BIM-based methodological framework for traffic analysis and simulation at road intersection design

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ABSTRACT

Traffic analysis at road intersections is an important activity in the project design and planning phases because it allows selecting the most suitable traffic requirements and site characteristics. Therefore, traffic simulation models are indispensable and useful tools to support collaborative decision-making. The building information modeling (BIM) approach shows great potential to contribute to the traffic analysis and road design improvement; however, BIM has been adopted mainly in the building sector, rather than road infrastructure projects. Therefore, this paper presents a BIM-based methodological framework for traffic analysis and simulation of road intersection design. The proposed framework has five main steps: 1) BIM models and traffic information collection; 2) BIM model configuration; 3) BIM simulation, analysis, and calibration; 4) BIM cost analysis and documentation; and 5) alternatives comparison and recommendations. The application of the proposed framework to a case study shows several BIM implementation benefits in the traffic analysis at road intersections. Some of the most prominent BIM benefits

observed in the case study are a better understanding of design, improved project quality, more efficient communications, scope clarification, and speed up the design process.

KEYWORDS: road intersections, road infrastructure, traffic simulation, building information modeling, methodological framework.

1. INTRODUCTION

The growth of the population and urban centers has caused notable increases in the demand for road infrastructure projects; some are focused on increasing capacity and improving existing infrastructure. Others are needed to connect urban centers and production areas (Papilloud, Röthlisberger, Loreti, & Keiler, 2020). Road intersections are one of the main components in a road infrastructure network, formed from crossing two or more road corridors in a specific area. Different traffic issues of pedestrians, bicycles, and vehicles emerge in road intersections (Zafri, Sultana, Himal, & Tabassum, 2020). Analyzing traffic at a road intersection is a crucial part of design, planning, control, management, and accident prevention, among others (Peiris et al., 2018; Zhao, Knoop, & Wang, 2020).

Traffic analysis is one of the activities carried out at the design phase of most intersections, characterized by many variables, some of them with high levels of complexity (Sadia & Polus, 2013; Shen, Tian, & Wang, 2013). Several platforms are used for traffic analysis in road projects: VISSIM, TSIS, AIMSUM, Paramics, and TransModeler (Chao et al., 2020; Yu, Zhang, Wang, & Bian, 2014). However, most platforms present difficulties in integrating information and traffic models with other disciplines involved in the road project life cycle. At the design phase, compatibility and consistency issues could lead to design and analysis errors that can turn into unwanted events such as delays, cost overruns, claims, and disputes (Aziz & Abdel-Hakam, 2016; Mejía, Sánchez, Castañeda, & Pellicer, 2020; Park & Papadopoulou, 2012; Sánchez, Castañeda, Herrera, & Pellicer, 2019). For this reason, methodologies and technologies that allow integrating traffic analysis and simulation to other project information are needed.

The building information modeling (BIM) approach has shown notable benefits in the information management and integration of construction projects (Gouda, Abdallah, & Marzouk, 2020) because a BIM model is assimilated as a parametric representation of the physical and functional characteristics of a construction project (Eastman, Liston, Sacks, & Liston, 2008). BIM makes it possible to guarantee coherence and compatibility, considering that the project information is stored and integrated into a digital database (Sampaio, Ferreira, Rosário, & Martins, 2010; Sánchez, Galvis, Porras, Ardila, & Martínez, 2017). BIM's uses and benefits have been widely explored and tested in the building sector (Bohórquez, Porras, Sánchez, & Mariño, 2018; Gouda et al., 2020; Tang, Shelden, Eastman, Pishdad-Bozorgi, & Gao, 2020). However, BIM is an emerging issue in road infrastructure projects.

The use of BIM in road infrastructure projects has been mainly focused on geometric road design, where efforts focus on improving, automating, and optimizing the geometry of road projects (Biancardo, Capano, de Oliveira, & Tibaut, 2020; Bongiorno, Bosurgi, Carbone, Pellegrino, & Sollazzo, 2019). Some studies have focused on integrating traffic data and BIM models in particular case studies (Adibfar & Costin, 2019; Aziz, Riaz, & Arslan, 2017; Costin et al., 2018). However, there is no previous contribution to the BIM-based methodological framework for traffic analysis at road intersections specifically; this gap will be justified later in Section 2.

Therefore, this study aims to propose a BIM-based methodological framework for traffic analysis at road intersection design. The methodological framework designed has five main steps: 1) BIM models and traffic information collection; 2) BIM model configuration; 3) BIM simulation, analysis, and calibration; 4) BIM costs analysis and documentation; and 5) alternatives comparison and recommendations.

2. LITERATURE BACKGROUND

2.1. Traffic congestion and the need for traffic analysis and simulation

The increasing traffic volume on the world's road networks has affected the quality of life and mental health of road users due to traffic jams resulting from vehicle congestion (Nadrian, Hossein, & Pouyesh, 2019). This problem has led to a continuous search for solutions to congestion problems and identifying and explaining the causative factors to propose solutions that minimize road congestion. Traffic jams occur when the traffic demand exceeds the capacity of the existing road infrastructure, which can be caused by traffic volumes, driver behavior, non-compliance with traffic regulations, deficiencies in the traffic control elements, road network geometry and characteristics, entrances to buildings and parking lots, weather effects, accidents, transportation systems operation, and construction and maintenance activities (Chidi & Ideh, 2018; Lee, Ibbs, & Thomas, 2005; Shen et al., 2020; Thoker, Gupta, & Kumar, 2020). As a result, the study of traffic is associated with a high level of complexity, a large volume of information, and extensive procedures.

Road congestion and associated issues have led to a growing demand for new road infrastructure projects that require detailed traffic analysis during the early project phases to ensure that project characteristics are aligned to the requirements. Therefore, different technical aspects must be included in the traffic analysis. Some of the most important are: profiles, alignments, geometry, capacity, service levels, traffic volumes, vehicle characteristics, parameters related to driver behavior, road characteristics, circulation rules, intersections, pedestrian crossings, elements of traffic control and road safety (Zhong, Lu, & Gang, 2007). The number and variety of variables involved lead to computer-aided simulation models being indispensable for traffic analysis activities, which allow studying the impact of road solutions in the future traffic development and the operation of project characteristics according to the needs that led to the project (Calvert & van Arem, 2020). Therefore, the elaboration of a traffic simulation model implies the development of a set of stages. According to Barcelo (2010), the main stages are: 1) real system observation, 2) real system analysis, 3) conceptual model, 4) translation verification, 5) simulation, analysis of results and feedback (see Figure 1).

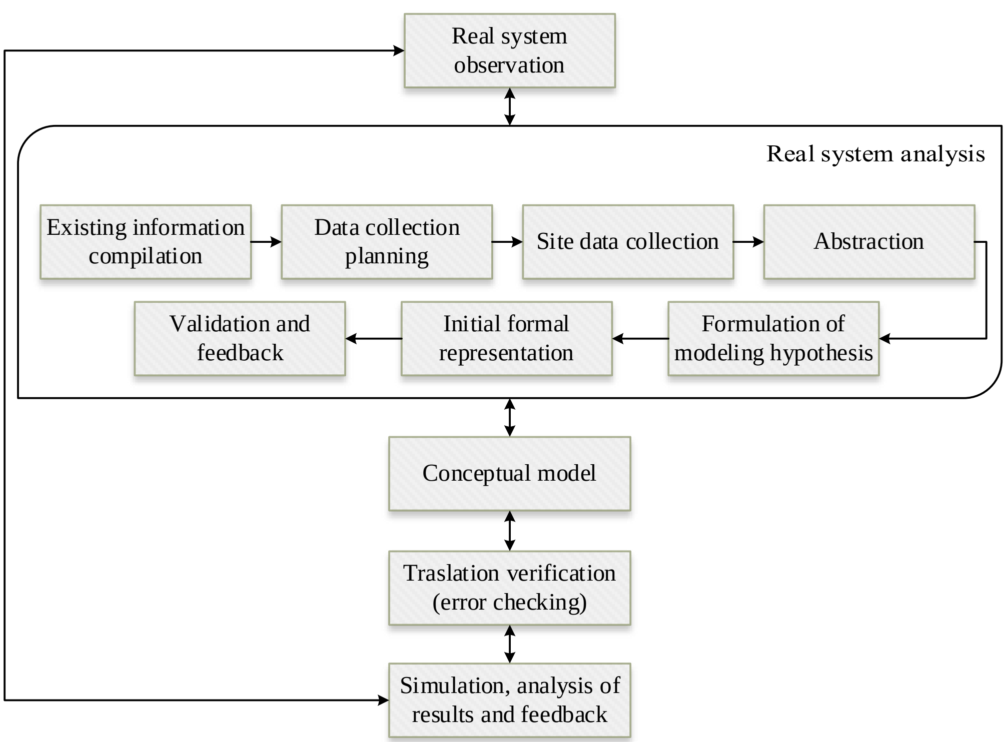

Figure 1. Methodological steps for developing a traffic simulation model. An adaptation from Barcelo (2010).

