

Article

Comprehensive Analysis of Scheduling Processes in Road Intersections: Associating Deficiencies and Their Consequences in Colombian Projects

Karen Castañeda ^{1,2}, Omar Sánchez ³ , Carlos A. Peña ^{4,5} , Rodrigo F. Herrera ^{2,*}  and Guillermo Mejía ¹ 

¹ Department of Civil Engineering, Universidad Industrial de Santander, Bucaramanga 680002, Colombia; karen2178721@correo.uis.edu.co or karen.castaneda@pucv.cl (K.C.); gmejia@uis.edu.co (G.M.)

² School of Civil Engineering, Pontificia Universidad Católica de Valparaíso, Valparaíso 2374631, Chile

³ Department of Civil Engineering, Pontificia Universidad Javeriana, Bogotá 111711, Colombia; omar_sanchezr@javeriana.edu.co

⁴ Department of Civil Engineering, Universitat Politècnica de València, 46022 Valencia, Spain; carpesol@upv.edu.es or carlosalbertops@ufps.edu.co

⁵ Department of Civil Engineering, Universidad Francisco de Paula Santander, Cúcuta 540003, Colombia

* Correspondence: rodrigo.herrera@pucv.cl

Abstract: Road intersection projects are crucial for road infrastructure networks' safe and efficient operation. Despite their importance, the construction of these projects faces significant challenges, such as delays, cost overruns, and litigation. Several causal factors for these phenomena have been identified as being associated with the construction schedule planning process. However, more studies need to be conducted to analyze the construction schedule planning process in detail. Therefore, the purpose of this paper is to analyze the schedule planning process of road intersection projects, emphasizing identifying and associating deficiencies in the planning process with their consequences on Colombian projects. The research method comprises three main stages: (1) identification of the schedule planning processes, (2) relation of the causes of deficiencies to the identified processes, and (3) analysis of the consequences of these deficiencies on the projects. A total of 29 schedule planning processes were identified, to which 22 causes of deficiency were assigned based on interviews with ten experts. The influence of these causes on schedule and budget deviations was analyzed based on the study of 25 Colombian road intersections. The results show that the lack of experience of the planner and poor estimation of material quantities strongly influence the generation of schedule and budget deviations in road intersection projects. Thus, this study contributes to improving the schedule planning process of road intersection projects by identifying the shortcomings and processes that can lead to schedule and budget deviations.

Keywords: road intersections; scheduling; construction planning; deficiencies; planning process



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1. Introduction

Road construction projects are crucial for enabling the movement of goods and people between various geographical locations, significantly contributing to regions' economic and social development [1]. The magnitude and functions of these projects create significant economic and social benefits in the surrounding areas [2]. A well-developed road infrastructure network promotes economic activity and makes it easier for people to access essential services, which are crucial for the well-being of communities [3]. As a result, governments worldwide prioritize allocating significant financial resources to build new infrastructure

and maintain existing ones. Global infrastructure investment is projected to grow at an average annual rate of approximately 3.4% between 2016 and 2040, reflecting a sustained increase in government and private sector commitments to infrastructure development [4]. Due to their characteristics, road projects require significant financial resources that can be compromised in the case of delays and cost overruns [5]. Therefore, delivering these projects on time is essential. To achieve this, careful planning of construction schedules is crucial, enabling efficient control and monitoring processes [6]. This allows for informed decision-making during construction and early mitigation of possible extensions to the initially projected deadlines and budgets [7].

The planning of construction schedules in road intersection projects involves several key processes. These include defining activities, estimating durations, allocating resources, and analyzing precedence relationships [6]. Thus, a proper schedule planning exercise promotes efficiency and optimization of construction resources and facilitates communication and coordination between the different disciplines involved in the project [8]. A well-planned schedule enables analysis of the financial requirements at various stages of construction and allows for task adjustments based on the organization's technical and functional capabilities [9]. An efficient schedule planning exercise allows the construction manager to identify the resources required for the development of the activities, as well as the dates and sequences in which they must be carried out [10]. In this way, the construction schedule becomes an indispensable input for monitoring and controlling the construction process, both in terms of time and budget performance, for which various techniques can be adopted, such as the Last Planner System [11] and the Earned Value Management technique [12,13]. Therefore, due to the critical role of scheduling in road construction projects, it is crucial for managers to identify potential deficiencies and areas where shortcomings could significantly impact the construction phase's progress [14].

