in space use planning and traffic management provides critical support for logistics and operational efficiency, addressing site constraints and public traffic interference challenges. By using BIM for Quantity Take-Off and Schedule Estimation, project teams gain more reliable and traceable data, reducing errors and improving planning accuracy. Identifying interactions between BIM uses and deficiency causes

also supports the development of more targeted risk management strategies, enabling practitioners to address vulnerabilities in the planning process proactively. The focus on road projects and the exclusive participation of professionals experienced in this sector limits generalizability to other project types. Additionally, the study emphasizes BIM-based solutions, excluding complementary methodologies. Future research could expand to different project types and explore the combined application of BIM and Lean Construction to develop comprehensive strategies for mitigating schedule planning deficiencies, leveraging the strengths of both approaches.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su17062729/s1>, Supplementary Material S1. Questionnaire A; Supplementary Material S2. Questionnaire B; Supplementary Material S3. Informed consent to participate in an interview for the development of a research project; Supplementary Material S4. Description of the potential of how BIM can help to mitigate the causes of deficiencies in the planning of construction process schedules in road projects.

Author Contributions: Conceptualization, K.C., O.S., C.A.P., R.F.H. and G.M.; methodology, K.C., O.S., C.A.P., R.F.H. and G.M.; results analysis, K.C., O.S., C.A.P., R.F.H. and G.M.; writing—original draft preparation, K.C., O.S., C.A.P. and R.F.H.; writing—review and editing, K.C., O.S., C.A.P., R.F.H. and G.M.; visualization, K.C., C.A.P. and O.S.; supervision, K.C., O.S., C.A.P., R.F.H. and G.M. All authors have read and agreed to the published version of the manuscript.

Funding: Omar Sánchez gratefully acknowledges the financial support from the Pontificia Universidad Javeriana, Colombia, through “Apoyo a proyectos de investigación liderados por profesores que se encuentran en su primera etapa 2023” with the project entitled “Planificación de la construcción de proyectos viales, mediante la integración de simulaciones digitales BIM nD, líneas de balance y Last Planner System” (ID 20673). Rodrigo F. Herrera acknowledge the financial support from ANID FONDECYT Iniciación 2023 No. 11230455.

Institutional Review Board Statement: Ethical review and approval were waived for this study because it involved only interviews to gather the opinions of a group of experts who provided informed consent prior to participation. All measures were implemented to ensure participant anonymity and safeguard their data in compliance with relevant policies.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: Karen Castañeda thanks the Technology, Innovation, Management, and Sustainability in Civil Engineering (TIMS) research group of the Pontificia Universidad Católica de Valparaíso for the support received during her research internship.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Professional Profiles of Experts Who Participated in the Questionnaire

Id	Profession (Grade)	Country	Rol	Years of Experience
1	Civil Engineer, M.Sc.	Chile	Contractor	>15
2	Civil Engineer, M.Sc., Ph.D.	Colombia	Consultant	>15
3	Civil Engineer, Esp.	Chile	Owner	>15
4	Civil Engineer, M.Sc.	Colombia	Designer	>15
5	Civil Engineer, M.Sc., Ph.D.	Colombia	Academic/Researcher	>15
6	Civil Engineer, Esp.	Chile	Designer	>10

Id	Profession (Grade)	Country	Rol	Years of Experience
7	Civil Engineer, M.Sc., Ph.D.	Chile	Designer	>10
8	Civil Engineer, Esp.	Chile	Contractor	>10
9	Civil Engineer, M.Sc., Ph.D.	Colombia	Academic/Researcher	>10
10	Civil Engineer, M.Sc.	Colombia	Academic/Researcher	>5
11	Civil Engineer, M.Sc.	Colombia	Contractor	>5
12	Civil Engineer, M.Sc., Ph.D.	Colombia	Academic/Researcher	>5