2.2. Types of traffic simulation models

The three principal types of traffic simulation models are microscopic, mesoscopic, and macroscopic (Barcelo, 2010; Bi, Mao, Wang, & Deng, 2020). The *microscopic* simulation model is based on describing the behavior of drivers and vehicles individually and with a high level of detail. Both the environment and the behavior of vehicles in different situations must be described in great detail. Thus, the representation of a vehicle lane change is described as a chain of events and decisions that consider both the origin and destination lane conditions. In the *mesoscopic* simulation model, the vehicles are studied together; therefore, the lane change maneuver is an instantaneous event in which the lane change decision is based on lane density and differential speeds, without considering the other vehicles individually. The *macroscopic* simulation model studies the behavior of vehicles on a large scale, where it is assumed that the behavior of drivers depends on traffic conditions, and variables such as flow, speed, and density are included; therefore, lane change maneuvers are not represented (Pérez, Bautista, Salazar, & Macias, 2014).

2.3. BIM adoption in road design activities

Wide adoption and development of CAD 3D tools have been observed in road design. The perceived BIM benefits and functionalities in building projects have shown the feasibility of BIM adoption in road projects as a complement to the existing CAD 3D tools. Despite the potential to improve different project aspects, the adoption of BIM in road design activities is an emerging topic in scientific research, shown by recent developments and the moderate number of related academic documents. Huang, Chen, and Dzeng (2011) analyze the feasibility of applying a dynamic BIM model in real-time to design alignments by comparing the traditional design method with the BIM design method. The comparison shows that BIM simplifies processes, increases automation capabilities, and reduces the time required for alignment design.

Kim et al. (2014) propose BIM adoption in the road design for the automatic generation of multiple road alignments alternatives with their respective cut and fill quantities, costs, and schedules; the findings show BIM benefits are related to the formulation of optimal solutions on time, in addition to improvements in the selection and comparison processes of design alternatives. Bongiorno et al (2019) present the advantages of an algorithm based on the particle swarm optimization method for road alignment optimization with a BIM environment implementation. The authors conclude that integrating BIM and optimization algorithms can increase the quality of both optimization processes and the corresponding solution and simplify the representation, modification, and comparison of various optimal alignment solutions. Zhao, Liu, and Mbachu (2019) propose an approach for the road alignment optimization founded on the integration of geographic information system (GIS) and BIM, based on the genetic algorithm method (GA). The approach allows the alignment of surroundings analysis for location planning using three-dimensional models, which promotes effectiveness and efficiency in the planning and design processes, reduction of existing gaps in the information integration between roads and other areas, improvements in communication, design failures reduction, risk management, and cost and time optimization. Biancardo, Capano, de Oliveira, and Tibaut (2020) present a procedural model focused on the road infrastructure design, based on integrating BIM environments with programming languages to adjust the input parameters of the geometric road design. Lee, Kim, Tanoli, and Seo (2020) develop a system to partition the BIM model of a road alignment according to user requirements, allowing users to enter start and endpoints, establish interval units of the design baseline, and incorporate information related to earthworks. The authors carry out a case study incorporating the developed system showing that the alignment analysis by segments improves the process management.

Despite the progress in the BIM adoption in road design activities, it is evident that there are gaps in the BIM adoption in the traffic analysis and design activities of road intersections. BIM can significantly improve project quality and generate integrated and automated methodologies that allow exploring alternatives with reduced time and effort.

2.4. BIM for road data management

During the project life cycle phases, the road infrastructure characteristics lead to a large information volume being generated, stored, consulted and used with different purposes, levels of complexity, variables and stakeholders involved (Aziz, Riaz, & Arslan, 2017). Information management activities are essential for project success because it allows supporting crucial decision-making processes and project activities development. Information is often stored in different file formats that can cause difficulties in the integration due to compatibility and inconsistency issues. Therefore, the BIM implementation can support the information management processes because the project life cycle information could be stored and managed in digital databases with coherence and compatibility, including information related to traffic issues.

Few studies focused on BIM adoption for road information integration and management. Aziz et al (2017) present a review of opportunities for managing the life cycle data using Big Data and BIM models. The information produced in the design and construction phases can be integrated with information obtained from sensors to better understand and optimize operation variables, maintenance activity planning, and support to key decision-making processes. Kim, Shen, Moon, Ju, and Choi (2015) propose an intelligent BIM 3D model to represent road project information electronically based on international standards. To verify the model viability, the authors develop a prototype focused on developing a road project in Seoul, Korea, through which earth movements (cut and fill), costs and times are estimated; data are compared with the real project, obtaining a difference of 3.95%.

2.5. BIM tools for road design and traffic analysis

Technological advances in the informatics field have led to the development of BIM tools to support activities in the design and planning phases of road projects. These advances allow designers and analysts to obtain remarkable benefits to automate traffic analysis and road design activities that require extensive calculations and tedious information processing, integration, and management. One of the best-known and functional BIM tools is Autodesk Infraworks, which enables interoperability with other BIM tools specialized in the analysis of structural, architectural, network and other elements (Abd, Hameed, & Nsaif, 2020) and can be integrated with collaborative work approaches supported by work methodologies in the cloud. Infraworks has a module specialized in traffic analysis and simulation, allowing traffic information to be integrated and compatible with other project information. Other computational tools support traffic analysis and simulation activities, such as VISSIM, TSIS, AIMSUM, Paramics, and

TransModeler (Chao et al., 2020; Yu et al., 2014). Some of these tools are based on three-dimensional models; however, it does not have all the characteristics of the BIM approach.

2.6. BIM adoption in road projects: A summary

Several advances in BIM adoption in road infrastructure projects correspond to the topic of road design, in which efforts are observed to improve, automate, and optimize the geometric design of road projects (Biancardo et al., 2020; Bongiorno et al., 2019; Chong, Lopez, Wang, Wang, & Zhao, 2016; Costin et al., 2018; Huang et al., 2011; Kim et al., 2014; Lee et al., 2020; Zhao et al., 2019). On the other hand, there are initiatives to integrate BIM with geographic information systems (GIS) to improve road projects' management and data integration processes. Some studies are focused on data exchanges between different BIM packages by applying industry foundation classes (IFC) formats. (Biancardo et al., 2020; Fosu, Suprabhas, Rathore, & Cory, 2015; Huang et al., 2011; Kim et al., 2014, 2015; Zhao et al., 2019). Some studies focused on the integration of traffic data to BIM models to certify green buildings through the analysis of transport from the building to places that are frequent destinations; other studies focus on the capture of traffic information with devices to manage different decision-making processes of the life cycle of road projects (Adibfar & Costin, 2019; Aziz et al., 2017; Costin et al., 2018; Wang et al., 2014). Despite the existing advances in BIM adoption in traffic analysis activities, there is a lack of progress in using BIM for traffic analysis during the design stage of road projects.

In the literature, methodological frameworks based on BIM are observed with different purposes: Zhao, Liu, and Mbachu (2019) propose a methodological framework to optimize road alignments by integrating BIM and GIS processes. Kim, Shen, Moon, Ju, and Choi (2015) propose a methodological framework for planning and simulating the construction process in road infrastructure projects. Chen and Nguyen (2017) present a framework for integrating BIM and Web Map Service technologies to certify green buildings by analyzing transport from the building to places that involve frequent trips.

Despite the existing advances, few studies address traffic analysis frameworks to support the decision-making processes required to design road intersection projects. Table 1 shows the type of contribution and the research topic for each of the main studies related to the BIM adoption in road projects. Table 1 includes the details of this study. The studies are classified into five categories based on the type of contribution: 1) case study, 2) literature review or discussion, 3) methodological framework, 4) new BIM tool, and 5) data models. The studies are classified into six main research topics: 1) road design, 2) road construction planning, 3) road construction, 4) traffic analysis, 5) road data management, and 6) sustainability. Considering that some studies have more than one type of contribution and research topic, the main topic or type is marked with the symbol ✓ and the secondary one with ✓^{s}.

Taking into consideration the previous contributions listed in Table 1 and, therefore, finding a gap in the field of knowledge, this study proposes an innovative BIM-based framework for traffic analysis and simulation in the design of road intersections, which integrates data from traffic with information from the disciplines involved in the design stage of a road intersection.

Table 1. Studies that address the topic of BIM adoption in road infrastructure projects.