Road intersection projects present unique complexity and operational challenges. Unlike linear roadway segments, intersections concentrate traffic flows and often require integration with subway and overhead utility networks, leading to more intricate planning requirements. In addition, these projects often require the implementation of detailed Traffic Management Plans to maintain safe and continuous circulation during construction. These factors make intersection projects particularly sensitive to planning deficiencies, which can result in significant cost overruns and delays. By focusing on these types of projects, the study provides a more detailed and specific analysis that contributes to improved scheduling practices under more demanding conditions. The planning of schedules in road intersection projects often faces several challenges that can hinder successful development and continuity. These challenges include errors in estimating construction quantities, overly optimistic expectations about labor and machinery performance, failures in predicting weather conditions, and coordination deficiencies with public services and government entities [15]. These shortcomings can lead to schedules that do not accurately represent the reality of the construction process, resulting in delays, cost overruns, and disputes. In addition, given the high complexity of road infrastructure projects, planners face difficulty in accurately conceptualizing the construction process and managing critical resources such as machinery and human resources [16]. Hence, the planning process's intricate nature and associated challenges highlight the importance of project managers in promptly resolving these issues to prevent them from derailing the project's success. In this context, it is crucial to conduct a comprehensive analysis of schedule planning processes and identify factors that may hinder their effective implementation [17].

The success of road infrastructure projects depends largely on thorough schedule planning from the early stages of the project [18]. Various studies have suggested methods to improve this planning, including optimization techniques [19–23], linear and dynamic

programming [24–28], lean construction [9], Building Information Modelling (BIM) [6,29], location-based approaches [30], and artificial intelligence (AI) [31]. However, there is still a lack of studies analyzing the shortcomings in planning processes and their impact on road construction. This study aims to fill this gap with three main research objectives: (1) identify the processes and data inputs involved in planning road intersection project schedules, (2) determine which processes are prone to deficiencies, and (3) analyze the consequences of these deficiencies in planning road intersection project schedules. The methods, contributions, and discussions are detailed in three main sections: The Research Method (Section 2), outlining the process of achieving the proposed objectives; the Results and Analysis (Section 3), divided into four subsections reporting and analyzing the study findings, and the Discussion (Section 3) divided into two subsections. For a complete list of abbreviations used throughout the manuscript, see Abbreviations section.

2. Research Method

This study employed a mixed methods approach to identify the processes and data inputs involved in scheduling road intersection projects and to associate deficiencies with their consequent impacts. The research methodology was divided into three main stages. First, the processes and data inputs were identified through a systematic literature review (see Section 2.1). In the second stage, the causes of scheduling deficiencies were analyzed and linked to the stages of the processes identified in the first stage (see Section 2.2). Finally, in the third stage, the consequences of these scheduling deficiencies were examined by analyzing a set of road intersection construction projects (see Section 2.3). Figure 1 illustrates the objectives, methods, tools, and analyses carried out for each stage of the research method.

2.1. Identification of Processes and Data Inputs in the Planning of Road Schedules

A five-step systematic review was conducted to identify the processes and data inputs involved in planning road intersection construction schedules. This systematic review ensures a detailed and structured consultation of the information contained in various documents [32]. It allows for summarizing and synthesizing findings reported in the existing literature and facilitates the methodical and manual extraction of crucial information to understand a specific field of study [33]. The implementation of this review is particularly justified for small analysis samples and narrow review scopes [34]. The systematic review methodology adopted in this study was an adaptation of the methods reported by Castañeda et al. [35] and Saieg et al. [36]. The methodology utilized was divided into five main steps: (1) formulation of the research question, (2) search for relevant studies, (3) selection of documents based on predefined inclusion criteria, (4) analysis and synthesis of the gathered evidence, and (5) discussion of the results.