Appendix B. Characterization of Professional Roles and Years of Experience

Years of Experience	Less Than 5	From 5 to 10	From 10 to	More Than	
Professional Roles	Years	Years	15 Years	15 Years	Total
Designer	--	1	2	--	3
Consultant/Auditor	1	--	1	1	3
Contractor	1	5	1	6	13
Owner	1	--	--	--	1
Academic/Researcher	--	4	2	4	10
Other	--	--	--	--	--
Total	3	10	6	11	30

Appendix C. Professional Profiles of Experts Who Participated in the Questionnaire

Id	Profession (Grade)	Country	Rol	Years of Experience
1	Civil Engineer, M.Sc., Ph.D.	Spain	Academic/Researcher	>15
2	Civil Engineer, M.Sc., Ph.D.	Chile	Consultant/Designer	>15
3	Architect, Ph.D.	Spain	Academic/Researcher	>15
4	Civil Engineer, M.Sc., Ph.D.	Spain	Academic/Researcher	>15
5	Civil Engineer, M.Sc., Ph.D.	Colombia	Academic/Researcher	>10
6	Civil Engineer, M.Sc., Ph.D.	Colombia	Academic/Researcher	>10
7	Architect, M.Sc., Ph.D.	Spain	Academic/Designer	>10
8	Civil Engineer, M.Sc., Ph.D.	Colombia	Academic/Researcher	>7
9	Civil Engineer, M.Sc.,	Colombia	Consultant/Designer	>7
10	Civil Engineer, Ph.D.	Chile	Researcher/Designer	>5

References

- Koike, A.; Tavasszy, L.; Sato, K.; Monma, T. Spatial Incidence of Economic Benefit of Road-Network Investments: Case Studies under the Usual and Disaster Scenarios. *J. Infrastruct. Syst.* **2012**, *18*, 252–260. [\[CrossRef\]](#)
- Miralinaghi, M.; Davatgari, A.; Seilabi, S.E.; Labi, S. Contract Bundling Considerations in Urban Road Project Scheduling. *Comput. -Aided Civil. Infrastruct. Eng.* **2022**, *37*, 427–450. [\[CrossRef\]](#)
- Castañeda, K.; Sánchez, O.; Herrera, R.F.; Mejía, G. Highway Planning Trends: A Bibliometric Analysis. *Sustainability* **2022**, *14*, 5544. [\[CrossRef\]](#)
- Giunta, M. Assessment of the Environmental Impact of Road Construction: Modelling and Prediction of Fine Particulate Matter Emissions. *Build. Environ.* **2020**, *176*, 106865. [\[CrossRef\]](#)
- Mejía, G.; Sánchez, O.; Castañeda, K.; Pellicer, E. Stakeholders' Issues as a Source of Project Delays: A Meta-Analy-Sis between Building and Road Projects. *Rev. Constr.* **2023**, *22*, 51–73. [\[CrossRef\]](#)
- Hosseininasab, S.M.; Shetab-Boushehri, S.N.; Hejazi, S.R.; Karimi, H. A Multi-Objective Integrated Model for Selecting, Scheduling, and Budgeting Road Construction Projects. *Eur. J. Oper. Res.* **2018**, *271*, 262–277. [\[CrossRef\]](#)