				Type of contribution*					Research topic*					
Reference	**Location**	**Area**	**Type of project**	**Case Study**	**Literature review or discussion**	**Methodological framework**	**New BIM tool**	**Data models**	**Road design**	**Road construction planning**	**Road construction**	**Traffic analysis**	**Road data management**	**Sustainability**
Huang et al., 2011	China	Asia	Railway	✓					✓				✓^{s}	
Kim et al., 2014	Korea	Asia	Road infrastructure	✓^{s}				✓	✓				✓^{s}	
Bongiorno et al., 2019	--	--	Road infrastructure	✓					✓					
L. Zhao et al., 2019	China	Asia	Road infrastructure	✓^{s}		✓			✓				✓^{s}	
Biancardo et al., 2020	Italia	Europa	Road infrastructure	✓^{s}			✓		✓				✓^{s}	
S. S. Lee et al., 2020	Korea	Asia	Road infrastructure	✓^{s}			✓		✓					
Chong et al., 2016	Australia and China	Oceania and Asia	Road infrastructure	✓					✓		✓			
Abd et al., 2020	Iraq	Asia	Road infrastructure	✓									✓	
Wang et al., 2014	China	Asia	Road infrastructure	✓								✓		
Z. Aziz et al., 2017	England	Europe	Road infrastructure	✓^{s}			✓					✓^{s}	✓	
Kim et al., 2015	Korea	Asia	Road infrastructure	✓^{s}		✓				✓			✓^{s}	
Adibfar and Costin, 2019	United States	North America	Bridge		✓							✓^{s}	✓	
Chen and Nguyen, 2017	--	--	Building and Road infrastructure	✓^{s}		✓	✓							✓
Costin et al., 2018	--	--	Transportation infrastructure		✓				✓	✓	✓	✓	✓	✓
Fosu et al., 2015	--	--	Various		✓								✓	
This study	Colombia	South America	Road infrastructure	✓^{s}		✓			✓^{s}			✓		

*✓: principal; ✓^{s} secondary.

3. METHODOLOGICAL FRAMEWORK DESIGN

Several guides and studies provide recommendations for implementing BIM in construction projects, including the *BIM Project Execution Planning Guide* by Penn State (Messner et al., 2019), the *BIM Guidelines of New York City* (Bloomberg, Burney, & Resninck, 2012), the *Singapore BIM Guide* (Building and Construction Authority, 2013), and the *BIM Procurement Guide Harvard* (Harvard University Construction Management Council, 2010). The Penn State guide provides a literature background, a classification of uses in the project life cycle, and a definition of BIM uses associated with specific objectives and a specific purpose (Rojas et al., 2019). Therefore, the BIM-based methodological framework design for the traffic analysis and simulation at road intersections was carried out following the *BIM Project Execution Planning Guide – Version 2.2.* (Messner et al., 2019). It was selected based on its great impact worldwide in the BIM implementation processes to different life cycle activities of construction projects. It is compatible with various BIM standards and project delivery methods, including the integrated project delivery method (IPD). The BIM-based methodological framework design for traffic analysis and simulation proposed by Messner et al. (2019) follows four steps: 1) identify project goals and BIM uses, 2) design the BIM project execution process, 3) develop information exchanges, and 4) define supporting infrastructure for BIM implementation.

3.1. Project goals and BIM uses

The first step for the BIM-based methodological framework design involves identifying uses and goals to be achieved through BIM implementation in project activities. Therefore, the process begins with defining the goals and continues with the allocation of appropriate BIM uses to support the development of the proposed goals. For this study, five goals were proposed by the authors considering both the current needs of traffic analysis activities and the potential contributions of the BIM adoption in the traffic issues, according to the findings of Costin et al. (2018). Eight BIM uses were selected from those described by Messner et al. (2019). Then, the selected BIM uses were associated with the proposed goals. Table 2 shows the relationships between the proposed goals and the selected BIM uses.

Table 2. Relationships between the proposed goals and the selected BIM uses.

Id	BIM implementation goals	BIM uses*							
		U_1	U_2	U_3	U_4	U_5	U_6	U_7	U_8
G_1	Integrate the traffic information to the other project disciplines information	✓		✓	✓				✓
G_2	Promote collaboration methodologies between traffic engineer and other project participants	✓	✓	✓	✓		✓	✓	✓
G_3	Automate the evaluation of different road intersections alternatives, configurations, and scenarios to obtain better cost-benefit ratios				✓	✓	✓	✓	✓
G_4	Integrate automated cost estimates into traffic analysis and simulation activities		✓	✓					✓
G_5	Automate documentation and feedback of traffic analysis and simulation related processes	✓	✓	✓	✓	✓	✓	✓	✓

*U_1: existing conditions modeling; U_2: cost estimation; U_3: 3D coordination; U_4: design authoring; U_5: code validation; U_6: design review; U_7: structural analysis; U_8: engineering analysis: traffic analysis and simulation.

3.2. BIM design processes

The second step for the methodological framework design consists of the design processes required to develop project activities when implementing BIM; maps representing the sequence of activities and related parameters are used. The maps allow the project team to overview the activities necessary to develop the deliverables, facilitating the identification of both the information requirements and the information produced in the different processes. Similarly, the map will allow project stakeholders to appreciate the sequence of activities, which improves the understanding of the characteristics and interactions with other stakeholders.

The BIM design process for traffic analysis and simulation uses the methodological steps for the development of a traffic simulation model proposed by Barcelo (2010) (see Figure 1) and the guidelines for the development of project processes and maps explained by Messner et al. (2019). Barcelo (2010) proposed a methodological scheme that provides a conceptual approach to developing a traffic simulation model. The *BIM Project Execution Planning Guide* by Penn State (Messner et al., 2019) presents a general guide for developing a set of activities for the BIM adoption in the life cycle processes of construction projects. However, Messner et al. (2019) do not contemplate BIM adoption on road infrastructure projects or traffic analysis and simulation activities. Therefore, this study's main contribution is a new BIM-based methodological framework for traffic analysis and simulation at road intersections.

The BIM processes are grouped into five principal steps: 1) BIM models and traffic information collection; 2) BIM model configuration; 3) BIM simulation, analysis, and calibration; 4) BIM costs analysis and documentation; 5) alternatives comparison and recommendations. Figure 2 shows steps, input information, processes, output information, information flows, and process sequences of the proposed methodological framework for traffic analysis and simulation at road intersections. Table 3 shows the BIM uses associated with the proposed steps of the methodological framework, according to the BIM uses selected (see Table 2).

Table 3. Methodological framework steps and BIM uses related.

Id	**BIM uses**	**Methodological framework steps**				
		I	**II**	**III**	**IV**	**V**

U_1	Existing conditions modeling	✓				
U_2	Cost estimation				✓	
U_3	3D coordination	✓				
U_4	Design authoring	✓	✓	✓	✓	
U_5	Code validation			✓		✓
U_6	Design review	✓	✓	✓		✓
U_7	Structural analysis	✓				
U_8	Traffic analysis and simulation		✓	✓		

