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Enhancing road construction management in Peru through virtual design and construction integration

Gerber Zavala[1], Michael Chacón[2], Victor Andre Ariza Flores[3]
[1] Universidad Nacional Mayor de San Marcos, Perú
[2] Universidad Ricardo Palma, Perú
[3] Universidad Tecnológica del Perú, Perú

ABSTRACT

This study examines the integration of Building Information Modeling (BIM) with Project Production Management (PPM) and Integrated Concurrent Engineering (ICE) under the Virtual Design and Construction (VDC) framework to address chronic inefficiencies in road infrastructure projects in Peru. Focusing on a 93 km road project in Puno, the research demonstrates that the combined VDC approach leads to significant improvements in project management. Key findings include a 25% reduction in project delays and a 15% decrease in overall project costs compared to traditional management methods. The implementation of VDC also resulted in a 90% reduction in design conflicts and a 95% improvement in the resolution of construction observations. Production metrics were established, showing that BIM scope fulfillment reached 100%, and key stakeholders' attendance at ICE sessions exceeded 85%, ensuring effective interdisciplinary coordination. The study highlights the critical role of coordinated BIM, PPM, and ICE processes in mitigating risks and enhancing project delivery in Peru. These results show that adopting the VDC framework can lead to substantial efficiency gains in future road infrastructure projects. Recommendations include the establishment of continuous training programs and the creation of robust digital infrastructures to support the widespread adoption of VDC in the Peruvian construction sector.

Keywords: BIM, Virtual design and construction, Project management, Road infrastructure

Corresponding Author:

Victor Andre Ariza Flores
Escuela de Posgrado
Universidad Continental
Av. San Carlos 1980, Huancayo 12001
E-mail: variza@continental.edu.pe

1 Introduction

Globally, infrastructure project management faces significant challenges that often result in delays and cost overruns [1], [2]. In countries such as Germany, France, Spain and Panama, numerous projects have suffered from time extensions and increases in the initially planned budget due to inefficient management, uncontrolled changes, unforeseen interferences and inadequate coordination between the various disciplines involved. For example, the Berlin-Brandenburg Airport project in Germany experienced multiple significant delays and cost overruns [3], while the Panama Canal expansion project [4], He also faced similar problems. In France and Spain, projects such as the Tours-Bordeaux high-speed line [5] and the AVE Madrid-Barcelona [6] have had to deal with complications that have affected their timely and on-budget delivery.

In Latin America, the situation is no different. Countries like Brazil [7] and Chile have experienced problems in the management of their road infrastructure projects, facing the same challenges of coordination, cost control and compliance with deadlines. The construction of Line 6 of the São Paulo metro in Brazil and Route 5 in Chile are clear examples where the lack of an efficient project management methodology has resulted in considerable delays and cost overruns.

In this global and regional context, Peru is no exception. The conventional project management methods in the country lack an efficient working methodology that allows for effective supervision and control throughout the project lifecycle. Recognizing this deficiency, the central government has developed the Plan BIM Peru. This document proposes the progressive implementation of the Building Information Modeling (BIM) methodology at the national level, establishing strategies that group the necessary actions and allow the structuring of the fundamental pillars to achieve the progressive adoption of BIM in the public sector by the year 2030.

To maximize the potential of BIM, it is necessary to integrate it as an essential part of project management. Road infrastructure projects have their own specific processes that need to be adapted to BIM capabilities [8], [9]. This does not mean eliminating current processes but rather improving and adapting them through the application of Project Production Management (PPM) and the multidisciplinary collaboration facilitated by Integrated Concurrent Engineering (ICE) sessions.

The primary objective of this research is to demonstrate how the Virtual Design and Construction (VDC) methodology, which integrates BIM, PPM, and ICE, can significantly enhance the management of road infrastructure projects in Peru. The specific objectives include: evaluating the effectiveness of integrating BIM, PPM, and ICE in road project management; establishing production metrics and controllable factors for quantification and goal setting in road infrastructure projects; identifying and analyzing bottlenecks in the workflow during the preparation of technical files; and comparing the results obtained through the VDC methodology with traditional project management methods.

The research questions guiding this study are: How does the integration of BIM, PPM, and ICE affect the efficiency and effectiveness of road project management in Peru? What production metrics and controllable factors are most relevant for evaluating the performance of road projects using the VDC methodology? What are the main bottlenecks in the workflow of road infrastructure projects, and how can they be mitigated through the VDC methodology? To what extent can the implementation of the VDC methodology reduce delays and cost overruns in road infrastructure projects compared to traditional methods?

The conventional methods of road infrastructure project management in Peru are inefficient and do not allow for adequate oversight throughout the project lifecycle. This problem is primarily reflected in missed deadlines and cost overruns due to time extensions, additional work, stoppages, arbitrations, and awards. The most common issues include a lack of interaction between disciplines, uncontrolled modifications, unidentified interferences, and inconsistencies between the design and the plans.

The BIM methodology has been progressively implemented in various European countries, achieving acceptable results as an information management tool. Based on these favorable experiences, Peru has decided to make this methodology mandatory in all its investment projects. However, it is crucial to recognize that merely applying BIM will not resolve all management problems. It is necessary to complement BIM with PPM and ICE to improve coordination and efficiency, reducing costs and delivery times.

The research is divided into four main parts: Virtual Design and Construction (VDC), where the application framework and components for road infrastructure are established; Project Production Management (PPM), where processes or workflows are defined, setting milestones for each specialty and their corresponding integration and/or compatibility, first concluding the design and its constructability, and then proceeding to measurements, laminations, budget, and construction schedule; Project Information Management (BIM), aligning workflows for road infrastructure and BIM; and proposals for production metrics and controllable factors for monitoring and controlling the results obtained through BIM, PPM, and ICE.

2 Research method

The methodology of this research focuses on a case study of a 93 km long road. This project is approached from the perspective of an external consultant. This approach allows for an impartial and detailed analysis of current project management practices and provides a solid foundation for proposing improvements. As with any engineering project, conducting research under a diverse approach helps to identify the most accurate actions to explain a phenomenon in engineering from multiple perspectives [10].

First, a comprehensive review of the existing literature on road infrastructure project management, BIM, PPM, and ICE was conducted, encompassing case studies from various countries, government reports, academic publications, and technical articles. This review facilitated the identification of best practices and common challenges in the implementation of these methodologies. Data was collected through interviews with project stakeholders, a review of technical documents, and direct observations. This analysis enabled the assessment of the effectiveness of integrating BIM, PPM, and ICE in managing these projects and understanding the specific challenges faced during the execution of road infrastructure projects.

Subsequently, surveys were designed and administered to construction sector professionals in Peru, focusing on their perception and knowledge of BIM, PPM, and ICE, the challenges in their implementation, and the perceived benefits. The collected data were analyzed using statistical techniques to identify trends and patterns.

Next, simulations and modeling were performed using BIM and PPM software to quantify the impact of these methodologies in terms of time, cost, and quality. These simulations allowed for the comparison of scenarios with and without the implementation of BIM, PPM, and ICE, providing a quantitative basis for the research conclusions.

Based on this case analysis, an improvement proposal was developed, grounded in the actions of expert consultants to optimize road infrastructure management practices. The proposal focuses on the effective integration of BIM, PPM, and ICE to enhance coordination, reduce costs and execution times, and increase project quality.

2.1 Theoretical foundations

The theoretical foundations of this research are based on various conceptual frameworks and theories related to project management, the BIM methodology, Project Production Management (PPM), and Integrated Concurrent Engineering (ICE).

Project management theory provides a general framework for understanding the processes and practices necessary to plan, execute, and control infrastructure projects. It includes principles such as time management, cost management, quality management, human resource management, communication management, and risk management. These principles are fundamental to any project and are integrally applied in the analysis of road project management.

The Building Information Modeling (BIM) methodology is based on the creation and use of digital information models for buildings and infrastructure projects. These models contain both graphical and non-graphical data that can be used to support decision-making throughout the project lifecycle. BIM theory emphasizes the importance of collaboration and information integration among all disciplines involved in a project, leading to greater efficiency and accuracy in project management.

Project Production Management (PPM) theory focuses on improving production efficiency by applying production management principles to project delivery. This involves optimizing workflows, reducing waste, and ensuring that every step in the process adds value to the outcome. Project Production Management (PPM) derives from principles of production and manufacturing, applied to the context of construction projects. It focuses on optimizing production processes, minimizing variability, and improving workflow. PPM employs techniques such as workflow planning, production control, and resource management to enhance project efficiency and effectiveness. PPM theory complements BIM by providing a structured and systematic approach to project management.

Integrated Concurrent Engineering (ICE) theory supports multidisciplinary collaboration and the concurrent development of project components. ICE emphasizes the importance of early and continuous involvement of all stakeholders, allowing for real-time feedback and adjustments, which helps to prevent issues and delays. Together, these theories provide a comprehensive framework for evaluating and improving the management of road infrastructure projects through the integration of BIM, PPM, and ICE methodologies. [11], [12]. Integrated Concurrent Engineering (ICE) is a project management approach that promotes the simultaneous collaboration of multiple disciplines during the design and construction phases. ICE theory is based on integrating multidisciplinary teams to identify and resolve design issues at early stages, thereby reducing rework and improving project quality. ICE complements BIM and PPM by providing a collaborative and coordinated environment for project management.

The theoretical foundations provide a comprehensive framework for the research, allowing for the analysis of how the integration of BIM, PPM, and ICE can enhance the management of road infrastructure projects in Peru. The combination of these theories offers a solid basis for developing and evaluating new methodologies and practices in construction project management.

VDC not only integrates but synchronizes the capabilities of BIM, PPM, and ICE, where BIM facilitates digital visualization, PPM optimizes production, and ICE coordinates stakeholders in a collaborative environment, ensuring all disciplines work in harmony from the project's early stages.

2.2 Overview of VDC in Peru

The Public Procurement Law in Peru regulates the acquisition of goods, services, and works by public entities, ensuring transparency, efficiency, and competition in the contracting processes. This law establishes that public works must be executed considering efficiency throughout their entire lifecycle, from design to operation and maintenance.

In 2019, through Supreme Decree No. 082-2019-EF, this law was reinforced with specific criteria for the progressive incorporation of digital information modeling tools. These tools, such as Building Information Modeling (BIM), aim to improve the quality and efficiency of public projects. The National Competitiveness and Productivity Plan 2019-2030, approved by Supreme Decree No. 237-2019-EF, establishes the adoption of collaborative digital modeling methodologies for construction in the public sector as a priority policy measure. This plan, known as Plan BIM Peru, includes a roadmap and specific measures for its implementation. The Ministry of Economy and Finance (MEF) of Peru is the entity responsible for the country's economic and financial policy. In 2019, through Supreme Decree No. 289-2019-EF, the MEF mandated the progressive incorporation of BIM in public investment processes, indicating principles and criteria for its adoption and use. This effort is part of the National System of Multiyear Programming and Investment Management, which oversees the planning and management of public investments in Peru.