7. Kim, K.; De La Garza, J.M. Evaluation of the Resource-Constrained Critical Path Method Algorithms. *J. Constr. Eng. Manag.* **2005**, *131*, 522–532. [\[CrossRef\]](#)
8. Lu, M.; Li, H. Resource-Activity Critical-Path Method for Construction Planning. *J. Constr. Eng. Manag.* **2003**, *129*, 412–420. [\[CrossRef\]](#)
9. Olivieri, H.; Seppänen, O.; Alves, T.D.C.L.; Scala, N.M.; Schiavone, V.; Liu, M.; Granja, A.D. Survey Comparing Critical Path Method, Last Planner System, and Location-Based Techniques. *J. Constr. Eng. Manag.* **2019**, *145*, 04019077. [\[CrossRef\]](#)
10. Lozano-Ramírez, N.E.; Sánchez, O.; Carrasco-Beltrán, D.; Vidal-Méndez, S.; Castañeda, K. Digitalization and Sustainability in Linear Projects Trends: A Bibliometric Analysis. *Sustainability* **2023**, *15*, 15962. [\[CrossRef\]](#)
11. Sigalov, K.; König, M. Recognition of Process Patterns for BIM-Based Construction Schedules. *Adv. Eng. Inform.* **2017**, *33*, 456–472. [\[CrossRef\]](#)
12. Chen, C.; Tang, L. BIM-Based Integrated Management Workflow Design for Schedule and Cost Planning of Building Fabric Maintenance. *Autom. Constr.* **2019**, *107*, 102944. [\[CrossRef\]](#)
13. Nusen, P.; Boonyung, W.; Nusen, S.; Panuwatwanich, K.; Champrasert, P.; Kaewmoracharoen, M. Construction Planning and Scheduling of a Renovation Project Using Bim-Based Multi-Objective Genetic Algorithm. *Appl. Sci.* **2021**, *11*, 4716. [\[CrossRef\]](#)
14. Kim, S.; Peavy, M.; Huang, P.; Kim, K. Development of BIM-Integrated Construction Robot Task Planning and Simulation System. *Autom. Constr.* **2021**, *127*, 103720. [\[CrossRef\]](#)
15. Abdulwahhab, R.; Naimi, S.; Abdullah, R. Managing Cost and Schedule Evaluation of a Construction Project via BIM Technology and Experts' Points of View. *Math. Model. Eng. Probl.* **2022**, *9*, 1515–1522. [\[CrossRef\]](#)
16. ElMenshawhy, M.; Marzouk, M. Automated BIM Schedule Generation Approach for Solving Time–Cost Trade-off Problems. *Eng. Constr. Archit. Manag.* **2021**, *28*, 3346–3367. [\[CrossRef\]](#)
17. Singh, J.; Cheng, J.C.P.; Anumba, C.J. BIM-Based Approach for Automatic Pipe Systems Installation Coordination and Schedule Optimization. *J. Constr. Eng. Manag.* **2021**, *147*, 04021143. [\[CrossRef\]](#)
18. Nguyen, D.T.; Chou, J.S.; Tran, D.H. Integrating a Novel Multiple-Objective FBI with BIM to Determine Tradeoff among Resources in Project Scheduling. *Knowl. Based Syst.* **2022**, *235*, 107640. [\[CrossRef\]](#)
19. Yuzhuo, Z.; Hyuk, J.; Qinghe, W.; Xinlong, Z. Research on Schedule Control of Large Scale Complex Project Based on BIM and PDCA Theory. *J. Archit. Civil. Eng.* **2022**, *39*, 183–191. [\[CrossRef\]](#)
20. Mahamid, I.; Bruland, A.; Dmaid, N. Causes of Delay in Road Construction Projects. *J. Manag. Eng.* **2012**, *28*, 300–310. [\[CrossRef\]](#)
21. Herrera, R.F.; Sánchez, O.; Castañeda, K.; Porras, H. Cost Overrun Causative Factors in Road Infrastructure Projects: A Frequency and Importance Analysis. *Appl. Sci.* **2020**, *10*, 5506. [\[CrossRef\]](#)
22. Amoatey, C.; Okanta, A. Exploring Critical Road Project Delay Factors in Ghana. *J. Facil. Manag.* **2017**, *15*, 110–127. [\[CrossRef\]](#)
23. Castañeda, K.; Sánchez, O.; Herrera, R.F.; Pellicer, E.; Porras, H. BIM-Based Traffic Analysis and Simulation at Road Intersection Design. *Autom. Constr.* **2021**, *131*, 103911. [\[CrossRef\]](#)
24. Oreto, C.; Massotti, L.; Biancardo, S.A.; Veropalumbo, R.; Viscione, N.; Russo, F. BIM-Based Pavement Management Tool for Scheduling Urban Road Maintenance. *Infrastructures* **2021**, *6*, 148. [\[CrossRef\]](#)
25. Zhang, S.; Wang, X. Quantifying Schedule Delay Risk in Construction Projects: A Data-Driven Approach with BIM and Probabilistic Reliability Analysis. *Adv. Civil. Eng.* **2023**, *2023*, 5525655. [\[CrossRef\]](#)
26. Kehily, D.; Underwood, J. Embedding Life Cycle Costing in 5D BIM. *J. Inf. Technol. Constr.* **2017**, *22*, 145–167.
27. Guo, H.; Ye, X.; Ren, Q.; Luo, Z. Automatic Generation of Construction Schedules Based on BIM and Rule Reasoning. *Qinghua Daxue Xuebao/J. Tsinghua Univ.* **2022**, *62*, 189–198. [\[CrossRef\]](#)
28. Sami Ur Rehman, M.; Thaheem, M.J.; Nasir, A.R.; Khan, K.I.A. Project Schedule Risk Management through Building Information Modelling. *Int. J. Constr. Manag.* **2022**, *22*, 1489–1499. [\[CrossRef\]](#)
29. Lamas, D.; Justo, A.; Soilán, M.; Riveiro, B. 3D Point Cloud to Bim: Automated Application to Define IFC Alignment and Roadway Width Entities from Mls-Acquired Lidar Data of Mountain Roads. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2022**, *10*, 169–176. [\[CrossRef\]](#)
30. Dolson, G.A. Scheduling and Management Improvements Accelerate Roadway Design. *Transp. Res. Rec.* **1999**, *2*, 92–97. [\[CrossRef\]](#)
31. Castañeda, K. Marco Metodológico para la Integración de Planes de Manejo de Tráfico en la Planificación de Procesos Constructivos de Intersecciones Viales, a Través de BIM y LEAN. Ph.D. Thesis, Industrial University of Santander, Bucaramanga, Colombia, 2024.
32. Mirboland, M.; Smarsly, K. BIM-Based Description of Intelligent Transportation Systems for Roads. *Infrastructures* **2021**, *6*, 51. [\[CrossRef\]](#)
33. Soilán, M.; Justo, A.; Sánchez-Rodríguez, A.; Riveiro, B. 3D Point Cloud to BIM: Semi-Automated Framework to Define IFC Alignment Entities from MLS-Acquired LiDAR Data of Highway Roads. *Remote Sens* **2020**, *12*, 2301. [\[CrossRef\]](#)
34. Cafiso, S.; Di Graziano, A.; Pappalardo, G.; Severino, A. Bim of an Existing Road Using Advanced Monitoring Systems. *Int. J. Eng. Appl.* **2021**, *9*, 243–250. [\[CrossRef\]](#)