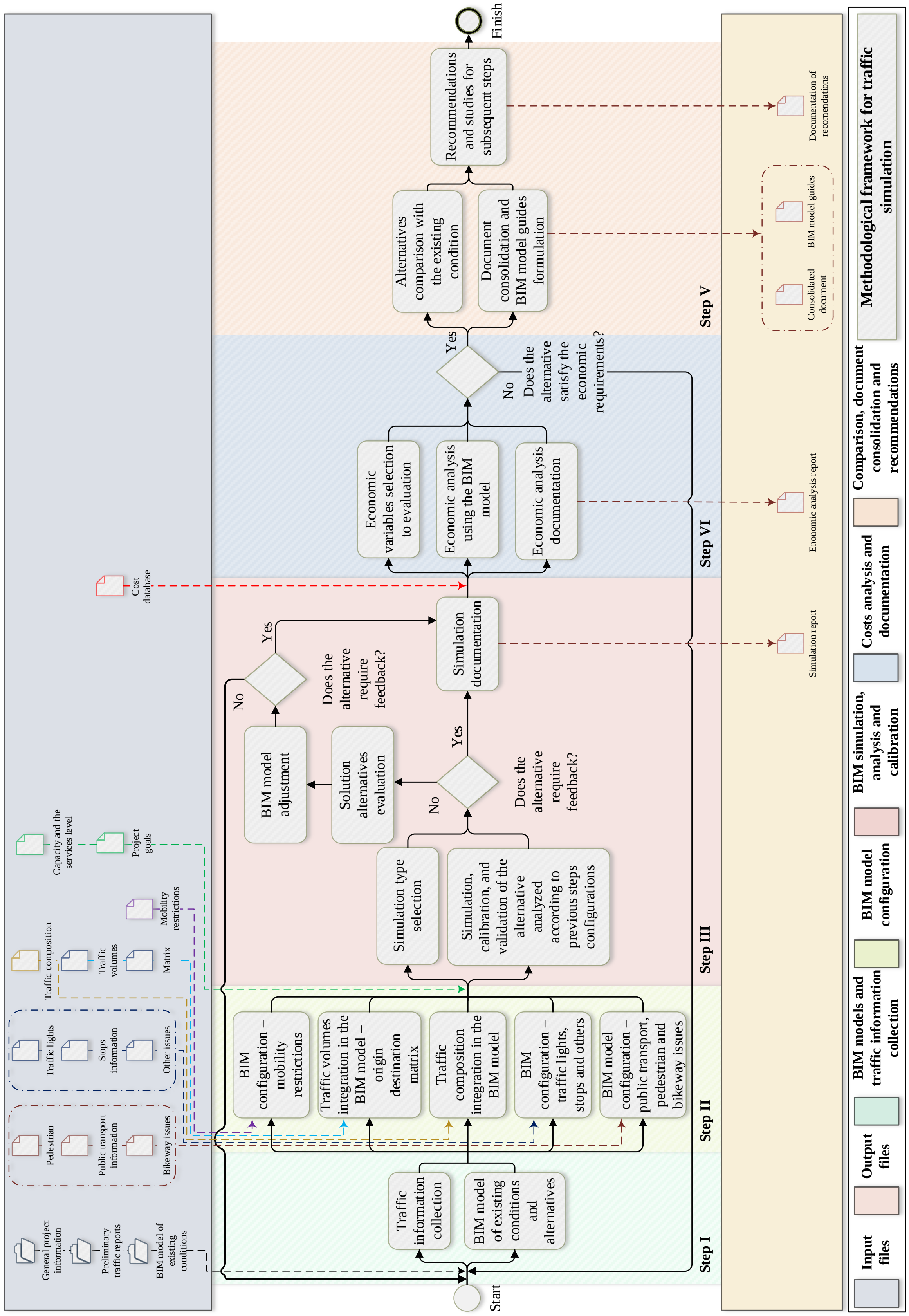

Figure 2. BIM-based methodological framework for traffic analysis and simulation.

3.2.1. Step I. BIM models and traffic information collection

This step consists of traffic information and parameter collection, in addition to the BIM model preparation and collection of existing conditions and road intersection alternatives to be analyzed. Therefore, one of the main input documents is the preliminary traffic study with information related to traffic volumes, service levels, traffic composition, traffic growth projections, and other necessary traffic simulation information. BIM models can be developed at this step or collected from the results obtained by other design disciplines. Therefore, the BIM uses “existing conditions modeling” to obtain digital replicas of the road intersection alternatives. The models become a virtual platform to carry out traffic analysis and simulation activities and support collaborative activities between the design disciplines. This platform, added to the application of the BIM uses “design review,” “design authoring,” and “3D coordination,” allows early identification of design issues such as clashes, missing information, terrain issues, and site impacts (Costin et al., 2018; Eastman et al., 2008; John Messner et al., 2011).

3.2.2. Step II. BIM model configuration

This step includes the integration and configuration of traffic parameters in the BIM models of existing conditions, which is done with the traffic information collected from Step I. Thus, in the BIM model, the analysts integrate and configure parameters associated with mobility and operation restrictions, traffic volumes and composition, speeds, traffic lights, stops, pedestrian crossings, public transport issues, cycle routes, driver behavior issues, origin-destination movements, lanes direction, turns, and parking lots. The BIM uses “design authoring” and “traffic analysis and simulation” are applied to integrate traffic information into the BIM models obtained in Step I. The BIM use “design review” is applied to verify the compatibility between the traffic information and the project characteristics represented in the BIM model.

3.2.3. Step III. BIM simulation, analysis, and calibration

This step begins with the BIM model obtained from Step II and the definition of simulation conditions required for traffic analysis. These are defined parameters such as simulation type, study areas, display options, and simulation times and periods. Then, the traffic simulation and calibration are carried out. The information obtained from the simulation is considered for calibration: travel times and distances, stop and start times, vehicle queue lengths, traffic delays, vehicle volumes, speeds, vehicle flows behavior, mobility restrictions, pedestrian and bicycle flows, and other aspects. The model is calibrated by comparing the simulation results with the information collected in Step I; if the simulation does not represent the expected behavior, adjustments are made to the model. The BIM model's analysis of capacity and service level is carried out using the feedback process shown in Figure 2. Finally, Step III concludes with the simulation results documentation. At this step, the BIM uses "design authoring," "code validation," and "design review" are applied, through which it is possible to automatically detect different traffic issues. This step allows effective model feedback, which promotes high efficiency in calibration processes. The BIM use "traffic analysis and simulation" is applied to analyze the traffic based on the traffic data integrated into the BIM model in Step II.

3.2.4. Step IV. BIM costs analysis and documentation

This step includes the analysis of the costs associated with the road intersection alternatives studied. Therefore, the analysis begins with selecting the variables to be analyzed, which could be related to costs associated with construction, transportation, environmental impacts, land acquisition, and any other parameters. Once the economic variables have been selected, the process integrates cost databases into the BIM model. This step concludes with the BIM cost analysis documentation and the comparison between results and the project financial requirements (see Figure 2). The cost analysis uses collaborative workflows among the project stakeholders, with the application of the BIM uses “cost estimation” and “design authoring.”

3.2.5. Step V. Alternatives comparison and recommendations

The final step consists of comparing the proposed road intersection alternatives and the existing intersection, using the information obtained in the previous step. The comparison evaluates and documents the cost-benefit ratio associated with each of the alternatives, which is crucial information for the subsequent step, where one of the alternatives must be selected. In addition, the BIM model management guides are developed for traffic information integration, which will be useful later when the BIM model is consolidated with information from other design disciplines. Finally, a set of recommendations is developed focused on supporting the decision-making processes of later phases. Models, reports, and other information are documented according to the indications established at the project beginning. The design and planning phases that depend on the traffic simulation results can begin. The BIM uses “code validation” and “design review” can be applied to compare the alternatives.

3.3. Develop information exchanges

Considering the variety of processes and variables, the traffic analysis and the simulation development require continuous information exchange. Therefore, it is necessary to design workflows that allow satisfying the information requirements with the principles of the lean construction tool "Just-in-Time (JIT)" (Tezel, Koskela, & Aziz, 2018). Information required by a certain process must be available at the right time: not before, because the information may be out of date, nor later because the lack of information can delay the process development or even affect the project quality. In addition, the information generated in the processes must satisfy the requirements of subsequent processes (see Figure 3).

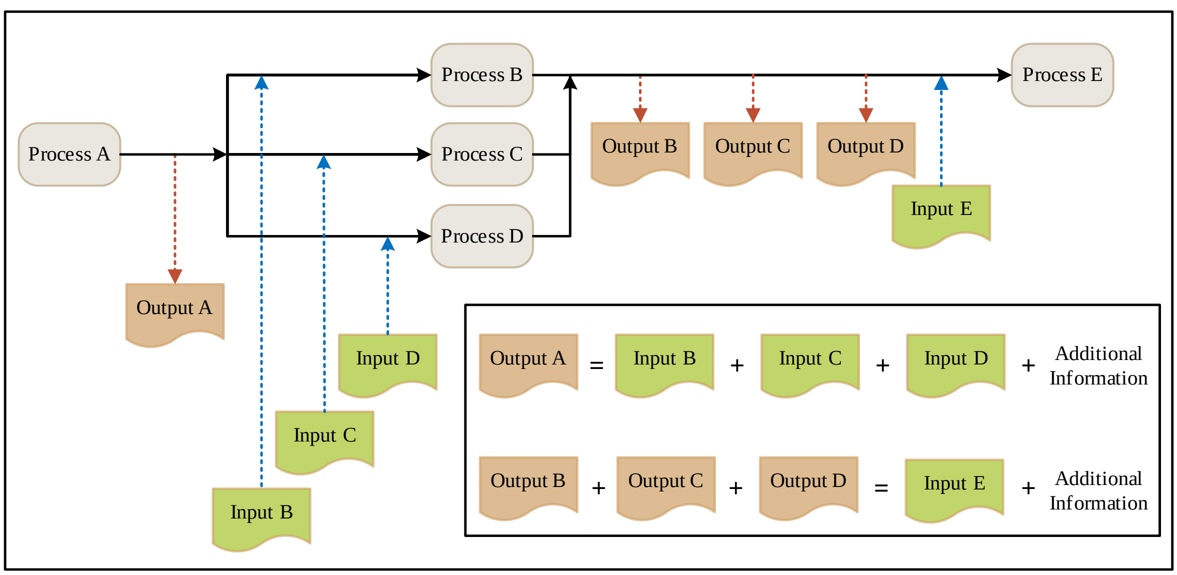

Figure 3. Information exchange: inputs and outputs (adapted from Messner et al., 2019).

The information exchange illustrated in Figure 2 is proposed for the proposed methodological framework. However, because traffic analysis and simulation is one of several activities that make up the design of a road intersection, it is recommended to develop a general map with all the processes related to the design phase, as proposed by Messner et al. (2019), through the concept of the "Level 1: BIM Overview Map." In this way, the traffic analysis and simulation corresponds to one of the "BIM Overview Map" processes, and the map shown in Figure 2 represents a "Level 2: Detailed BIM Use Process Map" as proposed by Messner et al. (2019).