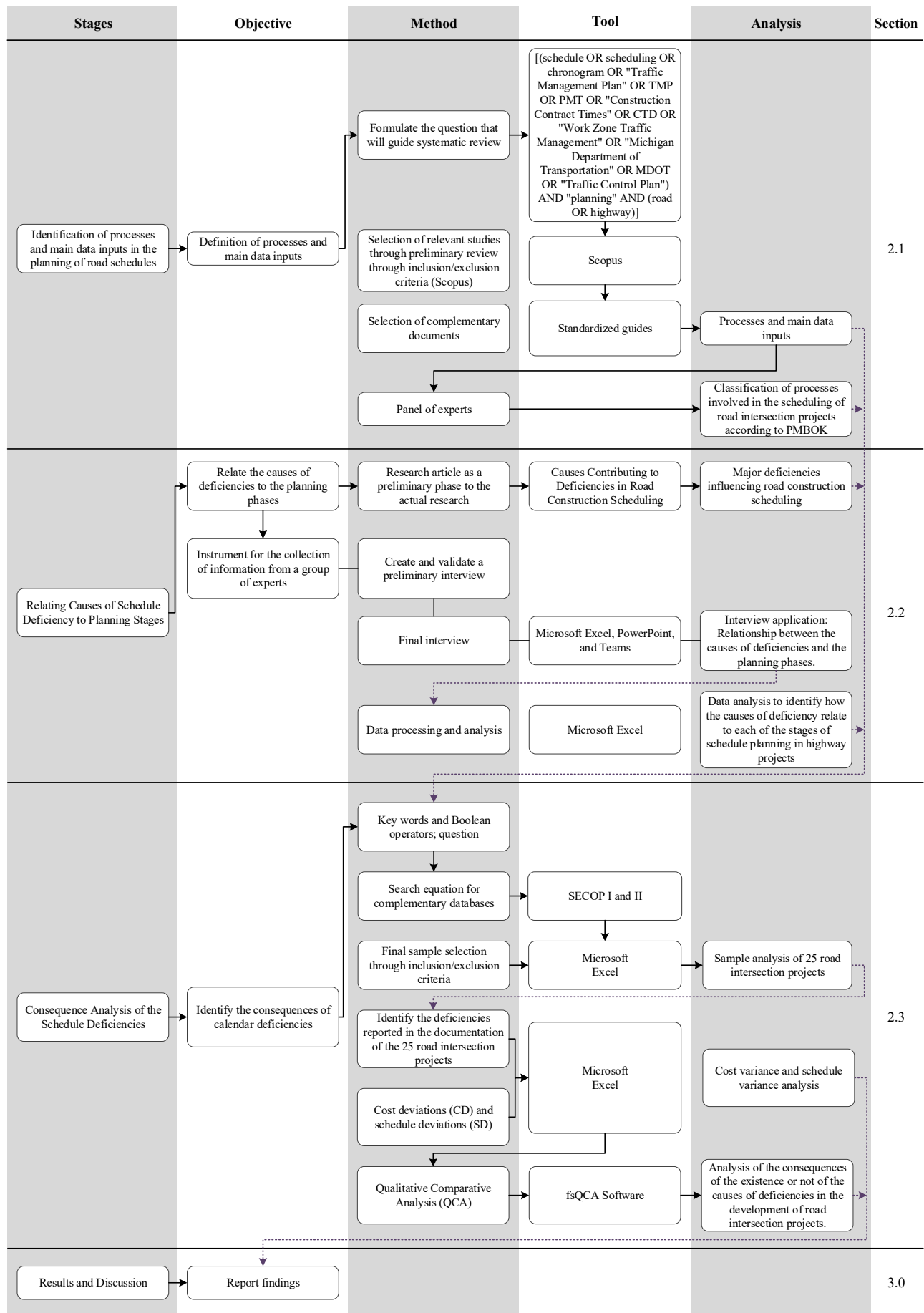


Figure 1. Research method stages.

The initial step, formulation of the guiding question for the systematic review, is defined as a core research question centered on identifying the processes and data inputs used in scheduling planning for road intersection projects. This question steered the selection of keywords and laid the groundwork for the subsequent phases of the review. In the second step, a preliminary review was conducted using Scopus to select relevant studies, applying inclusion/exclusion criteria. This resulted in an initial set of studies retrieved by applying the defined keywords and Boolean operators. To refine the search and ensure alignment with the research question, the authors implemented relevant filters, including publication year, subject area, document type, and language. Each article's abstract was reviewed to confirm its relevance to the scope, identifying those that reported on construction schedule planning processes and traffic management variables pertinent to road projects. The third step, the selection of complementary documents, involved reviewing standardized guides and technical documents from national and international transportation departments to address potential gaps in the academic literature. These additional documents were evaluated based on their explicit references to scheduling tasks, data inputs, and recommended best practices for road infrastructure projects. Finally, a panel of experts, consisting of five professionals with over five years of experience in road project planning and management, validated the preliminary list of processes and data inputs. This group assessed the consolidated findings from previous steps, suggested refinements, and reached a consensus regarding the categorization of the scheduling processes.