35. Tang, F.; Ma, T.; Zhang, J.; Guan, Y.; Chen, L. Integrating Three-Dimensional Road Design and Pavement Structure Analysis Based on BIM. *Autom. Constr.* **2020**, *113*, 103152. [\[CrossRef\]](#)
36. Justo, A.; Soillán, M.; Sánchez-Rodríguez, A.; Riveiro, B. Scan-to-BIM for the Infrastructure Domain: Generation of IFC-Complaint Models of Road Infrastructure Assets and Semantics Using 3D Point Cloud Data. *Autom. Constr.* **2021**, *127*, 103703. [\[CrossRef\]](#)
37. Han, C.; Han, T.; Ma, T.; Tong, Z.; Wang, S.; Hei, T. End-to-End BIM-Based Optimization for Dual-Objective Road Alignment Design with Driving Safety and Construction Cost Efficiency. *Autom. Constr.* **2023**, *151*, 104884. [\[CrossRef\]](#)
38. Li, C.; Ding, L.; Zhong, B. Highway Planning and Design in the Qinghai–Tibet Plateau of China: A Cost–Safety Balance Perspective. *Engineering* **2019**, *5*, 337–349. [\[CrossRef\]](#)
39. Toca, C.; Bastos Costa, D. Increasing Production Efficiency through the Reduction of Transportation Activities and Time Using 4D BIM Simulations. *Eng. Constr. Andarchitectural Manag.* **2022**, *28*, 2222–2247. [\[CrossRef\]](#)
40. Costin, A.; Adibfar, A.; Hu, H.; Chen, S.S. Building Information Modeling (BIM) for Transportation Infrastructure—Literature Review, Applications, Challenges, and Recommendations. *Autom. Constr.* **2018**, *94*, 257–281. [\[CrossRef\]](#)
41. Biancardo, S.A.; Capano, A.; de Oliveira, S.G.; Tibaut, A. Integration of BIM and Procedural Modeling Tools for Road Design. *Infrastructures* **2020**, *5*, 37. [\[CrossRef\]](#)
42. Ait-Lamallam, S.; Sebari, I.; Yaagoubi, R.; Doukari, O. IFCInfra4OM: An Ontology to Integrate Operation and Maintenance Information in Highway Information Modelling. *ISPRS Int. J. Geoinf.* **2021**, *10*, 305. [\[CrossRef\]](#)
43. Eslahi, M.; El Meouche, R.; Doukari, O.; Ruas, A. BIM and Contribution to IFC-Bridge Development: Application on Raymond Barre Bridge. In *Advances in Building Information Modeling, Proceedings of the First Eurasian BIM Forum, EBF 2019, Istanbul, Turkey, 31 May 2019*; Communications in Computer and Information Science Series CCIS; Springer: Berlin/Heidelberg, Germany, 2020; Volume 1188, pp. 182–194.
44. Esser, S.; Aicher, K. IfcBridge Model. Generation Using. Visual Programming. In Proceedings of the Forum Bauinformatik, Berlin, Germany, 11–13 September 2019.
45. Ding, L.; Li, K.; Zhou, Y.; Love, P.E.D. An IFC-Inspection Process Model for Infrastructure Projects: Enabling Real-Time Quality Monitoring and Control. *Autom. Constr.* **2017**, *84*, 96–110. [\[CrossRef\]](#)
46. Report, U.M.L.M.; Elements, R. *IFC Road Conceptual Model Report*; buildingSMART: Hertfordshire, UK, 2020.
47. Esmaeili, B.; Hallowell, M. Integration of Safety Risk Data with Highway Construction Schedules. *Constr. Manag. Econ.* **2013**, *31*, 528–541. [\[CrossRef\]](#)
48. Sharma, H.; McIntyre, C.; Gao, Z.; Nguyen, T.-H. Developing a Traffic Closure Integrated Linear Schedule for Highway Rehabilitation Projects. *J. Constr. Eng. Manag.* **2009**, *135*, 146–155. [\[CrossRef\]](#)