3.4. Define supporting infrastructure for BIM implementation

The final step consists of the design and definition of the infrastructure required for BIM implementation. This step entails reviewing and defining the issues related to the following categories: 1) human resources, roles, and responsibilities, 2) information exchanges between stakeholders involved, 3) facility data requirements, 4) collaboration procedures, 5) quality control and supervision protocols, 6) technological infrastructure needs, 7) BIM model and files structure, and 8) other necessary issues. Before starting the traffic analysis and simulation development with BIM implementation, a BIM manager should be appointed, who will have the functions of making and managing the BIM implementation plan, advising on BIM workflows, coordinating permissions to view, edit and download information, and other necessary activities according to the project and organizational requirements. The proposed methodological framework characteristics (see Figure 2) can be applied with different commercial and experimental BIM packages. However, the authors recommend using Autodesk Infraworks because it integrates the BIM model of road design with the traffic analysis and simulation. The Traffic Analyst module contains several functions and tools that facilitate planning and evaluating the geometric road design through automated traffic analysis and simulation.

4. METHODOLOGICAL FRAMEWORK APPLICATION

4.1. Case study

The proposed methodological framework was applied in a Y-type road intersection located in Piedecuesta, Santander, Colombia, a real project with an academic focus. In the search for solutions to the vehicular congestion issues presented in the case study, four road intersection alternatives were proposed and analyzed: 1) existing road intersection, 2) level-canalized road intersection, 3) roundabout intersection, and 4) trumpet-type intersection. Autodesk Infraworks 2020, Autodesk Revit 2020, Autodesk Robot Structural Analysis 2020, and Autodesk BIM 360 Team were used to apply the methodological framework to the case study. Traffic data were obtained from the site and projected over twenty years.

The second alternative corresponds to a level-canalized road intersection, which is obtained by adding some elements to improve the existing road intersection, such as splitter islands, acceleration and deceleration lanes, canalized turn lanes, and a traffic light. The level-canalized road intersection alternative was proposed considering the low environmental, economic, and social impact in the project area. In addition, the provision of acceleration, deceleration, and turning lanes can contribute to improved mobility on the site. The third alternative is a roundabout intersection, in which the accesses converge to a ring where traffic circulates around a central island. This alternative was proposed considering that the terrain characteristics are adequate for the construction. In addition, the traffic lane can contribute to reducing waiting times by avoiding stops at traffic lights. The fourth alternative is a trumpet intersection. The intersection of the road corridors occurs on two levels, and their interconnection is carried out using connecting corridors complemented by acceleration and deceleration lanes. This intersection was proposed because the different crossing levels avoid vehicle stops, complemented by the acceleration and deceleration lanes that reduce waiting times.

As shown in Table 4, two proposed alternatives correspond to intersections where the corridors intersect at the same level: level-canalized intersection and roundabout intersection. An alternative in which the crossover is carried out at two levels is a trumpet intersection. Due to its characteristics, the trumpet intersection is the alternative that involves a larger construction area and environmental impact. In comparison, the level-canalized intersection involves a smaller construction area and environmental impact. Between the three proposed alternatives, the only one that includes traffic lights is the level-canalized intersection. Acceleration and deceleration lanes are not required in the roundabout intersection, while they are required in the level-canalized intersection and the trumpet intersection. All of the proposed alternatives involve splitter islands.

Table 4. Characteristics of the road intersection alternatives.

Id	Alternative	Type	Construction area [m^2]	Green area intervention [m^2]	Traffic lights	Acceleration lanes	Deceleration lanes	Splitter island
1	Existing road intersection	Level intersection	-	-	No	No	No	No
2	Level-canalized intersection	Level intersection	7,960	37,804	Yes	Yes	Yes	Yes
3	Roundabout intersection	Level intersection	21,730	83,766	No	No	No	Yes
4	Trumpet intersection	Road interchange	66,981	138,118	No	Yes	Yes	Yes

4.2. Stakeholders and collaborative workflow

A team of nine professionals located in four different countries was formed to apply the methodological framework (see Table 5). Team members were assigned roles and responsibilities according to the specialization areas and project requirements.

Collaborative workflows and interactions between stakeholders used the Autodesk BIM 360 Team platform, in which each stakeholder could access project information according to the permissions assigned by the "BIM manager." Each participant could make comments based on the BIM model uploaded to the cloud, which allowed a continuous communication flow between the project stakeholders (see Figure 4).

Table 5. Stakeholders and principal responsibilities.

Id	Stakeholder	Academic degree	Professional experience	Location	Principal responsibilities
S_1	BIM manager and cost engineer	Ph. D. (c)	9 years	Spain	• BIM implementation plan • BIM model management • Information management • Cost estimation • Permissions to view, edit and download information
S_2	Road designer	M. Sc.	5 years	Spain	• Road elements dimensioning and modeling • Review of compliance with the road design code
S_3	Structural engineer	M. Sc. (c)	4 years	United States	• Structural elements dimensioning and modeling
S_4	Sanitary engineer	M. Sc.	8 years	United States	• Hydraulic and sanitary elements dimensioning and modeling
S_5	Design manager	Ph. D.	>30 years	Colombia	• Personnel and technological resources management • Quality control and supervision • Existing project information collection
S_6	Traffic engineer	M. Sc.	6 years	Colombia	• Traffic data collection • Traffic analysis and simulation
S_7	Owner representative	Civil Eng.	>20 years	Colombia	• Verification of land acquisition issues • Communication and supervision of project requirements
S_8	Architect	M. Sc. (c)	5 years	Australia	• Architectural elements dimensioning and modeling • Advice on architectural issues related to the alternatives analyzed

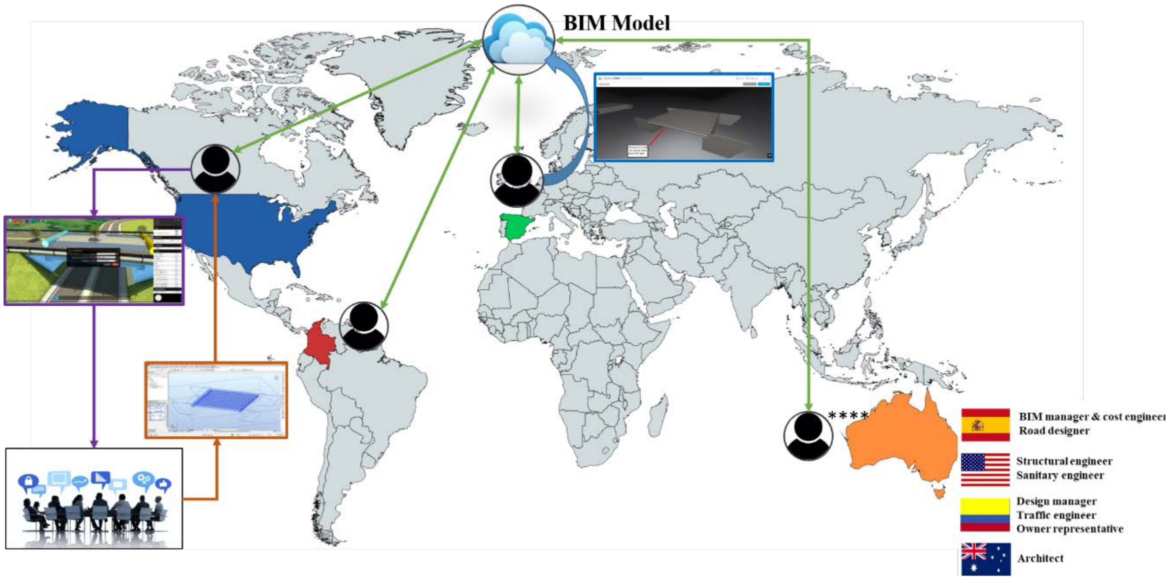

Figure 4. Collaborative workflow scheme.

4.3. BIM models of existing conditions and road intersection alternatives

Information related to topography, utility networks, site photographs, and other existing documents was collected to develop the existing conditions BIM model. This information was distributed to stakeholders according to the role and responsibilities assigned (see Table 5). The BIM modeling process was carried out collaboratively using the Autodesk BIM 360 Team platform workflow, and the project elements were modeled on Autodesk Infraworks and Autodesk Revit software. Figure 5 shows three views of the existing conditions BIM model and their respective site photographs.