The first step involved identifying the analysis sample guided by the research question: "What processes and data inputs are involved in scheduling road intersection projects?". This question helped define the search keywords, which were complemented with the Boolean operators "AND" and "OR" to develop a search equation: [(schedule OR scheduling OR chronogram OR "Traffic Management Plan" OR TMP OR PMT OR "Construction Contract Times" OR CTD OR "Work Zone Traffic Management" OR "Michigan Department of Transportation" OR MDOT OR "Traffic Control Plan") AND "planning" AND (road OR highway)]. This initial review was conducted using the Scopus search engine, yielding 1896 documents. These results were refined by applying filters such as publication year, subject areas, document types, and language (see Figure 2). After using these filters, a preliminary sample of 646 documents was obtained, which was then transferred to advanced analysis for further examination. The analysis introduces a structured approach to evaluate the relevance, scope, and methodological rigor of the remaining documents. Unlike traditional methods, which primarily rely on keyword matching or citation counts, this study employed a two-tiered evaluation process. First, a detailed review of abstracts and conclusions was conducted to determine whether each publication addressed scheduling processes and data inputs relevant to road infrastructure. This initial step ensured that only documents directly related to the study's objectives moved on to the second evaluation phase. Second, the selected documents were systematically assessed based on predefined criteria for quality and completeness. These criteria included the clarity of research methods, the alignment of findings with intersection-related scheduling, and adherence to rigorous peer-review standards. During this stage, a matrix was used to cross-reference the topic relevance, study design (including qualitative, quantitative, or mixed-methods), and the depth of focus on traffic management approaches.

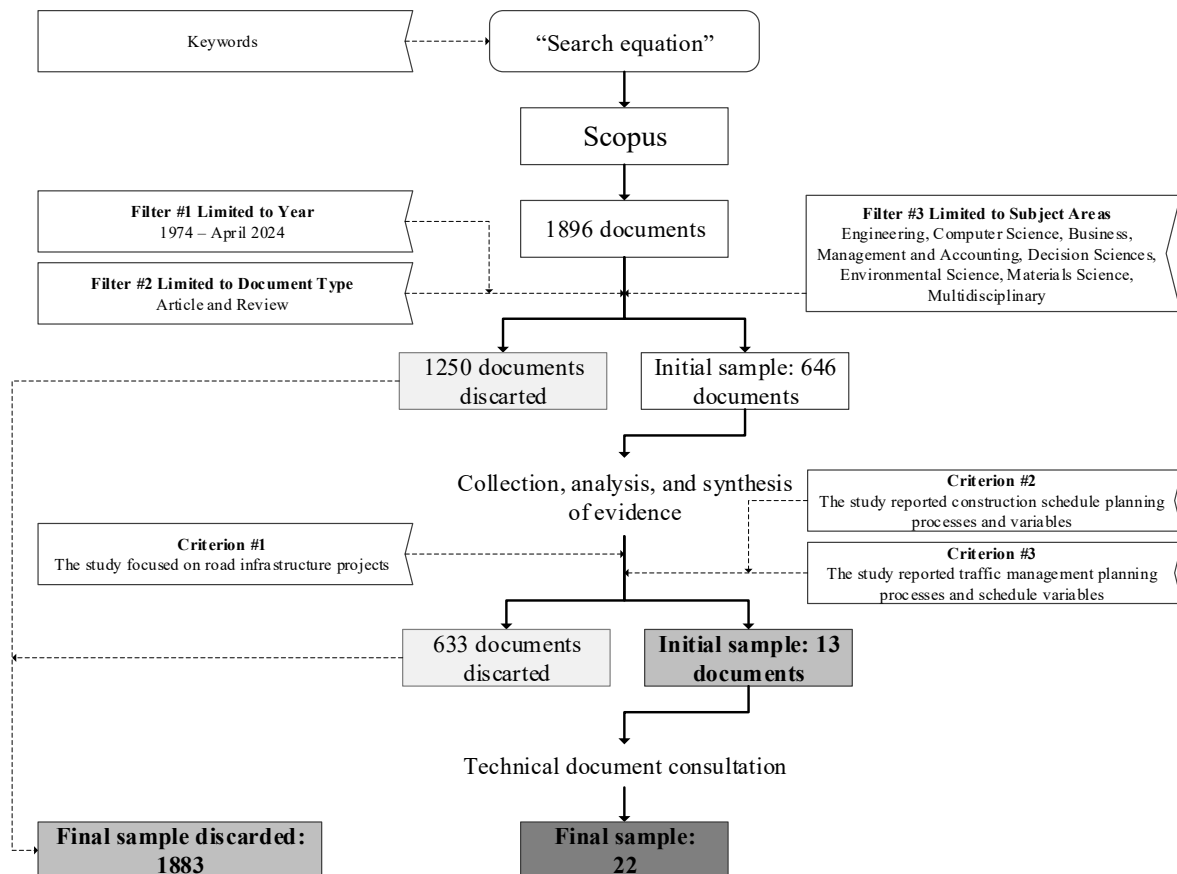


Figure 2. Document flow in the systematic review.