49. Sukumaran, P.; Bayraktar, M.E.; Hong, T.; Hastak, M. Model for Analysis of Factors Affecting Construction Schedule in Highway Work Zones. *J. Transp. Eng.* **2006**, *132*, 508–517. [\[CrossRef\]](#)
50. Yin, Y.; Choi, K.; Jeong, H.D.; Touran, A. Integration of Schedule, Cost, Traffic, and Risk into the Determination of Construction Contract Times. *J. Manag. Eng.* **2022**, *38*, 04022061. [\[CrossRef\]](#)
51. Li, Y.; Al-Haddad, S.; Taylor, T.R.B.; Goodrum, P.M.; Sturgill, R.E. Impact of Utilizing Construction Engineering and Inspection Consultants on Highway Construction Project Cost and Schedule Performance. *Transp. Res. Rec.* **2019**, *2673*, 716–725. [\[CrossRef\]](#)
52. Xia, Y.; Zhang, C.; Wang, C.; Liu, H.; Sang, X.; Liu, R.; Zhao, P.; An, G.; Fang, H.; Shi, M.; et al. Prediction of Bending Strength of Glass Fiber Reinforced Methacrylate-Based Pipeline UV-CIPP Rehabilitation Materials Based on Machine Learning. *Tunn. Undergr. Space Technol.* **2023**, *140*, 105319. [\[CrossRef\]](#)
53. Liu, B.; Lu, W.; Olofsson, T.; Zhuang, X.; Rabczuk, T. Stochastic Interpretable Machine Learning Based Multiscale Modeling in Thermal Conductivity of Polymeric Graphene-Enhanced Composites. *Compos. Struct.* **2024**, *327*, 117601. [\[CrossRef\]](#)
54. Liu, B.; Vu-Bac, N.; Zhuang, X.; Fu, X.; Rabczuk, T. Stochastic Integrated Machine Learning Based Multiscale Approach for the Prediction of the Thermal Conductivity in Carbon Nanotube Reinforced Polymeric Composites. *Compos. Sci. Technol.* **2022**, *224*, 109425. [\[CrossRef\]](#)
55. Liu, B.; Vu-Bac, N.; Rabczuk, T. A Stochastic Multiscale Method for the Prediction of the Thermal Conductivity of Polymer Nanocomposites through Hybrid Machine Learning Algorithms. *Compos. Struct.* **2021**, *273*, 114269. [\[CrossRef\]](#)
56. Liu, B.; Vu-Bac, N.; Zhuang, X.; Lu, W.; Fu, X.; Rabczuk, T. Al-DeMat: A Web-Based Expert System Platform for Computationally Expensive Models in Materials Design. *Adv. Eng. Softw.* **2023**, *176*, 103398. [\[CrossRef\]](#)
57. Lim, C.P.; Yussof, M.M.; Sopian, S.F.; Jaganathan, J. Review on the Non-Destructive Test (NDT) Approaches on Concrete Crack Mapping Prediction. *J. Adv. Res. Appl. Mech.* **2025**, *131*, 172–184. [\[CrossRef\]](#)
58. Naji, K.; Gowid, S.; Ghani, S. AI and IoT-Based Concrete Column Base Cover Localization and Degradation Detection Algorithm Using Deep Learning Techniques. *Ain Shams Eng. J.* **2023**, *14*, 102520. [\[CrossRef\]](#)
59. Van Giang, H.; Anh, N.T.; Nam, L.H.; Nam, T.P.; Tu, T.T. Challenges on application of digital technology in building operation and maintenance of high-rise buildings in vietnam. *Malays. Constr. Res. J.* **2024**, *23*, 131–149.
60. Waqar, A.; Bheel, N.; Tayeh, B.A. Modeling the Effect of Implementation of Artificial Intelligence Powered Image Analysis and Pattern Recognition Algorithms in Concrete Industry. *Dev. Built Environ.* **2024**, *17*, 100349. [\[CrossRef\]](#)