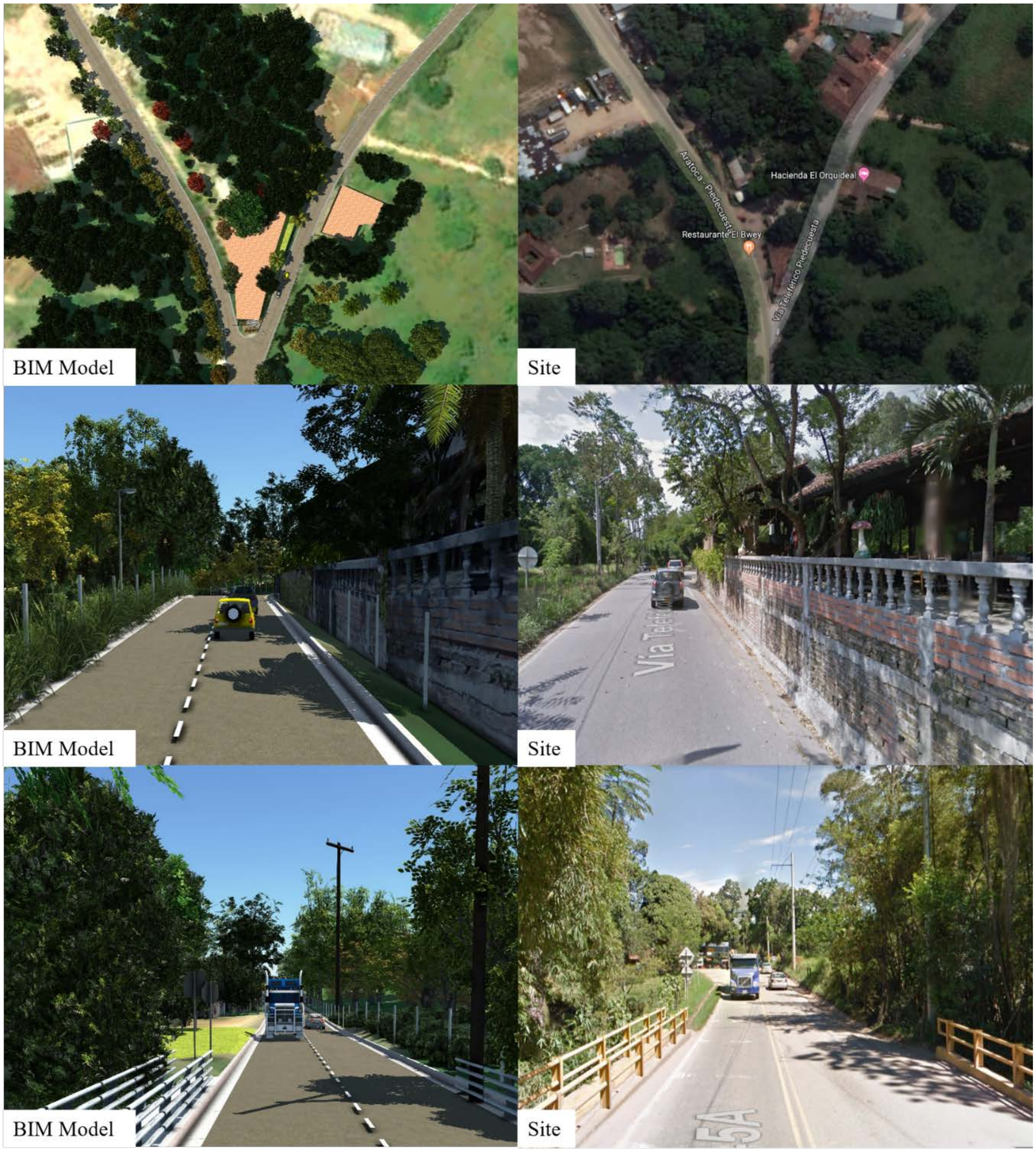

Figure 5. Existing conditions BIM model

The collaborative workflow offered notable advantages to the development of the BIM model. Crucial decision-making processes had the participation of various stakeholders, who had opportunities to propose configurations that were debated and, in some cases, improved by other stakeholders. In addition, the collaboration processes benefitted from the communication options between specialized design BIM tools. One example is shown in Figure 6, which illustrates an observation made by the road designer to the structural engineer in the BIM 360 Team platform. The observation focused on a request for a bridge pre-dimensioning required in the trumpet-type intersection alternative. Thus, the structural engineer exported the information to the Autodesk Robot tool, which specializes in structural analysis and design. Once the pre-dimensioning was done in Autodesk Robot, the information was updated in the central BIM model of Autodesk Infraworks. The other stakeholders were able to visualize, evaluate, and propose modifications to what was proposed by the structural engineer.

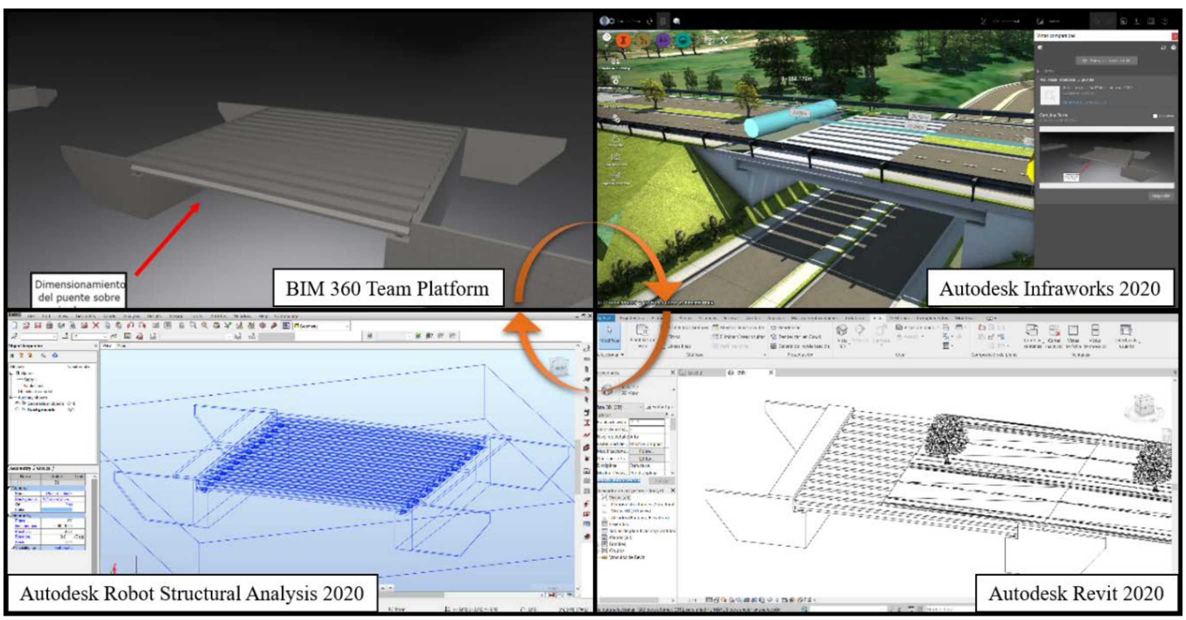

Figure 6. The collaborative workflow in the bridge pre-dimensioning.

The BIM methodology's visualization options lead to improvements in the decision-making processes related to effects on the environment and neighboring properties. Figure 7 shows some illustrations of the effect generated by the analyzed alternatives. Different scenarios were shown to the team members, who were able to evaluate, redefine, and optimize different aspects to mitigate affectations at the site.