In 2021, the MEF, through Supreme Decree No. 0002-2021-EF/63.01, approved the Implementation Plan and the Roadmap of Plan BIM Peru. This plan highlights the importance of national BIM adoption, based on a detailed analysis of the current state of the construction industry. The analysis revealed that BIM adoption efforts so far have been isolated, indicating the need for a more coordinated and integrated approach. This regulatory and strategic framework reflects the Peruvian government's commitment to modernization and efficiency in the management of public infrastructure projects. The adoption of BIM is considered a key tool to improve the planning, execution, and maintenance of public works, promoting transparency, efficiency, and quality in public investment projects.

2.3 Purpose and limitations of the study

The primary purpose of this study is to evaluate the effectiveness of the Virtual Design and Construction (VDC) methodology in enhancing the management of road infrastructure projects in Peru. The research aims to demonstrate how the integration of Building Information Modeling (BIM), Project Production Management (PPM), and Integrated Concurrent Engineering (ICE) within the VDC framework can significantly improve project outcomes, particularly in terms of time efficiency, cost reduction, and overall project quality. The study seeks to provide evidence-based insights into the benefits of adopting VDC in the context of Peruvian infrastructure projects.

This study is subject to several limitations. First, the research focuses primarily on road infrastructure projects, which may limit the generalizability of the findings to other types of construction projects. Second, the case studies and data used in the research are limited to projects in Peru, which may not fully capture the diversity of challenges faced in different geographical or economic contexts. Additionally, the adoption of VDC is still relatively new in Peru, and the long-term impact of its implementation remains to be fully understood. The study also relies on the availability of data from ongoing projects, which may introduce biases if the data is incomplete or not fully representative of all project phases.

2.4 A case study

This case study focuses on a 93 km long road located in the Puno region of Peru. It was analyzed from the perspective of an external consultant. The objective is to evaluate the effectiveness of current project management practices and develop an improvement proposal based on the integration of BIM, PPM, and ICE methodologies.

Data collection was carried out through structured interviews with project managers, reviews of technical documents, and direct field observations. The interviews included questions about current project management practices, challenges faced, and the perception and knowledge of BIM, PPM, and ICE methodologies. Additionally, schedules, budgets, and project progress records were analyzed to assess their performance.

The analysis of current project management practices revealed several common deficiencies, such as inadequate coordination between disciplines, lack of control over modifications, and difficulties in identifying and resolving interferences in a timely manner. These deficiencies resulted in significant delays and cost overruns in several of the projects analyzed. The lack of an integrated information and production management methodology was identified as a key factor contributing to these problems.

3 Results and discussion

The Virtual Design and Construction (VDC) methodology represents an advanced integration of the design, construction and operation phases from the initial stages of a project, based on virtual models such as Building Information Modeling (BIM) and Project Production Management (PPM) [13]. This methodology involves a detailed monitoring of virtual information, using production metrics and controllable factors generated by both BIM and PPM, which converge in decision-making during the Integrated Concurrent Engineering (ICE) sessions.

The first criterion for virtual design and construction is to establish the client's objectives. This involves clearly defining the client's expectations and goals to ensure that the project meets their specific requirements. Secondly, project objectives must be established by identifying and articulating the overall goals, including key milestones, budget, and schedule.

The definition of Project Production Management (PPM) is fundamental for understanding, controlling, and improving project delivery. This process encompasses reducing project variability by implementing measures to minimize uncertainties and variations. Moreover, workflow planning is essential to establish an efficient flow that coordinates all project activities. Resource management also plays a crucial role in optimally identifying and allocating the necessary resources.

Building Information Modeling (BIM) provides a digital and visual representation of the project, integrating relevant information about each element of the infrastructure. BIM facilitates the presentation of project challenges, enabling the team and clients to visualize and better understand potential issues. Additionally, BIM supports decision-making using accurate data and 3D visualization to enhance project planning and execution. [15]. BIM has been used in projects to ensure the constructability of road infrastructure [16], [17].

Integrated Concurrent Engineering (ICE) is another key component of the VDC methodology. ICE organizes multidisciplinary meetings that allow stakeholders to simultaneously participate in the creation and evaluation of VDC models. The goal of ICE is to reduce the time required for decision-making, improve the quality of the outcome, and achieve better integration between the different disciplines involved in the project.

Together, the implementation of VDC, supported by BIM and PPM and facilitated through ICE, provides a robust framework for managing complex infrastructure projects. This approach allows for more precise planning, more efficient execution, and more sustainable operation of construction projects. By integrating these methodologies, it ensures that client objectives are met, and available resources are optimized, promoting more effective and efficient project management.

3.1 Project production management

To achieve the potential of BIM, we must consider it as part of Project Management, as road infrastructure projects have their own processes that BIM must assimilate into. This means we will not discard the existing processes used in road infrastructure projects, but rather enhance and adapt them by adding the potential of BIM, applying PPM, and thereby making multidisciplinary collaboration effective and concrete through ICE sessions.

Figure 1 outlines the key processes involved in the development of technical documentation for road infrastructure projects. The sequence begins with basic engineering studies, including traffic analysis, topography, hydrology, and geotechnics, which are fundamental for assessing the project's feasibility. Next, the design phase covers geometric layouts, structural details, and safety measures.

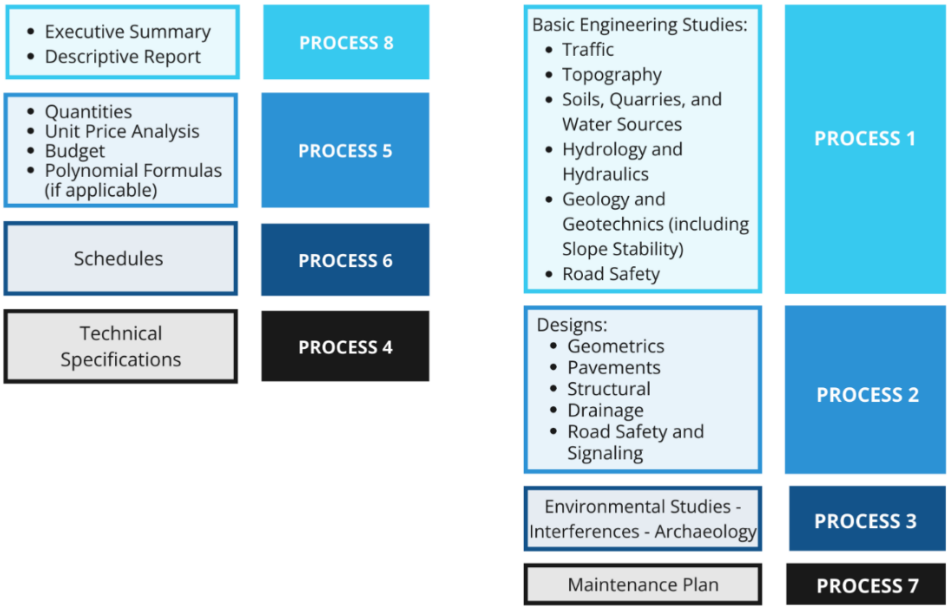


Figure 1. Processes in technical documentation for road infrastructure

Environmental studies and assessments of interferences, including archaeological considerations, follow the design phase. The process then advances to the preparation of technical specifications, quantity calculations, unit price analysis, and budget formulation, ensuring accurate cost estimations. Scheduling is addressed to align project activities with the planned timeline.

The final steps include the preparation of the executive summary and descriptive report, which compiles all project information, and the development of the maintenance plan to support the infrastructure's long-term upkeep. Each process is integral to achieving a comprehensive and well-documented project plan.

3.1.1 Processes or workflows

When defining processes or workflows, milestones must be established for each specialty and their corresponding integration and/or harmonization, first concluding the design and its constructability, and then proceeding to the quantity takeoff, drawings, budget, and construction schedule as summarized below in Figure 2.

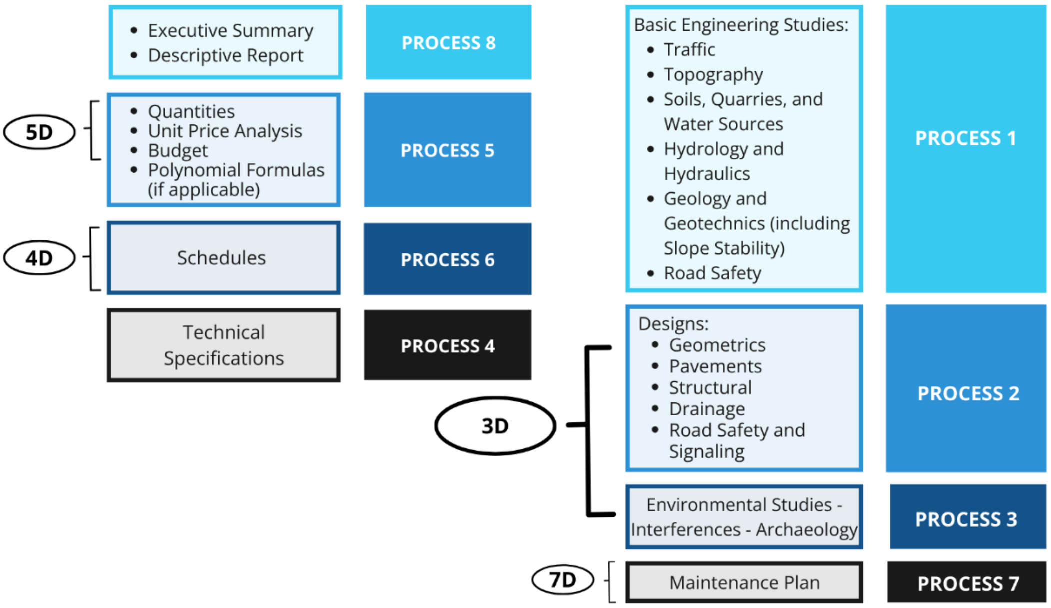


Figure 2. Processes for preparing technical documentation considering BIM processes

Some considerations include:

1. Establish an iterative workflow for virtual construction during the design phase to integrate or fit with the digital terrain, harmonize, resolve conflicts, and address observations of the components. Virtually traverse the road by sector or integrally to verify if the solutions cover the entire section or if there are others that were not identified in the initial stage, always comparing with the digital terrain.
2. Integrate and harmonize the drainage and subdrainage systems, structures, and pavements with the geometry of the road infrastructure.
3. Technically resolve those solutions that affect the population (to reduce the risk of social conflicts), such as pedestrian or vehicular crossings (accesses) in ditches, animal crossings in cut or embankment areas, delineation of the affected property area, among others that can only be identified in virtual construction.
4. Once the previous step is completed by sectors or integrally, proceed to perform the quantity takeoff as this indicates that the virtual construction is complete.
5. Once the previous step is completed by sectors or integrally, proceed to perform the simulation and/or scheduling as this indicates that the virtual construction is complete.
6. Only when the quantity takeoff is completed can the drawings for construction be prepared.
7. The control and monitoring of the workflow and identification of bottlenecks are carried out as if we were performing the actual construction; this allows us to use and distribute resources effectively and efficiently, with daily, weekly, and monthly goals, ensuring that we know when we can deliver the project.