61. Zou, X.; Yan, G.; Mohammed, K.J.; Suhatri, M.; Khadimallah, M.A.; Marzouki, R.; Almirante, H.; Escorcia-Gutierrez, J. Advancements in Nano-Enhanced Steel Structures for Earthquake Resilience: Integrating Metallic Elements, AI, and Sensor Technology for Engineering Disasters Mitigation in Steel Buildings. *Steel Compos. Struct.* **2024**, *53*, 443–460. [\[CrossRef\]](#)
62. Uaissova, M.; Zharlykassov, B. Application of AI Techniques for Asphalt Concrete Mix Production Optimization. *J. Eur. Des. Syst. Autom.* **2024**, *57*, 353–361. [\[CrossRef\]](#)
63. Ramadan, S.; Kassem, H.; ElKordi, A.; Joumblat, R. Incorporating Artificial Intelligence Applications in Flexible Pavements: A Comprehensive Overview. *Int. J. Pavement Res. Technol.* **2024**. [\[CrossRef\]](#)
64. Castañeda, K.; Sánchez, O.; Herrera, R.F.; Gómez-Cabrera, A.; Mejía, G. Building Information Modeling Uses and Complementary Technologies in Road Projects: A Systematic Review. *Buildings* **2024**, *14*, 563. [\[CrossRef\]](#)
65. Castañeda, K.; Sánchez, O.; Herrera, R.F.; Mejía, G. Deficiencies Causes in Road Construction Scheduling: Perspectives from Construction Professionals. *Heliyon* **2024**, *11*, e41514. [\[CrossRef\]](#) [\[PubMed\]](#)
66. Aladağ, H.; Demirdöğen, G.; Demirbağ, A.T.; Işık, Z. Understanding the Perception Differences on BIM Adoption Factors across the Professions of AEC Industry. *Ain Shams Eng. J.* **2023**, *14*, 102545. [\[CrossRef\]](#)
67. Yu, Q.; Li, K.; Luo, H. A BIM-Based Dynamic Model for Site Material Supply. *Procedia Eng.* **2016**, *164*, 526–533. [\[CrossRef\]](#)
68. Rashidi, A.; Yong, W.Y.; Maxwell, D.; Fang, Y. Construction Planning through 4D BIM-Based Virtual Reality for Light Steel Framing Building Projects. *Smart Sustain. Built Environ.* **2023**, *12*, 1153–1173. [\[CrossRef\]](#)
69. Essam, N.; Khodeir, L.; Fathy, F. Approaches for BIM-Based Multi-Objective Optimization in Construction Scheduling. *Ain Shams Eng. J.* **2023**, *14*, 102114. [\[CrossRef\]](#)
70. Malcher, A.; Saliba, A.; Wolgast, E. Herausforderungen Und Perspektiven Bei Der BIM-Planung von Brücken—Das Beispiel Der Geh- Und Radwegüberführung Riederwald. *Bautechnik* **2023**, *100*, 396–405. [\[CrossRef\]](#)
71. Xinting, G.; Weimin, Z. Apply Digital-Twin Model to Optimize the Planning of Equipment Pipeline System in the Laboratory Campus. In Proceedings of the International Conference on Computational Design and Robotic Fabrication, Shanghai, China, 24–25 June 2023; Springer: Singapore, 2024. Part F2072. pp. 260–272. [\[CrossRef\]](#)
72. Aranda, J.Á.; Santonja, M.M.; Saurí, M.G.; Peris-Fajarnés, G. Minimizing Shadow Area in Mountain Roads for Improving the Sustainability of Infrastructures. *Sustainability* **2021**, *13*, 5392. [\[CrossRef\]](#)
73. Al-Roumi, H.; Al-Sabah, R. Exploring the Rate of Adoption and Implementation Depth of Building Information Modeling (BIM): A Case of Kuwait. *J. Eng. Res.* **2023**, *12*, 86–99. [\[CrossRef\]](#)