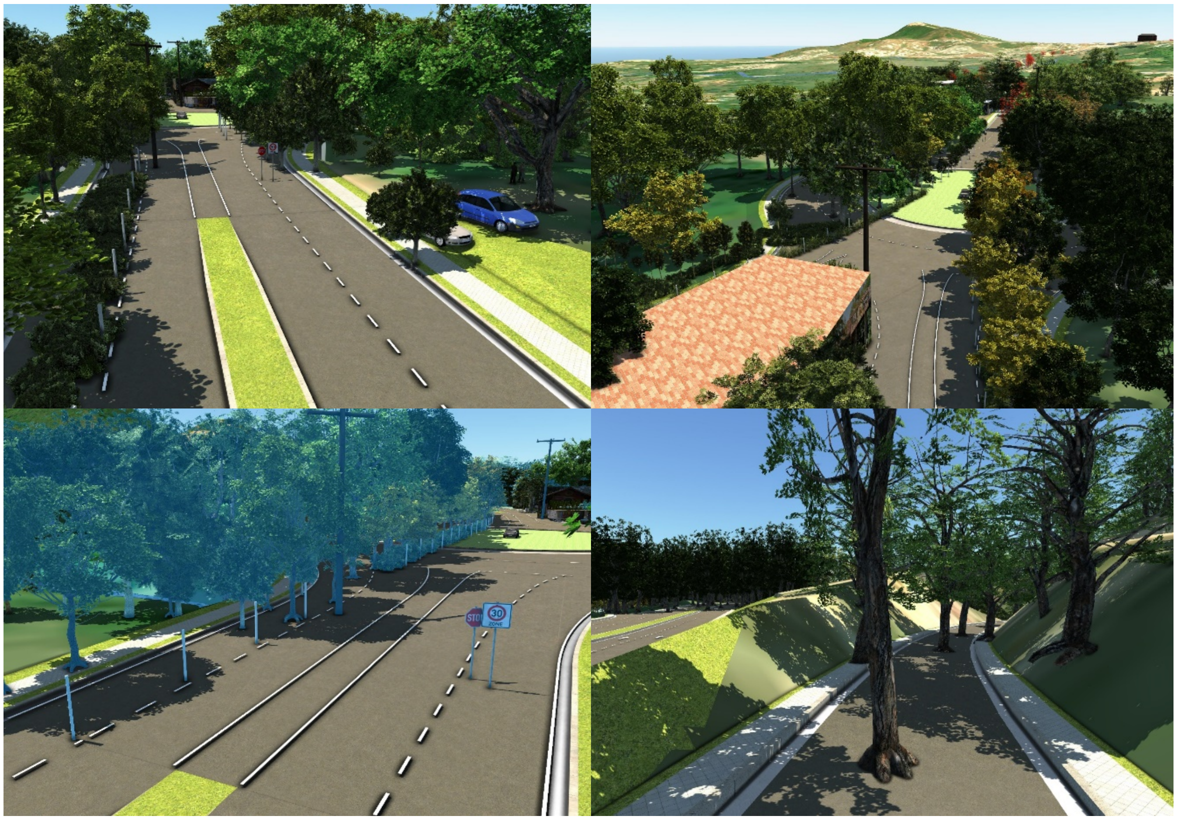

Figure 7. Visual management for mitigation of property and environmental damage.

4.4. Traffic analysis and simulation

The BIM models of the analyzed road intersection alternatives were developed from the existing-conditions model. The road designer performed a pre-dimensioning of the geometric design for the different alternatives following the guidelines of the *Manual de Diseño Geométrico INVIAS, Colombia* (Instituto Nacional de Vías, 2008). The configuration of the traffic analysis parameters was performed by the traffic engineer in the Traffic Analyst module of the Autodesk Infraworks software. The traffic engineer used the BIM models and the traffic information collected on the site. Thus, traffic information was integrated into the other project information while configuring the BIM model, in addition to configurations related to mobility rules and restrictions, parameters of driver behavior, characteristics of traffic controllers, and simulation parameters (see Figure 8). The selected simulation type was mesoscopic based on the project requirements. Figure 9 shows the BIM models developed for the four alternatives analyzed during the traffic simulation process.

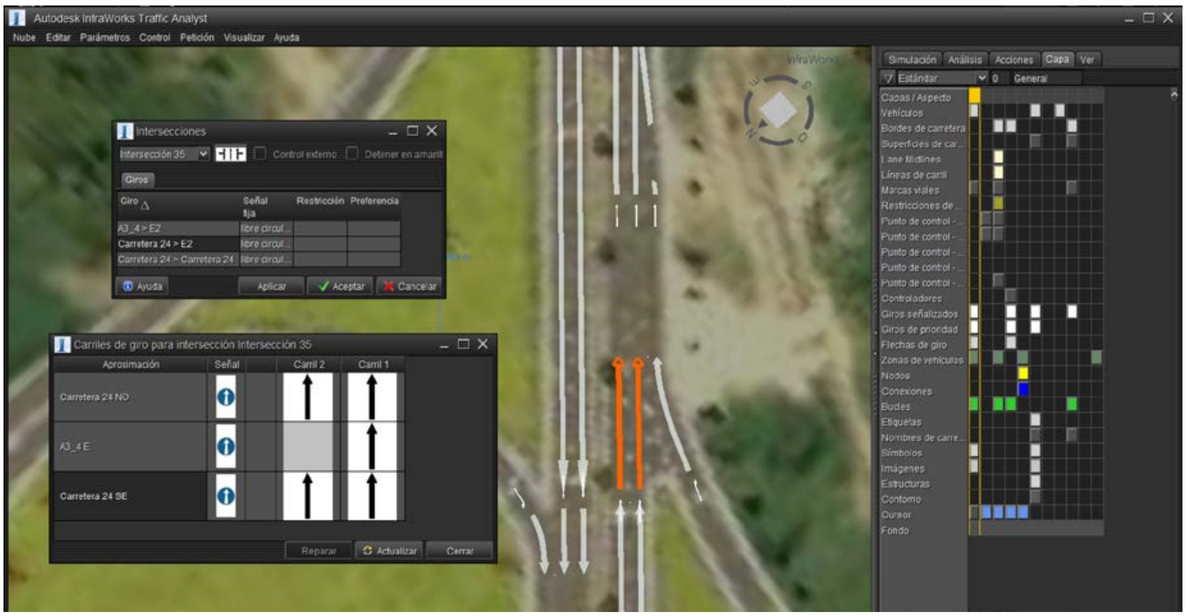

Figure 8. Traffic issues configuration into the BIM model.

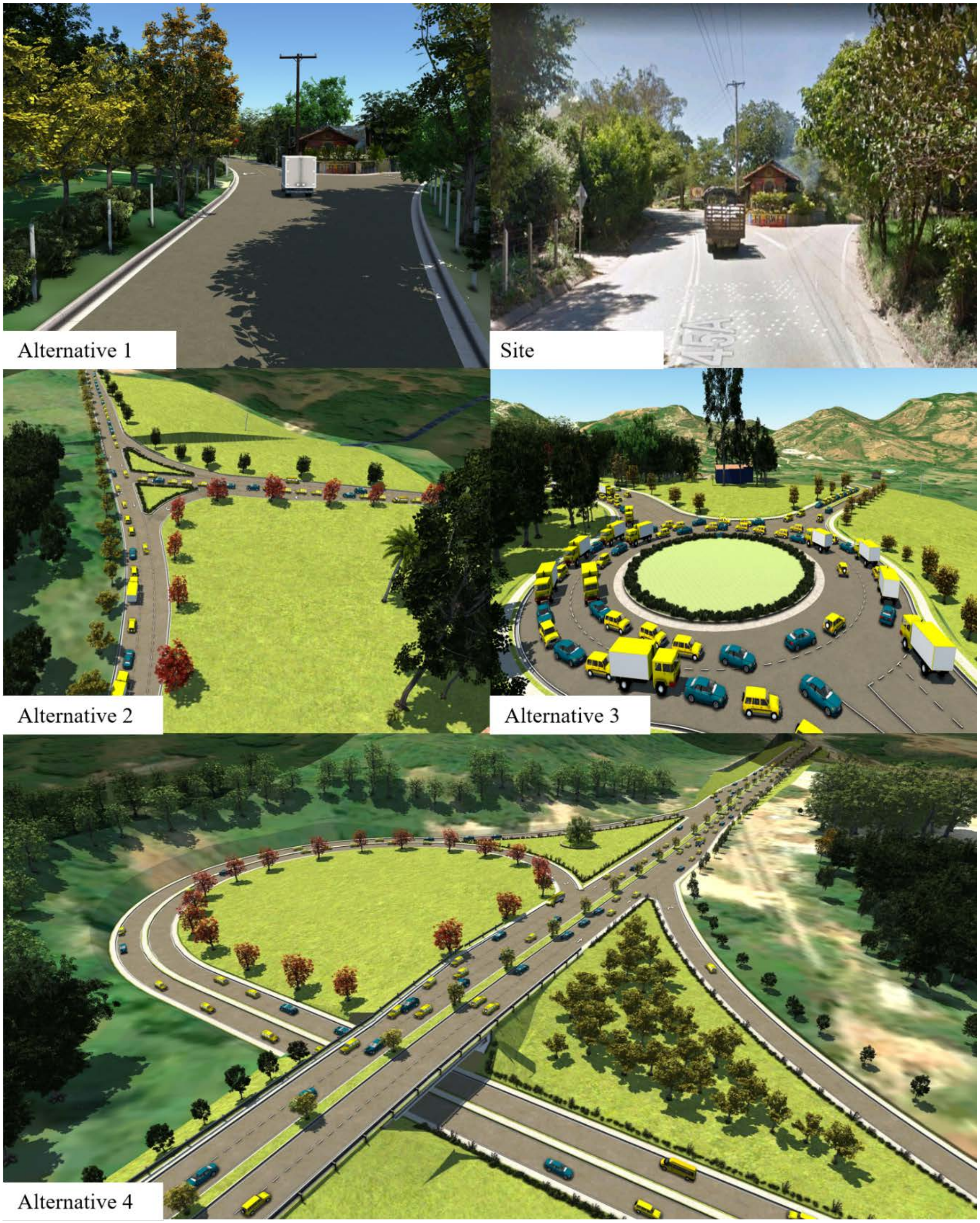

Figure 9. BIM models of the road intersections alternatives analyzed.