Three inclusion/exclusion criteria were established for this analysis: (1) the document focused on road infrastructure projects, (2) the document reported processes and data inputs related to construction schedule planning, and (3) the document reported processes and data inputs related to traffic management schedule planning. Applying these criteria resulted in a final sample of 13 documents. Given the small sample size aligned with the research question, a second review was conducted using national and international transportation department databases. This second search included standardized guides such as the Michigan Department of Transportation (MDOT) [37], the Contract Time Guidelines (CTD) [38,39], and the Project Management Body of Knowledge (PMBOK) Guide [40], among others. Consequently, 22 documents were established as the final sample for analysis (see Figure 2). This sample identified 29 processes for scheduling road infrastructure projects and the associated data inputs.

Based on the 29 processes identified through the systematic literature review, a preliminary classification of these processes involved in scheduling road intersection projects was proposed. This classification was proposed based on the schedule management stages listed in the PMBOK. To develop this classification, each process was examined in terms of its objective, required inputs, expected outputs, and logical position within a typical project timeline. The allocation of processes to each PMBOK stage was carried out considering their alignment with the specific purposes defined in the PMBOK's scheduling management structure. For example, processes that define baseline planning elements—such as time units, scheduling parameters, and planning methodologies—were assigned to the “Schedule Management Planning” stage. Processes related to the identification and breakdown of tasks, such as defining the WBS or identifying detailed activities, were associated with the “Definition of Construction Activities” stage. Similarly, tasks involving logical relationships

and sequencing were grouped under “Sequencing Construction Activities”, while those involving the calculation of durations and productivity rates were placed in “Estimating Activity Durations”. Finally, processes involving schedule modeling, analysis, evaluation, and documentation were linked to the “Schedule Development” stage. The selection of the PMBOK as a guide to structure the planning processes in this research is based on its worldwide recognition and acceptance as a standard of excellence in project management. The PMBOK offers a comprehensive and detailed framework that covers essential aspects of planning and scheduling management, making it possible to adopt a methodological and coherent approach in this study. Thus, the stages proposed in this study are: (1) Road Schedule Management Planning, (2) Definition of Construction Activities, (3) Sequencing Construction Activities, (4) Estimating Duration of Construction Activities, and (5) Road Construction Schedule Development. The preliminary classification was validated by a panel of experts consisting of five professionals with over five years of experience in road project planning and management (see Table 1). The recommendations and corrections suggested by these professionals were incorporated into the preliminary classification. This refined classification was then subjected to subsequent validation by the authors, resulting in a consensus on categorizing each of the 29 identified processes.

Table 1. Profiles of the experts consulted for the validation of processes and stages.

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

2.2. Relating Causes of Schedule Deficiency to Planning Stages

The relationship between the causes of deficiencies in road intersection construction schedules and the proposed scheduling stages was established through semi-structured interviews with professionals experienced in planning road construction project schedules. The causes of scheduling deficiencies were selected based on the most influential factors identified by Castañeda et al. [41], resulting in 22 chosen causes for this study. The selection of this study is justified by the reliability and rigor of the method used in this study. This article combines a comprehensive systematic review with detailed surveys, thus ensuring a thorough understanding of the causes that impact the planning of construction processes in road projects. In addition, analyzing the most frequent causes and their severity in construction process planning provides significant value by identifying critical patterns and trends in road project management. The robust methodology and proven results of this study provide a reliable basis for identifying and analyzing the relationships between causes and processes, thus ensuring the relevance and applicability of the findings. In addition, the 29 processes identified in the initial stage through the systematic literature review were considered. The semi-structured interviews aimed to classify each deficiency caused within the proposed scheduling stages from the initial phase to pinpoint the specific stage in the planning process where each deficiency arises. Thus, the results assist in formulating effective mitigation strategies to address these deficiencies promptly. Factors associated with scheduling deficiencies were identified from a previously published study focused on road construction processes. Following this, a preliminary interview protocol was created and tested with a small pilot group of experts to ensure the clarity and relevance of the interview questions. After refining the protocol, a final version was administered to a broader group of ten professionals. Subsequently, the data collected underwent a

systematic process of data processing and analysis. This involved thematic categorization and matrix-based comparisons using Microsoft Excel, ensuring a structured evaluation of how specific causes of deficiencies relate to each of the five stages in the road project scheduling framework.