74. Kovvuri, A.R. Web-Based Visual Project Progress (4D BIM) to Plan and Monitor in a More Lean and Efficient Way. In Proceedings of the Indian Lean Construction Conference, Hyderabad, India, 13–16 December 2022; Springer: Singapore, 2024; pp. 407–412. [\[CrossRef\]](#)
75. Schlosser, T.; Schlosser, P.; Zuzulová, A.; Cápayová, S.; Bálint, G. Traffic Planning as a Preliminary Tool in Project Documentation for BIM. *Buildings* **2022**, *12*, 381. [\[CrossRef\]](#)
76. RazaviAlavi, S.R.; AbouRizk, S. Construction Site Layout Planning Using a Simulation-Based Decision Support Tool. *Logistics* **2021**, *5*, 65. [\[CrossRef\]](#)
77. Le, P.L.; Dao, T.M.; Chaabane, A. BIM-Based Framework for Temporary Facility Layout Planning in Construction Site: A Hybrid Approach. *Constr. Innov.* **2019**, *19*, 424–464. [\[CrossRef\]](#)
78. Wang, F.; Zou, Y.; del Rey Castillo, E.; Ding, Y.; Xu, Z.; Zhao, H.; Lim, J.B.P. Automated UAV Path-Planning for High-Quality Photogrammetric 3D Bridge Reconstruction. *Struct. Infrastruct. Eng.* **2022**, *20*, 1595–1614. [\[CrossRef\]](#)
79. Zavari, M.; Shahhosseini, V.; Ardeshtir, A.; Sebt, M.H. Multi-Objective Optimization of Dynamic Construction Site Layout Using BIM and GIS. *J. Build. Eng.* **2022**, *52*, 104518. [\[CrossRef\]](#)
80. Hosny, A.; Nik-Bakht, M.; Moselhi, O. Physical Distancing Analytics for Construction Planning Using 4D BIM. *J. Comput. Civil. Eng.* **2022**, *36*, 04022012. [\[CrossRef\]](#)
81. Caldart, C.W.; Scheer, S. Construction Site Design Planning Using 4D BIM Modeling. *Gest. Prod.* **2022**, *29*, e5312. [\[CrossRef\]](#)
82. Kontrimovičius, R.; Ustinovichius, L. BIM-Based Prototype of a Mathematical Model of Construction Planning. *J. Civil. Eng. Manag.* **2023**, *29*, 1–14. [\[CrossRef\]](#)
83. Krasovskaya, O.A.; Vyaznikov, V.E.; Mamaeva, A.I. Application of BIM Technologies as IT Projects for Digital Transformation in Industry. In Proceedings of the International Scientific and Practical Conference Digital and Information Technologies in Economics and Management, Online, 2 November 2021; Lecture Notes in Networks and Systems LNNS; Springer: Cham, Switzerland, 2022; Volume 432, pp. 104–116. [\[CrossRef\]](#)
84. Magill, L.J.; Jafarifar, N.; Watson, A.; Omotayo, T. 4D BIM Integrated Construction Supply Chain Logistics to Optimise On-Site Production. *Int. J. Constr. Manag.* **2022**, *22*, 2325–2334. [\[CrossRef\]](#)
85. Chamikara, K.L.; Perera, B.A.K.S.; Kurukulasoorya, I.N. Use of building information modelling to mitigate cost overruns in design and build projects. *World Constr. Symp.* **2023**, *1*, 1104–1115. [\[CrossRef\]](#)
86. Elyano, M.R. Yuliastuti Analysis of Clash Detection and Quantity Take-off Using BIM for Warehouse Construction. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *794*, 012012. [\[CrossRef\]](#)