Additionally, by applying the workflow, each component of the road infrastructure is inserted like a puzzle onto the geometric design and digital terrain. This process verifies if the dimensions are sufficient, if they are compatible in the sector, what adjustments or improvements need to be made, what construction process problems will arise, and how to improve designs such as ditch or curb discharges that are often omitted, among other aspects.

Figure 3 illustrates the detailed workflow for developing a BIM-compliant design and preparing the technical documentation in a road infrastructure project. The process begins with the review of BIM design models by all specialties, ensuring that each discipline's inputs are coordinated. This initial phase takes 12 days and is followed by the detection and reporting of any incompatibilities.

Once incompatibilities are identified, sessions are held to resolve these issues, taking 4 days, followed by another review and resolution process that spans 6 days. The models are then finalized, and plans and documents are printed over a 5-day period. Approved preliminary studies initiate the next phase, where technical specifications and budgets are compiled. During this phase, any additional observations are addressed through a series of review and conformity supervision steps, each taking approximately 5-7 days.

Following the compilation of technical specifications and budget, the 2D plans are detailed, BIM content is verified, and measurements are documented. Each of these steps is meticulously planned to ensure no detail is overlooked, with verification steps and final observations taking an additional 7-9 days per step. The final preparation of the technical document involves several rounds of technical review and the resolution of any normative observations, ensuring the document's compliance with all technical standards. This phase culminates in the completion of the technical files, which are then approved and handed over for project supervision compliance.

This structured workflow ensures that all elements of the project are thoroughly checked and validated, reducing the risk of errors during the construction phase and ensuring a high level of coordination between all involved disciplines.

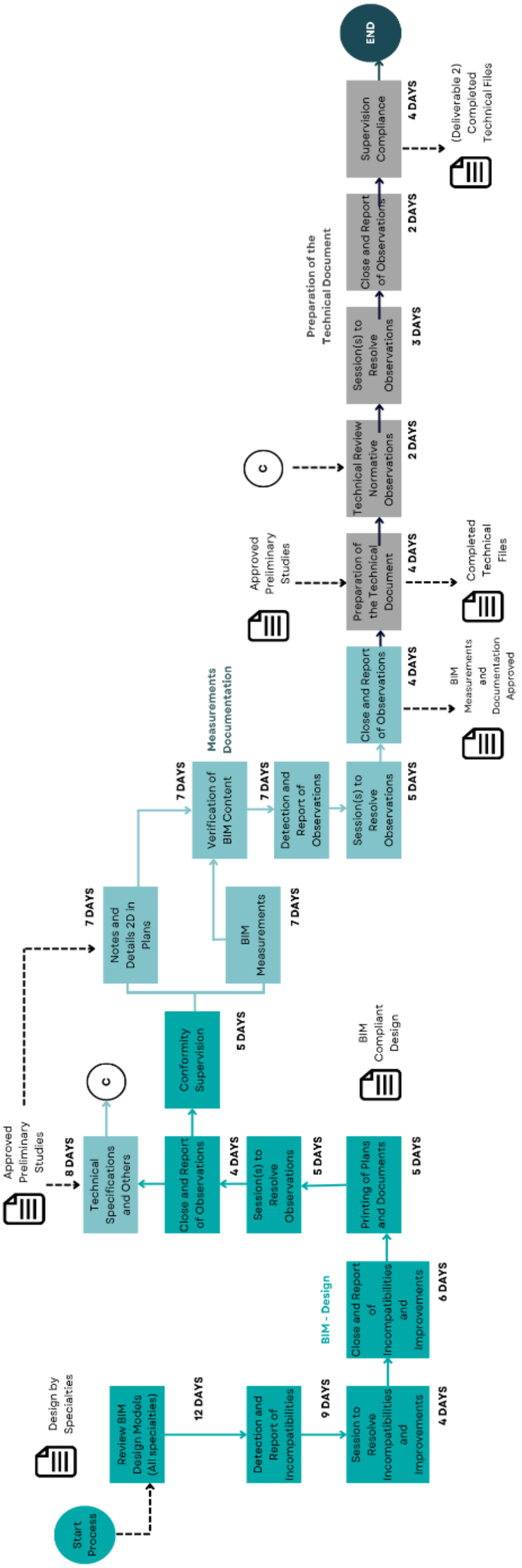


Figure 3. Example of Workflow with VDC (Virtual Design and Construction)

3.2 Building information modelling

3.2.1 BIM execution plan

The BIM Execution Plan is the initial document for the correct implementation of the BIM methodology in a project. For its development, each team must understand the needs and objectives of the client. Table 1 outlines the key points of the BIM Execution Plan (BEP), which serves as the foundational document for the effective implementation of BIM methodology in a project. The table emphasizes the importance of Identification in the BEP, focusing on establishing strategic objectives that are clearly understood by all parties involved. It also highlights the need to define specific strategies for BIM model development and the identification of the professionals responsible for the project. Additionally, the table underscores the significance of promoting a thorough understanding of the traceability of BIM implementation throughout the project's lifecycle, ensuring that all steps are aligned with the overall project goals.

Table 1. Main points of the BIM execution plan (BEP))

Identification
Establish strategic objectives that allow them to be understood among the parties involved
Define strategies for BIM model development
Identify the professionals involved in the project.
Promotes understanding of the traceability of BIM implementation throughout the project lifecycle.

3.2.2 Existing condition models

Surveying using a BIM model of the existing conditions reflects the current reality of the project, avoiding errors and rework. Figure 4 outlines the process of developing a Building Information Modeling (BIM) model based on existing infrastructure conditions. The workflow begins with the collection of Basic Information, which includes an inventory of the existing infrastructure, GIS information from all relevant disciplines, and a topographic survey of the current infrastructure. This foundational data is crucial for the accurate creation of a BIM model.

The process then moves to the Verification of Information stage, where the collected data is thoroughly reviewed to ensure its completeness. The figure highlights a decision point: "Is the information complete to create a BIM model?". If the information is deemed insufficient, the process loops back to documentation for further data collection or clarification. If the data is complete, the workflow progresses to the BIM development phase.

During BIM Development, the model is split into two main types: BIM model for linear works, as shown in Figure 5, and BIM model for point structures. These models are developed separately to cater to the specific characteristics and requirements of linear infrastructures like roads and point structures such as bridges or intersections.

Following the creation of these models, the process proceeds to the Coordination of BIM Models. In this step, the various BIM models, including linear and point models, are coordinated to ensure consistency and integration across the entire project. This coordination is essential for identifying and resolving any potential conflicts or discrepancies between the different models.

Finally, the coordinated BIM models are integrated into a Federated Model. This federated model serves as the comprehensive BIM representation of the existing infrastructure, combining all relevant data and ensuring that it is aligned and fully coordinated. The output from this phase is then transformed into various formats, including Native Models, Visualization Models (nwc), and Integrated Models (sqlite), which are shared via a Common Data Environment (CDE) to support further stages of the project.

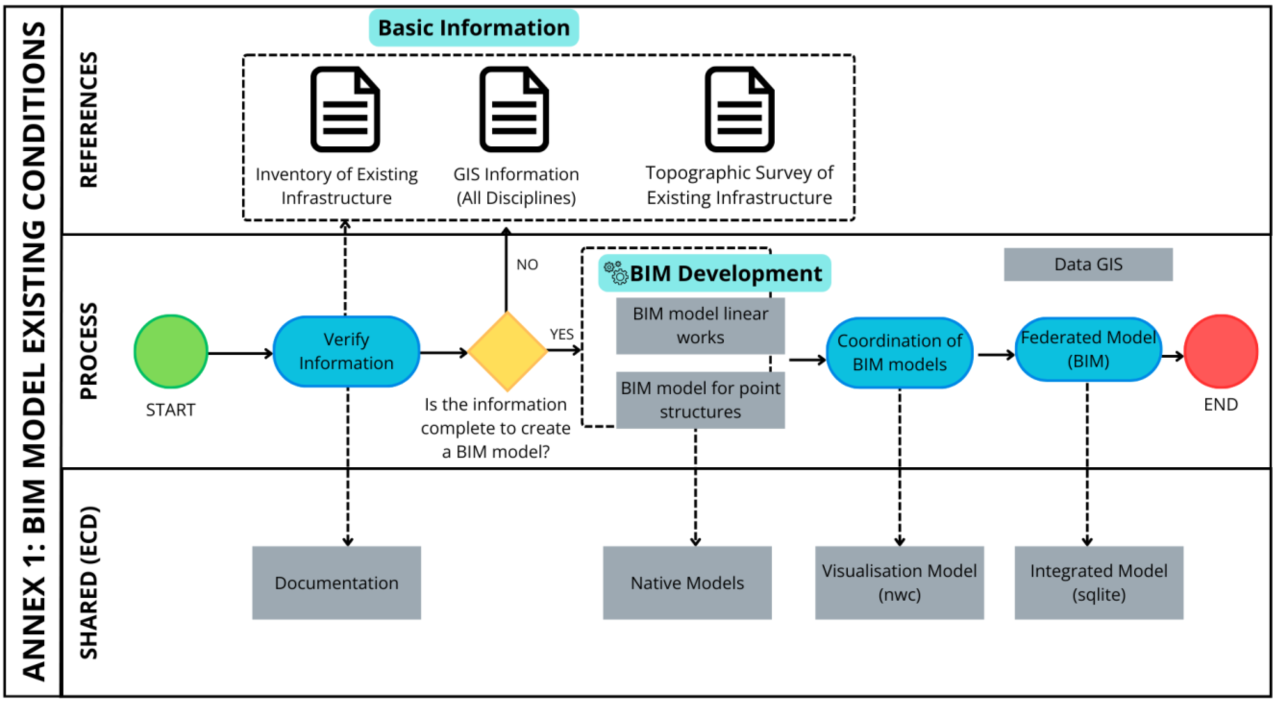
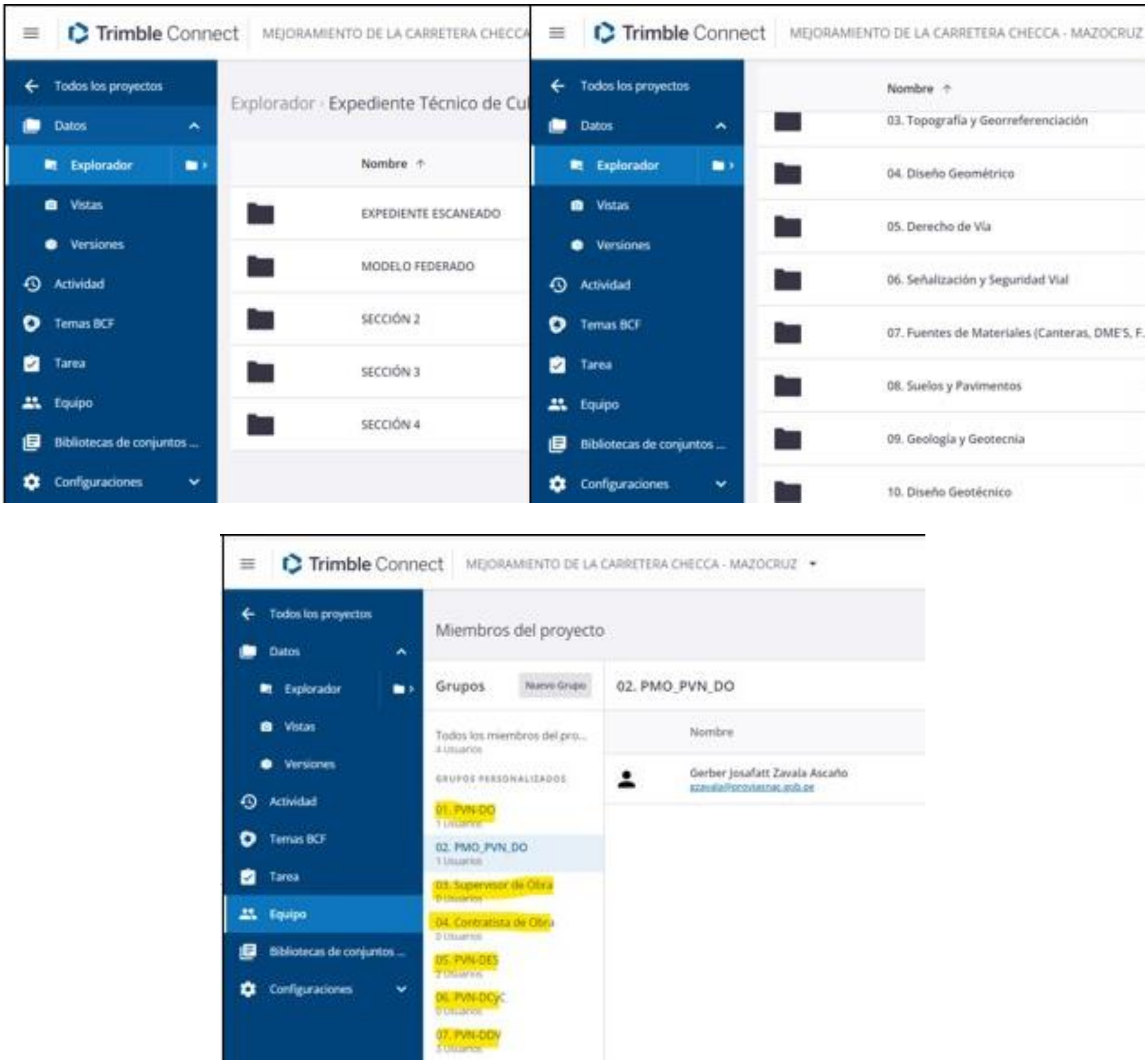