Table 6 presents service levels, estimated construction costs, and land required for each alternative. The trumpet-type road intersection is the one that obtains the best service level (B) according to the levels defined by Cerquera (2007); however, it is the alternative with the highest estimated construction cost (US $3,048,973). On the other hand, level-canalized and roundabout intersection alternatives are associated with moderate construction costs (US $270,860 and US $760,200, respectively) but obtain an insufficient service level (E) to meet the projected traffic demands for twenty years. Therefore, these alternatives could meet short-term needs but not the long-term. A trumpet intersection requires a greater land acquisition area (42,175 m^2), an aspect that significantly increases the required investment. Level-canalized and roundabout alternatives require minor land acquisition areas (3,452 m^2 and 14,247 m^2, respectively).

Table 6. Service levels and costs for the road intersections alternatives analyzed.

Id	Alternative	Service Level	Variable	Estimation
1	Existing road intersection	F	Construction cost (US) Land acquisition (m^2)	- -
2	Level-canalized intersection	E	Construction cost (US) Land acquisition (m^2)	$ 270,860 3,452
3	Roundabout intersection	E	Construction cost (US) Land acquisition (m^2)	$ 760,200 14,247
4	Trumpet intersection	B	Construction cost (US) Land acquisition (m^2)	$ 3,048,973 42,175

5. BENEFITS OF BIM ADOPTION IN TRAFFIC ANALYSIS AND SIMULATION

The project stakeholders involved were interviewed about the benefits of applying the proposed methodological framework to the traffic analysis and simulation activities, using the benefits identified by Chan, Olawumi, and Ho (2019). Table 7 shows the benefits perceived by each stakeholder.

Table 7. BIM benefits and stakeholder perceptions.

Id	BIM benefit	Stakeholder*							
		S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8

B_1	Better construction planning and monitoring	✓			✓	✓		✓	
B_2	Better cost estimates and control	✓	✓			✓		✓	✓
B_3	A better understanding of design	✓	✓	✓	✓	✓	✓	✓	✓
B_4	Enhance organizational image					✓		✓	✓
B_5	Improve project quality	✓	✓	✓	✓	✓	✓	✓	✓
B_6	Improve safety performance		✓	✓		✓	✓		
B_7	More efficient communications	✓	✓	✓	✓	✓	✓	✓	✓
B_8	Provide life cycle data	✓	✓	✓		✓	✓		✓
B_9	Reduce construction cost	✓				✓			
B_{10}	Reduce project duration	✓	✓				✓		
B_{11}	Scope clarification	✓	✓	✓	✓	✓	✓	✓	✓
B_{12}	Speed up the design process	✓	✓	✓	✓	✓	✓		✓

*S_1: BIM manager and cost engineer; S_2: road designer; S_3: structural engineer; S_4: sanitary engineer; S_5: design manager; S_6: traffic engineer; S_7: owner representative; S_8: architect.

The redesigning of an existing road intersection requires detailed planning of vehicle flows projected for the construction period to minimize work effects, accidents, road congestion, and other problems (Attab & Banyhussan, 2020). BIM traffic simulation can be integrated with BIM 4D simulations that allow visualizing, configuring and solving different aspects before starting the work on-site, benefiting the construction planning and reducing the negative work effects on road users. At the same time, BIM traffic simulation can be used to monitor, manage, and improve different variables related to the road intersection operation.

Considering the high investment required for road construction, maintenance and improvement are crucial issues, requiring cost estimation and control at different phases and processes of the project life cycle (Herrera, Sánchez, Castañeda, & Porras, 2020; Makovšek, 2014). Therefore, the automation of costs and estimates obtained by the BIM model favors the cost evaluation for different project alternatives and configurations compared to the manual measurement, promoting better cost-benefit ratios. Similarly, the exploration of alternatives and evaluation of traffic analysis at road intersections contribute to the construction cost reduction by adopting design characteristics based on the allocated budget and traffic requirements. These activities promote an optimization culture among stakeholders and, therefore, reductions in construction costs. The increase in the design quality and detail promoted by BIM mitigates delay and cost overruns, considering that one of the main causal factors of excess costs is design failures (Al Hosani, Dweiri, & Ojiako, 2020; Rachid, Toufik, & Mohammed, 2018).

In decision-making processes, stakeholders must understand the design to obtain the maximum benefit from their interaction. Therefore, the BIM adoption in traffic analysis of road intersections can improve decision-making processes by better understanding design supported by visualization, considering that the BIM model is a virtual project replica. In addition, road intersection analysis involves evaluating the project's impact on the environment, which allows identifying effects on trees, utility service networks, rivers, farms, buildings, and existing roads. This evaluation requires integrating and analyzing the project scope and the existing site conditions. Thus, the traffic analysis is improved from the BIM implementation because the simulation scenario uses the existing-conditions BIM model. Modification of project parameters allows analyzing the new scope and its impact quickly and automatically. Adding any new characteristics to the visualization allows making better decisions in the analysis of alternatives.

Developing a BIM model of the road intersection and the existing site conditions enable to speed up the design process because the geometric designer, structural engineer, sanitary engineer, architect, electrical engineer, and other design participants have the opportunity to base their contributions on the BIM model developed in the traffic analysis. Added to automation, specialized tools and collaborative methodologies make it possible to speed up the design process.

The visualization and high level of detail achieved in the BIM model impose rigor on stakeholders to detail and analyze the different project elements (Sacks, Koskela, Dave, & Owen, 2010). Traffic analysis benefits from a detailed analysis of the intersection alternatives and their respective elements. Added to a better understanding of the project and rapid evaluation of alternatives and configurations, the model contributes to improving project quality. Road intersections are often the site of accidents both during construction and in operation and maintenance phases; accidents that, in the worst cases, can cause fatalities and considerable economic losses (Yang, Li, Liu, Wang, & Zhao, 2020). BIM traffic analysis allows exploring and evaluating scenarios, elements, and configurations that are risky for road users and workers in a virtual environment where human lives and economic capital are not at risk, improving project safety performance.

The collaboration and visualization functions provided by BIM allow professionals located in different geographical locations to participate efficiently in the project (Oraee, Hosseini, Papadonikolaki, Palliyaguru, & Arashpour, 2017). Currently, the BIM collaboration platforms supported by cloud work methodologies improve communication efficiency. Greater communication efficiency strengthens decision-making processes. The magnitude and multidisciplinary nature of road intersections result in the production, storage and management of a large volume of data in the project life cycle (Aziz et al., 2017). Hence, the BIM adoption in traffic analysis benefits the integration of traffic information to the other project information. Consequently, the traffic simulation model is transformed from an independent model to an integrated model that other project disciplines can use at subsequent phases.

6. CONCLUSIONS

The main theorical contributions of this work are the creation of a methodological framework for traffic analysis through the application of Building Information Modeling; the proposal for an integration of geometric road design and traffic analysis in a BIM digital model; the information process required for a traffic analysis at road intersection when it is applied BIM simulations; and the integration of traffic information and others BIM model specialties, e.g., structural, architectural, mechanical, electrical and plumbing models. The BIM methodological framework for traffic analysis and simulation at road intersections in five principal steps: 1) BIM models and traffic information collection; 2) BIM model configuration; 3) BIM simulation, analysis, and calibration; 4) BIM costs analysis and documentation; and 5) alternatives comparison and recommendations.

The methodological framework application shows the potential of the BIM approach to improving processes associated with the traffic analysis at road intersections. The BIM model developed by other design disciplines is used as a simulation platform, avoiding the need to develop an independent model for traffic analysis. Thus, the information from the traffic analysis is integrated into the BIM model, promoting the reduction of design flaws both in the traffic analysis and in other design disciplines. The information is consistently and compatibly integrated into a single database. According to the eight participants in the case study, some of the most prominent BIM benefits are better understanding of design, improved project quality, more efficient communications, scope clarification, and speed up the design process.

An adequate design and planning exercise for a road intersection should involve evaluating different alternatives, configurations, and traffic simulation scenarios to promote selecting the project characteristics that best adapt to the traffic requirements that gave rise to the project. Aligned with this purpose, the automation provided by the BIM implementation in traffic simulations favors evaluating different road intersection alternatives in less time, which improves the quality of decision-making processes by exploring different scenarios. The most suitable alternative to meet the traffic demands and financial requirements associated with the project can be selected.

Limitations of this study are: 1) the lack of sustainability, environmental, and social issues in the proposed methodological framework, 2) the non-exploration of the microscopic-type traffic simulation model with BIM implementation, 3) traffic analysis was developed thought the traffic analyst module of the Autodesk Infraworks, therefore, a numerical algorithm was not developed, 4) the exploration of two variables in the economic analysis and not a larger number: construction cost, and land required, and 5) the proposed framework does not focus on decision-making processes. However, the background is developed for a subsequent decision-making process. Therefore, future works could focus on 1) studying the BIM implementation to evaluate and optimize sustainability, environmental, and social aspects of road intersections design, 2) studying the BIM implementation for the microscopic-type traffic simulation models development, 3) compare the results of the traffic analysis of various software and traffic numerical analysis algorithms to validate the data and traffic projections, and 4) studying the BIM application using different economic analyses in the road intersections design and planning.

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