87. Sampaio, A.Z.; Azevedo, G.; Gomes, A. BIM Manager Role in the Integration and Coordination of Construction Projects. *Buildings* **2023**, *13*, 2101. [[CrossRef](#)]
88. Rohani, M.; Shafabakhsh, G.; Haddad, A.; Asnaashari, E. Strategy Management of Construction Workspaces by Conflict Resolution Algorithm and Visualization Model Strategy Management of Construction Workspaces. *Eng. Constr. Archit. Manag.* **2018**, *25*, 1053–1074. [[CrossRef](#)]
89. Hui, S.; Jing, K.T.; Yee, H.C.; Siyao, C.; Zihao, D.; Yangle, S. The Impacts of 5D Building Information Modelling towards Cost Management in the Construction Industry. *J. Adv. Res. Appl. Sci. Eng. Technol.* **2023**, *32*, 471–487. [[CrossRef](#)]
90. Baldrich Aragó, A.; Roig Hernando, J.; Llovera Saez, F.J.; Coll Bertran, J. Quantity Surveying and BIM 5D. Its Implementation and Analysis Based on a Case Study Approach in Spain. *J. Build. Eng.* **2021**, *44*, 103234. [[CrossRef](#)]
91. Hussain, O.A.I.; Moehler, R.C.; Walsh, S.D.C.; Ahiaga-Dagbui, D.D. Minimizing Cost Overrun in Rail Projects through 5D-BIM: A Conceptual Governance Framework. *Buildings* **2024**, *14*, 478. [[CrossRef](#)]
92. Trochymiak, W.; Krygier, A.; Stachura, M.; Jaworski, J. The BIM 5D Model of the Bridge Built Using the Incremental Launching Method. *Arch. Civil. Eng.* **2023**, *69*, 157–172. [[CrossRef](#)]

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