Figure 4. Workflow diagram for the correct application of BIM

Figure 5. Digitized terrain and existing infrastructure components

3.2.3 Information management using CDE

The structure of information containers must be classified in a way that allows for efficient review, making it easy and accessible for all project stakeholders. While ISO 19650 standards provide a framework for the status of information containers, it is crucial for the BIM manager to coordinate with project area managers to define the most efficient structure, ensuring that the review process is as straightforward as possible. Figure 6 illustrates the organization of information within a Common Data Environment (CDE) using Trimble Connect. It demonstrates how project data is structured and categorized, enabling easy access and efficient review by all stakeholders, thereby ensuring streamlined communication and collaboration throughout the project lifecycle.



EXPEDIENTE ESCANEADO
MODELO FEDERADO
SECCIÓN 2
SECCIÓN 3
SECCIÓN 4

03. Topografía y Georreferenciación
04. Diseño Geométrico
05. Derecho de Vía
06. Señalización y Seguridad Vial
07. Fuentes de Materiales (Canteras, DME'S, F.
08. Suelos y Pavimentos
09. Geología y Geotecnia
10. Diseño Geotécnico

Todos los miembros del pro...
4 Usuarios
GRUPOS PERSONALIZADOS
01. PVN-DO
02. PMO_PVN_DO
1 Usuarios
03. Supervisor de Obra
04. Contratista de Obra
05. PVN-DES
06. PVN-DCyC
07. PVN-DDV

02. PMO_PVN_DO
Gerber Josafatt Zavala Ascaño

Figure 6. Information management through CDE (Common Data Environment)

3.3 Concurrent integrated engineering

The concept of Concurrent Integrated Engineering is not only related to construction. Its beginnings are mainly linked to the development of product engineering. This methodology evolved as a response to the increasing complexity of organizations and projects, which challenged traditional sequential development processes [18]. Concurrent engineering emphasizes teamwork and information sharing between various functions, from conception to disposal, including quality, cost, schedule, and user requirements [19], [20]. Years later, the concept was adopted in the construction industry [21], becoming a systematic approach to take into account downstream aspects of design and construction, as well as eliminating non-value-adding activities throughout the project lifecycle [22]. Today, these integrated practices encompass holistic approaches that achieve dynamic interaction between project participants, processes, and technologies throughout the entire project lifecycle [23].

3.3.1 Design and 3D view

In ICE sessions, using BIM/GIS models enhances the visualization of proposals by specialty, leading to a better understanding of processes and more informed decision-making. Additionally, from 2D documentation, we obtain the 3D model to benefit the end user. Figure 7 illustrates the workflow for developing a BIM model, beginning with the evaluation of approved reference information such as topography, geometric design, and typical sections of linear work. The process is divided into two main paths: the creation of linear works models and point structure models. Each path involves georeferencing, creating assemblies, and configuring the model for measurements and drawing production. The workflow ensures coordination between models, integration with GIS, and approval from all disciplines before finalizing into a federated model. The final outputs include various model types shared in a Common Data Environment (CDE) for further project use.

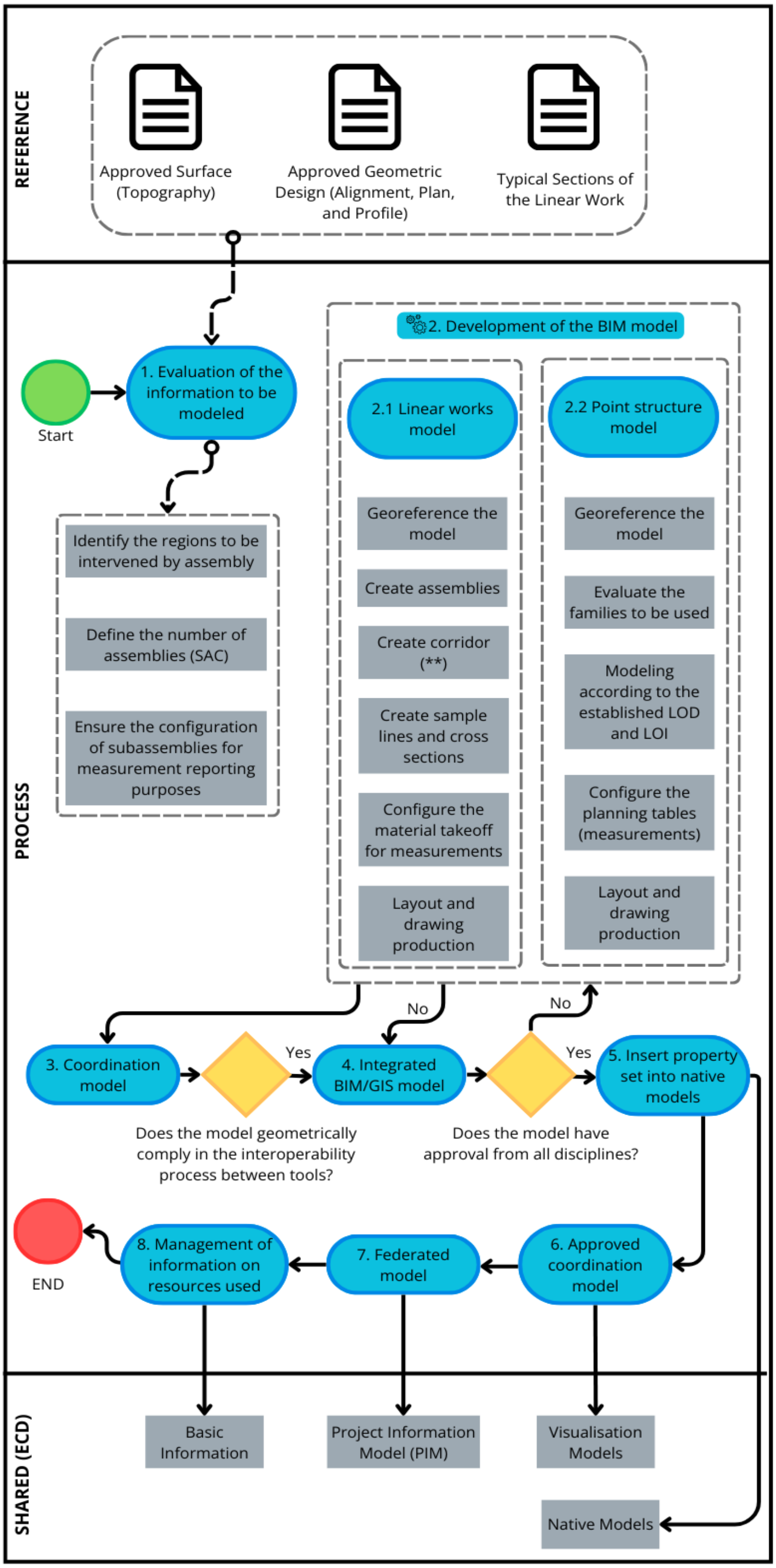


Figure 7. BIM workflow for final design

Then, Figure 8 compares the existing and improved conditions of a road project, highlighting the enhancements made through coordinated efforts among specialists. In the initial state, drainage issues and incomplete bridge abutments were identified. The improvements, developed collaboratively by experts in topography, hydrology, and structural engineering, address these issues, ensuring proper drainage and adequate coverage of river flow, all facilitated by advanced modeling tools. This visual representation emphasizes the importance of interdisciplinary collaboration in refining infrastructure designs.

En la carretera las cunetas están diseñadas y ubicadas donde corresponden.
Se identificó que estas no presentan descargas, por lo que se plantearon mejoras coordinadamente entre los especialistas.

En la carretera los estribos de los puente están construidos. En el expediente técnico original los diseños de las defensas ribereñas están en 2D o CAD.
Se identificó que estas no abarcan el área caudal del río, por lo que se plantearon mejoras coordinadamente entre los especialistas de topografía, hidrología, estructuras y jefe de proyecto, con la participación de los modeladores.

Figure 8. Improvement of solutions using BIM Model and ICE sessions

3.3.2 3D coordination and opportunity identification

By generating a coordinated BIM model, the project team can identify irregularities and incompatibilities among the different BIM models involved as shown in Figure 9. This early detection capability is crucial for optimizing the quality and consistency of deliverables, thus ensuring the constructability of assets during the execution phase. Identifying irregularities and incompatibilities through a coordinated BIM model allows for addressing potential issues before they become significant obstacles during construction. This proactive approach facilitates the resolution of conflicts between disciplines, such as structural, topography, hydrology and artworks systems, ensuring that all project components are perfectly aligned and functioning in harmony.

Sesión ICE, donde se identificó incompatibilidad entre los accesos transversales a la carretera, procediéndose a corregir mediante el empleo de orto foto y diseño geométrico.

Sesión ICE, donde se identificó incompatibilidad, procediéndose a corregir la altura del del buzon, mediante el empleo de modelamiento 3D; con la participación de los especialistas de: diseño geométrico y drenaje, jefe de proyecto.

Figure 9. Claim and incompatibility resolution using BIM

Additionally, the use of a coordinated BIM model improves project efficiency by reducing the need for rework and corrections on the construction site. By anticipating and resolving issues during the design phase, risks are minimized, and resources are used more effectively, reducing both costs and delivery times. The BIM model also provides a platform for continuous collaboration among all project participants, facilitating communication and informed decision-making. By sharing a common and updated model, all stakeholders have access to the same accurate information, enhancing coordination and consistency at every stage of the project.

3.3.3 4D construction sequence

To optimize the implementation of VDC, a strategy was developed that considers the value of resources, ensuring their optimal use. The construction sequence is activated once the detailed engineering has been approved, ensuring that all technical and structural aspects are fully defined. To execute this sequence, it is essential to establish smooth and constant communication between the construction team and the planning team. This coordination ensures that all activities align with the overall plan and that any necessary adjustments are made in a timely manner. The use of a BIM model is crucial at this stage, as it allows the construction sequence to be visually and detailedly reflected, facilitating understanding and monitoring by all involved [24].

Figure 10 illustrates the process of developing a 4D-enabled BIM model, starting from the extraction of solids from native BIM models of linear works and structures. The process begins with verifying whether the BIM model contains the necessary set of properties. If the model is complete and contains these properties, the workflow moves forward to create partitions on the solid according to the length of the asset, ensuring it aligns with the construction strategy. Next, assemblies are created based on item or material type. These assemblies are then used to generate a coordinated model, which integrates all elements of the project, including estimated construction planning. The final output is a federated BIM model that is shared in the Common Data Environment (CDE), enabling effective project coordination and planning.

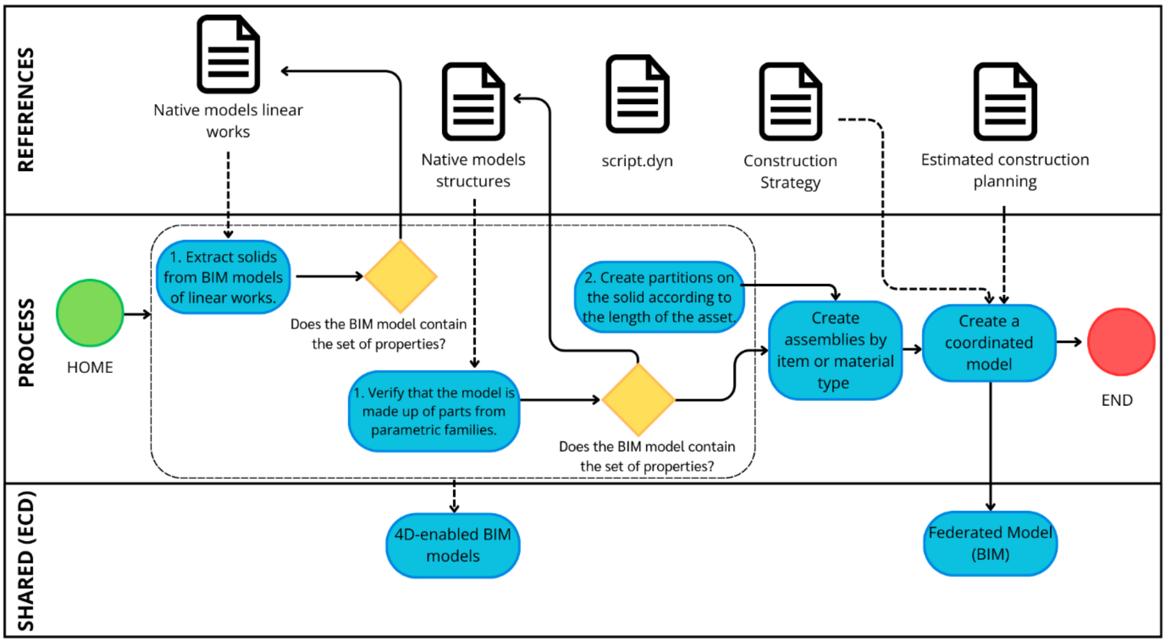


Figure 10. Construction workflow in 4D

The BIM model not only helps visualize the construction sequence, as shown in Figure 11, but also serves as an interactive tool to identify and resolve potential conflicts before they occur on the construction site, which can ultimately lead to disputes during the construction phase [25]. By integrating all disciplines and aspects of the project into a single model, a smoother and more efficient execution can be ensured. Finally, this construction sequence, detailed and visualized through the BIM model, is communicated to the client as an integral part of the pre-construction work plan. This not only provides the client with a clear understanding of the construction process but also allows them to actively participate in decision-making and project progress monitoring.

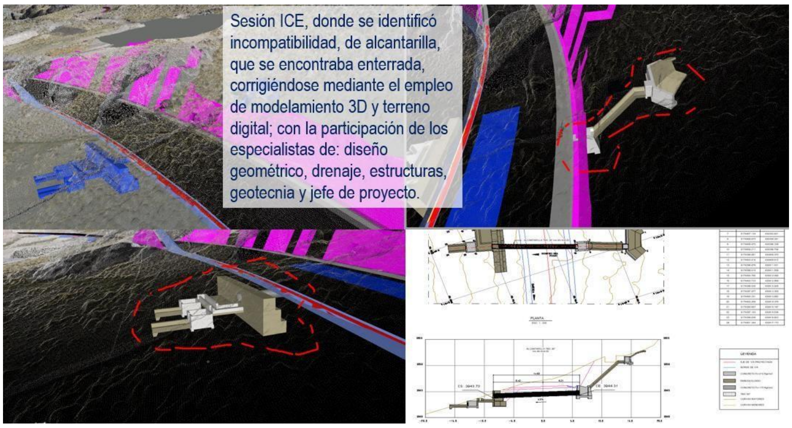

Sesión ICE, donde se identificó incompatibilidad, de alcantarilla, que se encontraba enterrada, corrigiéndose mediante el empleo de modelamiento 3D y terreno digital; con la participación de los especialistas de: diseño geométrico, drenaje, estructuras, geotecnia y jefe de proyecto.

Figure 11. Assessment of the construction sequence

This strategy ensures that all project participants are aligned and maximizes efficiency and effectiveness at each stage of the construction process. The integration of VDC and BIM in project planning and execution not only improves the quality of the final result but also optimizes resource use, reduces the risk of delays and cost overruns, and increases customer satisfaction by providing greater transparency and control over the project.

3.3.4 Obtaining quantities in 5D

Accurate material quantities were obtained from a BIM model by reviewing and validating the configurations in the models to generate a coherent material report. Once the progression of the structures was defined, the contour line coordinates were linked with the model. This allows for detailed and parametric engineering-level modeling, adapting to various dimensions according to the project's needs, as shown in Figure 12.

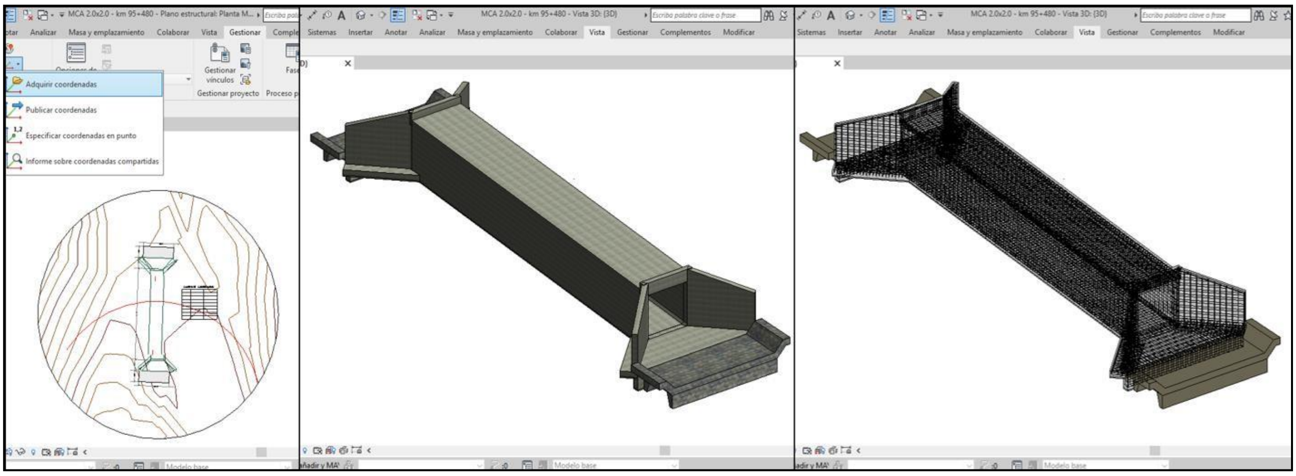
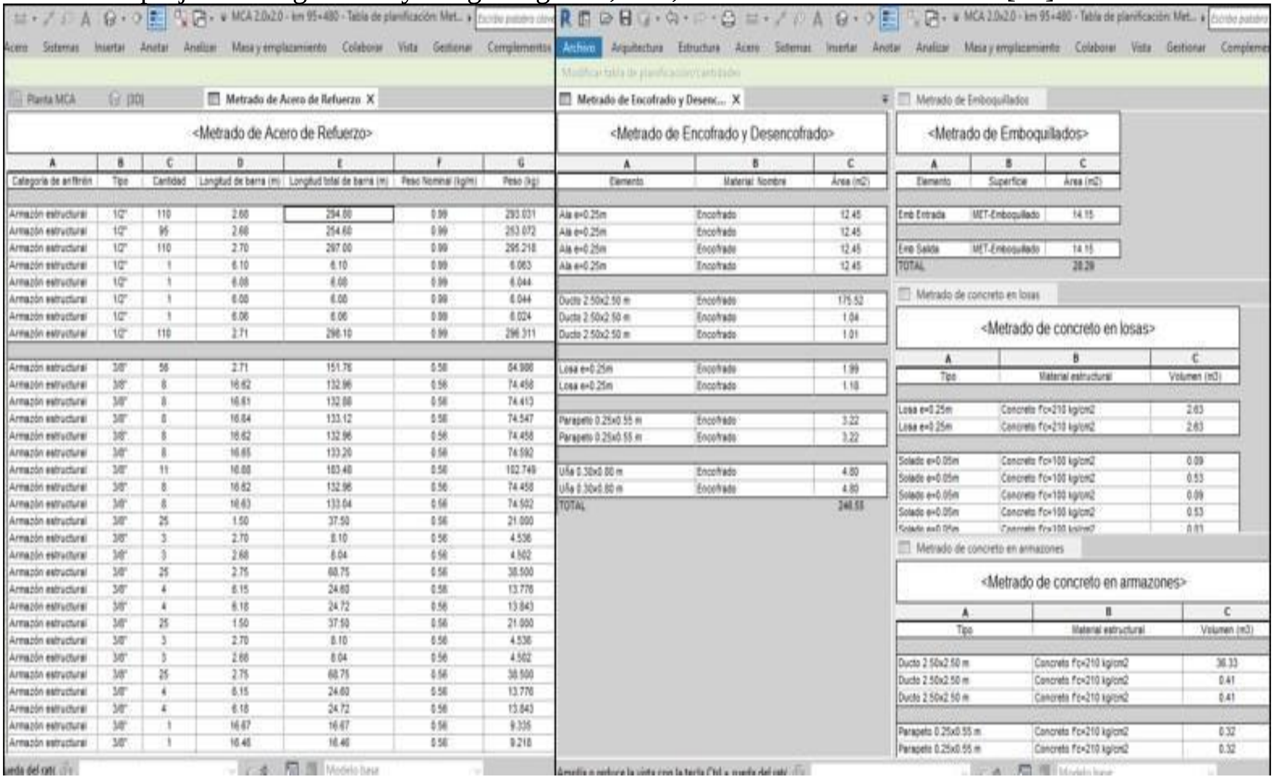


Figure 12. Linking to the terrain, detailed engineering and parameters

The quantities of reinforcing steel, formwork and stripping, embankments, and concrete are obtained directly from the BIM model. Detailed reinforcement drawings are then generated, following the sequence illustrated in Figure 13 (a and b). This process ensures that material quantities are accurate and aligned with the specific project requirements, thereby optimizing construction planning and execution. VDC with 5D BIM can improve construction project management by integrating time, cost, and 3D model information [26].



<Metrado de Acero de Refuerzo>

A	B	C	D	E	F	G
Categoría de anfitrión	Tipo	Cantidad	Longitud de barra (m)	Longitud total de barra (m)	Peso Nominal (kg/m)	Peso (kg)
Armazón estructural	1/2"	110	2.68	294.80	0.99	293.031
Armazón estructural	1/2"	95	2.68	254.60	0.99	253.072
Armazón estructural	1/2"	110	2.70	297.00	0.99	295.218
Armazón estructural	1/2"	1	6.10	6.10	0.99	6.063
Armazón estructural	1/2"	1	6.08	6.08	0.99	6.044
Armazón estructural	1/2"	1	6.08	6.08	0.99	6.044
Armazón estructural	1/2"	1	6.06	6.06	0.99	6.024
Armazón estructural	1/2"	110	2.71	298.10	0.99	296.311
Armazón estructural	3/8"	56	2.71	151.76	0.56	84.986
Armazón estructural	3/8"	8	16.62	132.96	0.56	74.458
Armazón estructural	3/8"	8	16.61	132.88	0.56	74.413
Armazón estructural	3/8"	8	16.64	133.12	0.56	74.547
Armazón estructural	3/8"	8	16.62	132.96	0.56	74.458
Armazón estructural	3/8"	8	16.65	133.20	0.56	74.592
Armazón estructural	3/8"	11	16.68	183.48	0.56	102.749
Armazón estructural	3/8"	8	16.62	132.96	0.56	74.458
Armazón estructural	3/8"	8	16.63	133.04	0.56	74.502
Armazón estructural	3/8"	25	1.50	37.50	0.56	21.000
Armazón estructural	3/8"	3	2.70	8.10	0.56	4.536
Armazón estructural	3/8"	3	2.68	8.04	0.56	4.502
Armazón estructural	3/8"	25	2.75	68.75	0.56	38.500
Armazón estructural	3/8"	4	6.15	24.60	0.56	13.776
Armazón estructural	3/8"	4	6.18	24.72	0.56	13.843
Armazón estructural	3/8"	25	1.50	37.50	0.56	21.000
Armazón estructural	3/8"	3	2.70	8.10	0.56	4.536
Armazón estructural	3/8"	3	2.68	8.04	0.56	4.502
Armazón estructural	3/8"	25	2.75	68.75	0.56	38.500
Armazón estructural	3/8"	4	6.15	24.60	0.56	13.776
Armazón estructural	3/8"	4	6.18	24.72	0.56	13.843
Armazón estructural	3/8"	1	16.67	16.67	0.56	9.335
Armazón estructural	3/8"	1	16.46	16.46	0.56	9.218

<Metrado de Encofrado y Desencofrado>

A	B	C
Elemento	Material: Nombre	Área (m2)
Ala e=0.25m	Encofrado	12.45
Ala e=0.25m	Encofrado	12.45
Ala e=0.25m	Encofrado	12.45
Ala e=0.25m	Encofrado	12.45
Ducto 2.50x2.50 m	Encofrado	175.52
Ducto 2.50x2.50 m	Encofrado	1.04
Ducto 2.50x2.50 m	Encofrado	1.01
Losa e=0.25m	Encofrado	1.99
Losa e=0.25m	Encofrado	1.18
Parapeto 0.25x0.55 m	Encofrado	3.22
Parapeto 0.25x0.55 m	Encofrado	3.22
Uña 0.30x0.80 m	Encofrado	4.80
Uña 0.30x0.80 m	Encofrado	4.80
TOTAL		246.55

<Metrado de Emboquillados>

A	B	C
Elemento	Superficie	Área (m2)
Emb Entrada	MET-Emboquillado	14.15
Emb Salida	MET-Emboquillado	14.15
TOTAL		28.29

<Metrado de concreto en losas>

A	B	C
Tipo	Material estructural	Volumen (m3)
Losa e=0.25m	Concreto f'c=210 kg/cm2	2.63
Losa e=0.25m	Concreto f'c=210 kg/cm2	2.63
Solado e=0.05m	Concreto f'c=100 kg/cm2	0.09
Solado e=0.05m	Concreto f'c=100 kg/cm2	0.53
Solado e=0.05m	Concreto f'c=100 kg/cm2	0.09
Solado e=0.05m	Concreto f'c=100 kg/cm2	0.53

<Metrado de concreto en armazones>

A	B	C
Tipo	Material estructural	Volumen (m3)
Ducto 2.50x2.50 m	Concreto f'c=210 kg/cm2	36.33
Ducto 2.50x2.50 m	Concreto f'c=210 kg/cm2	0.41
Ducto 2.50x2.50 m	Concreto f'c=210 kg/cm2	0.41
Parapeto 0.25x0.55 m	Concreto f'c=210 kg/cm2	0.32
Parapeto 0.25x0.55 m	Concreto f'c=210 kg/cm2	0.32

Figure 13a. Obtaining quantities and generating sheets from the model

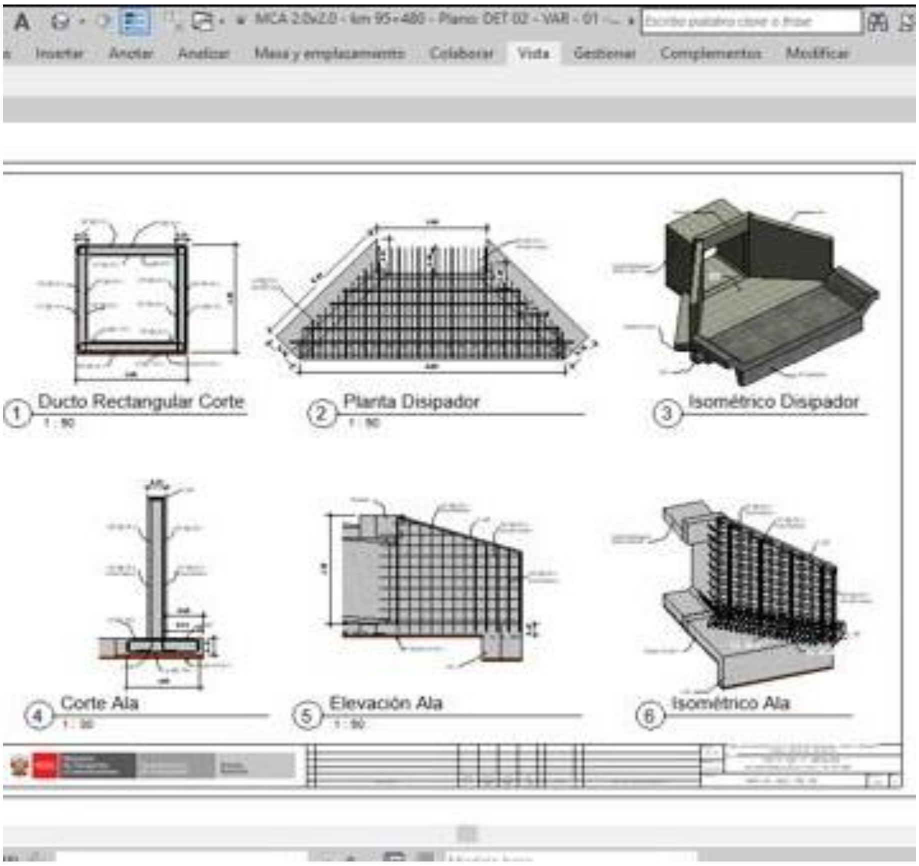


Figure 14b. Obtaining quantities and generating sheets from the model

3.3.5 Infographics and virtual tours

To develop virtual tours that allow for a thorough understanding of the project proposals, it is essential to use a tool that supports various BIM and GIS model formats, as shown in Figure 14. This tool should be capable of integrating and handling data from different sources, providing an accurate and coherent representation of the project environment. Additionally, the tool should allow for the generation of high-quality rendered animations. These animations are extremely useful for multiple purposes, such as social awareness campaigns in the sectors that will be affected by the project. Rendered animations can help communicate the benefits and impact of the project clearly and visually appealingly, facilitating understanding and acceptance by the community.

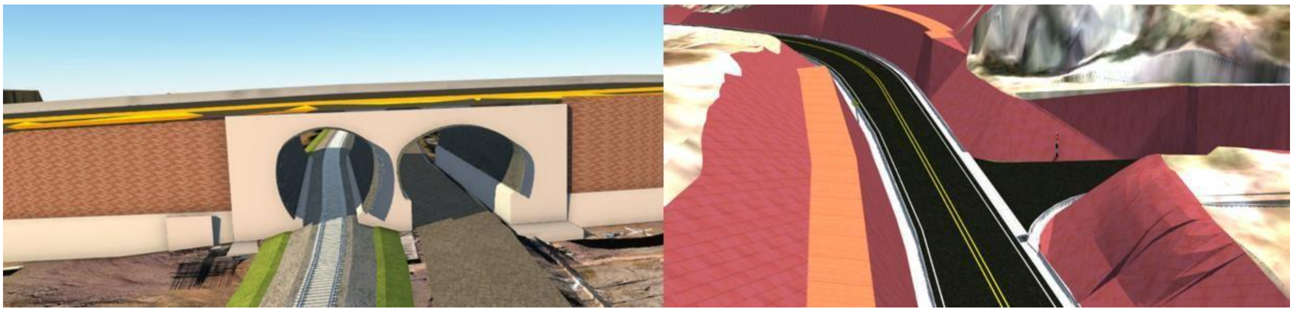


Figure 15. Virtual tour and animations to understand, evaluate and publicize the project

Additionally, these animations are valuable for everyone involved in the project, including designers, engineers, builders, and clients. They provide a realistic preview of how the project will look once completed, allowing for the identification and resolution of potential issues before they arise in the construction phase. This level of detail and realism enhances decision-making, as all stakeholders can visualize the project in its entirety and understand how each component interacts with the others. The ability to create virtual tours and rendered animations also facilitates presenting the project to investors and regulators, clearly showing the project's progress and feasibility. This not only helps secure necessary funding and approvals but also improves transparency and confidence in the project.

3.4 Production metrics and controllable factors

The implementation of Virtual Design and Construction (VDC) through the use of production metrics and controllable factors, in conjunction with Building Information Modeling (BIM), Integrated Concurrent Engineering (ICE), and Project Production Management (PPM), allows for objective and concrete tracking and control of the actual project progress, ensuring the achievement of daily, weekly, and/or monthly goals. The main metrics used are detailed in Table 2.

Table 2. Main metrics in VDC using

Metric	Objective	Achieved
% Fulfillment of BIM models and documentation scope	min 100%	100% achieved
# Design improvement options per specialty	0.03	0.036
Resolved observations / total observations	≥ 95%	1
% Pending incompatibilities resolved per ICE session	≥ 90%	1
% Tasks executed / tasks scheduled per week	≥ 85%	0.904
# Quantified items / total items	≥ 100%	0.887

Each week, as new data is acquired and the project progresses, the production metrics and controllable factors for PPM indicate the need for specific adjustments within the work team. Specific workflows were added to facilitate the implementation of VDC, allowing for the evaluation of production metrics and controllable factors, and the continuous identification of bottlenecks as the project advances. New processes were established to interrelate routine coordination meetings with ICE sessions. Additionally, processes were incorporated to conduct ICE sessions both to resolve incompatibilities and address pending issues.

Figure 15 illustrates the alignment of client and project objectives with production metrics and controllable factors within a road infrastructure project in Puno. The client objectives are focused on two main goals: completing the technical file for a 73 km road project within 95 days and ensuring that there are no deficiencies between the design and measurements for the tender scheduled in 2022. These overarching goals are translated into specific project objectives, such as the approval of the technical dossier within the stipulated timeframe.

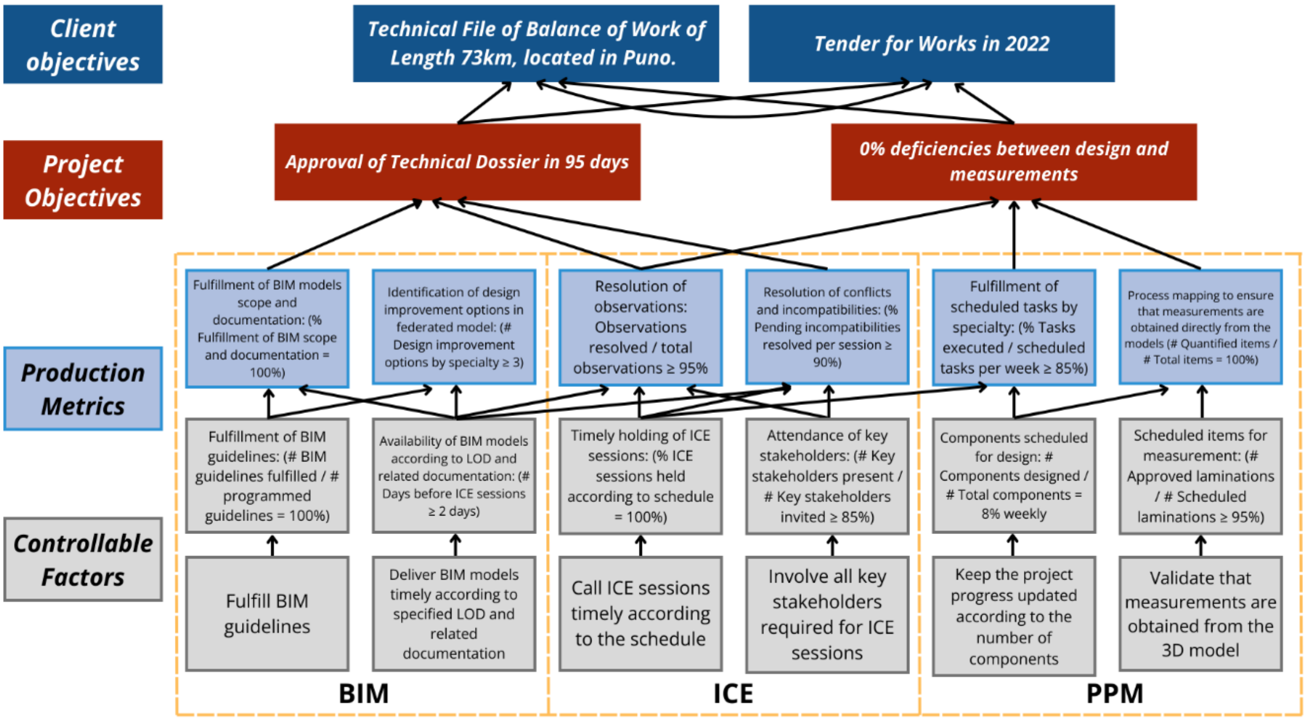


Figure 16. Alignment of client objectives with project metrics and controllable factors

The process then breaks down these project objectives into production metrics, which are used to monitor the fulfillment of goals across three key areas: BIM (Building Information Modeling), ICE (Integrated Concurrent Engineering), and PPM (Project Production Management). The production metrics track various aspects of the project, including the completion of BIM model scopes, the identification of design improvements, the resolution of observations, and the fulfillment of scheduled tasks by specialty. Each of these metrics has a specific target, such as achieving 100% fulfillment of BIM scope or resolving 95% of observations.

To achieve these metrics, the process outlines specific controllable factors for each area. In the BIM domain, the focus is on fulfilling BIM guidelines and ensuring the timely delivery of BIM models according to the required Level of Detail (LOD) and related documentation. In the ICE area, the controllable factors include the timely scheduling of ICE sessions, the involvement of all key stakeholders, and ensuring their participation in the sessions. For PPM, the focus is on keeping the project progress updated according to the number of components designed and validating those measurements are accurately derived from the 3D model.

3.5 Discussion

The integration of Virtual Design and Construction (VDC) methodologies, Building Information Modeling (BIM), Project Production Management (PPM), and Integrated Concurrent Engineering (ICE) in the management of road infrastructure projects in Peru has demonstrated significant benefits, although it also presents challenges.

One of the main observed benefits is the improvement in coordination and collaboration among project participants. The use of BIM facilitates the creation of comprehensive digital models that provide a clear visualization of all project components, allowing stakeholders to identify and resolve potential issues before construction activities begin. This preventive problem-solving reduces the likelihood of delays and cost overruns [27], issues that have historically affected infrastructure projects in Peru and other countries. BIM offers a valuable information base necessary for risk management to prevent potential future events from impacting the schedule and cost of the road infrastructure project [28], [29].

The application of PPM further strengthens project management by optimizing workflows and resource allocation. Through systematic planning and control of production processes, PPM minimizes variability and improves the predictability of project outcomes. This structured approach ensures that all project activities align with overall objectives, leading to more efficient and effective execution. Within PPM actions, it is crucial for project managers to make decisions to prevent future risks based on information widely provided by BIM. It may become important to introduce more robust approaches such as the epistemological approach to prevent risks that may escape the subjectivity of expert judgment [30].

ICE sessions play a crucial role in fostering multidisciplinary collaboration. By bringing together various specialists to work simultaneously on project models, ICE sessions facilitate quick decision-making and improve the quality of design solutions. This collaborative environment helps integrate different perspectives and specialized knowledge, resulting in more robust and well-founded project plans.

Despite these benefits, the implementation of VDC in Peru has encountered several challenges. A significant problem is the partial and uncoordinated application of BIM, PPM, and ICE methodologies in different projects. Many projects lack a common data environment, and the integration of multidisciplinary teams using BIM models remains inconsistent. This fragmented approach undermines the potential benefits of VDC, leading to missed opportunities for improving efficiency and quality.

One of the significant challenges in implementing VDC in Peruvian projects has been cultural resistance to change, where teams accustomed to traditional methods struggle to adapt to advanced digital tools. To overcome these challenges, it is crucial to implement training programs that develop competencies in BIM and PPM, establish adequate digital infrastructure, and support policies that facilitate VDC adoption in public projects

Additionally, there is an evident need for continuous training and development among project teams. Successful adoption of VDC methodologies requires all stakeholders, from engineers to project managers, to be proficient in using BIM tools and familiar with PPM and ICE processes. Investment in continuous professional development is essential to ensure that the workforce can effectively leverage these advanced methodologies.

Simulations conducted in this study provide quantitative evidence of the potential impact of complete VDC methodology integration. The results indicate that full integration could reduce project execution times by approximately 20% and costs by 15%. These findings underscore the value of adopting a comprehensive and coordinated approach to VDC, aligned with the strategic objectives set out in Peru's national infrastructure development plans.

Based on the findings of this study, several recommendations can be made to improve the implementation of VDC in road infrastructure projects in Peru. First, it is crucial to establish a common data environment (CDE) that ensures all stakeholders have access to accurate and up-to-date information. Second, multidisciplinary collaboration should be promoted through ICE sessions and other collaborative practices. Additionally, it is necessary to invest in regular training programs to improve project teams' skills in effectively using BIM, PPM, and ICE methodologies. Clear production metrics and controllable factors should also be developed and used to monitor project progress and make data-based adjustments as needed.

The integration of VDC, BIM, PPM, and ICE offers a path to improving road infrastructure project management in Peru. By addressing current challenges and implementing recommended practices, it is possible to achieve greater efficiency, profitability, and quality in project outcomes. This strategy not only optimizes resource use, reduces the risk of delays and cost overruns, but also increases client satisfaction by providing greater transparency and control over the project. Each methodology within VDC plays a specific role: BIM enhances visualization and planning, PPM ensures efficient and predictable processes, and ICE allows for agile resolution of interdisciplinary conflicts.

3.6 Future work

Future research should explore the application of VDC in other sectors of the construction industry, such as residential or commercial building projects, to determine whether the benefits observed in road infrastructure can be replicated. Additionally, longitudinal studies that track the long-term impact of VDC on project outcomes would provide valuable insights into its sustainability and effectiveness over time. Further investigation is also needed to develop strategies for overcoming the specific challenges of VDC implementation in different cultural and economic contexts. Finally, the integration of emerging technologies such as artificial intelligence and machine learning into the VDC framework presents an exciting avenue for future research, potentially leading to even greater improvements in project management and execution.

4 Conclusions

The integration of Virtual Design and Construction (VDC) methodologies, including Building Information Modeling (BIM), Project Production Management (PPM), and Integrated Concurrent Engineering (ICE), resulted in measurable improvements in the management of a road infrastructure project in Peru, as demonstrated in the case study. The project achieved 100% fulfillment of the BIM model scope and documentation.

In the case study, the number of design improvement options per specialty reached 0.036, surpassing the target of 0.03. The project recorded a 100% resolution rate for observations, meeting the objective of resolving all identified issues. Additionally, a 100% resolution rate for pending incompatibilities was achieved during ICE sessions, exceeding the target of 90%. The task execution rate was 90.4% of scheduled tasks per week, above the target of 85%, indicating effective project scheduling. The accuracy of item quantification from 3D models was 88.7%, approaching the target of 100%.

These results, specific to the case study, indicate that the application of VDC methodologies contributed to improved project management outcomes. Further research and broader implementation across different projects are necessary to confirm the generalizability of these findings. VDC be widely adopted in future projects with a focus on continuous training and the creation of robust digital infrastructures.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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Author contributions

Conceptualization: Gerber Zavala and Michael Chacón; Methodology: Gerber Zavala and Victor Andre Ariza Flores; Software: Gerber Zavala and Michael Chacón; Validation: Gerber Zavala and Victor Andre Ariza Flores; Formal Analysis: Gerber Zavala and Michael Chacón; Investigation: Gerber Zavala, Michael Chacón and Victor Andre Ariza Flores; Resources: Gerber Zavala; Data Curation: Gerber Zavala; Writing – Original Draft: Victor Andre Ariza Flores; Writing – Review & Editing: Gerber Zavala and Michael Chacón; Visualization: Gerber Zavala and Michael Chacón; Supervision: Gerber Zavala and Victor Andre Ariza Flores; Project Administration: Gerber Zavala.

References

[1] N. Darko Otoo, "Determinants of Schedule Delay and Cost Overruns in Infrastructure Projects in Ghana," *Academy of Accounting and Financial Studies Journal*, vol. 25, no. 5, 2021.

[2] O. Sánchez, K. Castañeda, G. Mejía, and E. Pellicer, "Delay Factors: A Comparative Analysis between Road Infrastructure and Building Projects," in *Construction Research Congress 2020: Project Management and Controls, Materials, and Contracts - Selected Papers from the Construction Research Congress 2020*, 2020. doi: 10.1061/9780784482889.024.

[3] C. Bowlby, "Berlín Brandenburg: el aeropuerto con medio millón de fallas que contradice la imagen de eficiencia de Alemania," BBC News.

[4] C. Juarez, "Retraso en inauguración de obras de ampliación del Canal de Panamá," *The Logistic Worlds*, Panamá, pp. 1–2, Feb. 07, 2019. Accessed: Jul. 21, 2024. [Online]. Available: https://acortar.link/6p8Z9s

[5] J.-P. Wolff, "La recomposition des jeux d'acteurs liée aux conflits induits par le projet de LGV Bordeaux – Toulouse," *Sud-Ouest européen*, no. 40, pp. 43–55, Dec. 2015, doi: 10.4000/soe.2145.

[6] A. Lara, "EL AVE MADRID-BARCELONA, una obra de mérito," *Ciencia y Técnica*, pp. 53–62, 2015.

[7] E. Kayelle, E. K. Rabbani, and M. Macedo, "Identifying the Causes of Delay Using the Analytic Hierarchy Process (AHP) Method in Brazilian Public Road Infrastructure Projects," *Journal of Management and Sustainability*, vol. 13, no. 2, 2023, doi: 10.5539/jms.v13n2p45.

[8] K. Castañeda, O. Sánchez, R. F. Herrera, A. Gómez-Cabrera, and G. Mejía, "Building Information Modeling Uses and Complementary Technologies in Road Projects: A Systematic Review," *Buildings*, vol. 14, no. 3, p. 563, Feb. 2024, doi: 10.3390/buildings14030563.

[9] D. Zhou, B. Pei, X. Li, D. Jiang, and L. Wen, "Innovative BIM technology application in the construction management of highway," *Sci Rep*, vol. 14, no. 1, p. 15298, Jul. 2024, doi: 10.1038/s41598-024-66232-5.

[10] C. H. G. Paniura *et al.*, "RESEARCH METHODOLOGIES IN ENGINEERING SCIENCES: A CRITICAL ANALYSIS," *Operational Research in Engineering Sciences: Theory and Applications*, vol. 6, no. 1, pp. 204–222, 2023, doi: 10.31181/oresta/060109.

[11] R. Sacks, C. Eastaman, G. Lee, and P. Teicholz, *BIM Handbook: A guide to Building Information Modeling for Owners, Designers, Engineers, Contractors and Facility Managers*, 3rd ed. Wiley, 2018.

[12] A. Darko, A. P. C. Chan, Y. Yang, and M. O. Tetteh, "Building information modeling (BIM)-based modular integrated construction risk management – Critical survey and future needs," *Comput Ind*, vol. 123, p. 103327, Dec. 2020, doi: 10.1016/j.compind.2020.103327.

[13] A. A. Del Savio, J. F. Vidal Quincot, A. D. Bazán Montalto, L. A. Rischmoller Delgado, and M. Fischer, "Virtual Design and Construction (VDC) Framework: A Current Review, Update and Discussion," 2022. doi: 10.3390/app122312178.

[14] A. Costin, A. Adibfar, H. Hu, and S. S. Chen, “Building Information Modeling (BIM) for transportation infrastructure – Literature review, applications, challenges, and recommendations,” *Autom Constr,* vol. 94, 2018, doi: 10.1016/j.autcon.2018.07.001.

[15] R. M. Aziz, T. I. Nasreldin, and O. M. Hashem, “The role of BIM as a lean tool in design phase,” *Journal of Engineering and Applied Science*, vol. 71, no. 1, p. 23, Dec. 2024, doi: 10.1186/s44147-023-00340-3.

[16] Y. H. Liau and Y. C. Lin, “Application of civil information modeling for constructability review for highway projects,” in *ISARC 2017 - Proceedings of the 34th International Symposium on Automation and Robotics in Construction*, 2017. doi: 10.22260/isarc2017/0057.

[17] J. C. P. Cheng, Q. Lu, and Y. Deng, “Analytical review and evaluation of civil information modeling,” 2016. doi: 10.1016/j.autcon.2016.02.006.

[18] B. Bowonder, S. Bhuyan, and K. J. Sharma, “Multiple perspectives of concurrent engineering and their integration,” *International Journal of Manufacturing Technology and Management*, vol. 6, no. 3/4, p. 372, 2004, doi: 10.1504/IJMTM.2004.005419.

[19] U. Menon and M. Graham, “Concurrent engineering: effective deployment strategies,” *Production*, vol. 6, no. 2, pp. 165–181, Dec. 1996, doi: 10.1590/S0103-65131996000200002.

[20] K. L. Kitto, “Integrating concurrent engineering into undergraduate design and research experiences,” in *Proceedings Frontiers in Education 1997 27th Annual Conference. Teaching and Learning in an Era of Change,* Stipes Publishing, pp. 955–959. doi: 10.1109/FIE.1997.636014.

[21] P. E. D. Love and A. Gunasekaran, “Concurrent Engineering in the Construction Industry,” *Concurrent Engineering*, vol. 5, no. 2, pp. 155–162, Jun. 1997, doi: 10.1177/1063293X9700500207.

[22] L. Pouchard and A. Cutting-Decelle, “Ontologies and standards-based approaches to interoperability for Concurrent Engineering,” in *Concurrent Engineering in Construction Projects*, Routledge, 2006, pp. 132–174. doi: 10.4324/9780203968918-14.

[23] A. E. Ikudayisi, A. P. C. Chan, A. Darko, and Y. M. D. Adedeji, “Integrated practices in the Architecture, Engineering, and Construction industry: Current scope and pathway towards Industry 5.0,” *Journal of Building Engineering*, vol. 73, p. 106788, Aug. 2023, doi: 10.1016/j.jobe.2023.106788.

[24] N. Salman and M. Hamadeh, “The Integration of Virtual Design and Construction (VDC) With the Fourth Dimension of Building Information Modeling (4D BIM),” *International Journal of BIM and Engineering Science*, vol. 7, no. 1, pp. 08–27, 2023, doi: 10.54216/IJBES.070101.

[25] A. Mohamed, A. Abd-Ellatif, and A. H. Nassar, “CLAIMS AND DISPUTES RESOLUTION USING BIM TECHNOLOGY AND VDC PROCESS IN CONSTRUCTION CONTRACT RISK ANALYSIS,” *INTERNATIONAL JOURNAL OF CIVIL ENGINEERING AND TECHNOLOGY (IJCIET)*, vol. 12, no. 4, Apr. 2021, doi: 10.34218/IJCIET.12.4.2021.007.

[26] M. L. Lee, W. T. Cheah, S. H. Lau, X. S. Lee, A. M. Abdullahi, and S. Y. Wong, “Evaluation of practicality of virtual design and construction (VDC) with 5D building information modelling (BIM) through a case study,” *IOP Conf Ser Mater Sci Eng*, vol. 943, no. 1, p. 012058, Oct. 2020, doi: 10.1088/1757-899X/943/1/012058.

[27] S. Melaku Belay, S. Tilahun, M. Yehualaw, J. Matos, H. Sousa, and E. T. Workneh, “Analysis of Cost Overrun and Schedule Delays of Infrastructure Projects in Low Income Economies: Case Studies in Ethiopia,” *Advances in Civil Engineering*, vol. 2021, 2021, doi: 10.1155/2021/4991204.

[28] V. A. Ariza Flores and R. Salvador, “Adaptive Risk Management in Road Construction: Oyon-Ambo Highway Insights, El Niño 2019 Case Study,” *E3S Web of Conferences*, vol. 497, p. 02020, Mar. 2024, doi: 10.1051/e3sconf/202449702020.

[29] K. N. Ali, H. H. Alhajlah, and M. A. Kassem, “Collaboration and Risk in Building Information Modelling (BIM): A Systematic Literature Review,” *Buildings*, vol. 12, no. 5, p. 571, Apr. 2022, doi: 10.3390/buildings12050571.

[30] V. Ariza Flores, F. O. de Sousa, and S. Oda, “Enhancing Risk Management in Road Infrastructure Facing Flash Floods through Epistemological Approaches,” *Buildings*, vol. 14, no. 7, p. 1931, Jun. 2024, doi: 10.3390/buildings14071931.