The semi-structured interviews were conducted with ten professionals, each with over five years of experience planning construction processes for road projects (see Table 2). It is worth noting that 90% of the professionals consulted have a doctorate degree. Additionally, 70% have more than 10 years of experience, 40% are from Spain, and 60% are from Chile and Colombia. The interviews lasted approximately 15 to 20 min and consisted of two parts. The first part included obtaining informed consent for participation in the interview. The second part involved relating the deficiency causes to each of the five proposed stages in the road project scheduling process: (1) Road Schedule Management Planning, (2) Definition of Construction Activities, (3) Sequencing Construction Activities, (4) Estimating Duration of Construction Activities, and (5) Road Construction Schedule Development. As a result of this analysis, a total of 22 deficiencies were categorized into the five defined scheduling stages. Six deficiencies were associated with the “Road Schedule Management Planning” stage, seven with “Definition of Construction Activities”, four with “Sequencing Construction Activities”, nine with “Estimating Duration of Construction”, and six with “Road Construction Schedule Development”. This quantitative distribution allowed the identification of critical phases in which deficiencies tend to concentrate, especially in the definition of construction activities and the estimation of durations. Section 3.2 presents the detailed association between each deficiency and the corresponding planning stage based on the evaluation of ten professionals from the construction industry. This relationship was further complemented by a discussion on the potential consequences on the planning road infrastructure project schedules due to the presence of these deficiencies in the planning stages assigned.

Table 2. Profiles of professionals who participated in the semi-structured interview.

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

To enhance the reliability of the expert-based connection between scheduling deficiencies and planning stages, some methodological safeguards were implemented. First, a rigorous selection process ensured that the experts interviewed each had over five years of professional experience in road construction planning, representing both academic and practitioner backgrounds from different countries. Second, the semi-structured interview protocol was developed based on a validated list of 22 causes previously identified through a systematic literature review and an earlier research publication. The protocol was pilot-tested with a subset of professionals to confirm the clarity and relevance of the questions. Although the sample size of ten experts may seem limited, it is consistent with qualitative research standards, which prioritize exploring diverse expert perspectives over achieving statistical generalizability. Additionally, the information gathered through interviews was

cross-validated with findings from the document analysis of 25 road intersection projects (see Section 2.3), allowing for the identification of patterns between causes and consequences. This mixed-methods approach addresses the limitations of a small expert sample and enhances the methodological rigor of the study.

2.3. Consequence Analysis of the Schedule Deficiencies

The consequences of schedule planning deficiencies in road intersection projects were analyzed through a comprehensive search of executed road intersection construction projects using the Electronic Public Procurement System (SECOP, the acronym in Spanish). SECOP is an online open-data platform that manages and supervises Colombian public procurement processes, including construction projects across various public sector types and characteristics. The search focused on different road intersections, including roundabouts, channelized intersections, and interchanges where road segments intersect at different levels. To ensure the projects met the necessary information requirements for this study, five inclusion/exclusion criteria were established: (1) the project focused on road infrastructure and involved road intersection construction, (2) the project provided documentation and records detailing incidences and schedule-related developments, (3) the project had a minimum budget of 350 Legal Minimum Monthly Wages in Force (SMLMV) in Colombia at the time of contract award, (4) the projects reported both initial and final planned and actual costs, and (5) the projects reported both planned and actual schedule durations. After applying the inclusion/exclusion criteria, an initial review identified a sample of 48 road intersection projects. From this sample, 25 projects were selected based on the availability of detailed documents explaining the causes of schedule deviations. Thus, a sample of 11 projects from SECOP I [42] and 14 from SECOP II [43] was obtained (Supplementary Materials).

The consequence analysis focused on cost deviations (CD) and schedule deviations (SD) observed in the projects, representing the variations between the planned and actual execution. These deviations in time and cost can lead to overruns and delays, significantly impacting the project's economic viability and timely delivery. Cost deviations were identified through the percentage variation between the planned cost (PC) during the early stages and the actual cost (AC) after construction (see Equation (1)). The cost deviation magnitudes were analyzed by converting the costs into Colombian minimum legal monthly wages, considering the year the project was contracted.

$$CD_i = \left(\frac{AC_i - PC_i}{PC_i} \right) * 100\% \quad (1)$$

Equation (2) was used to calculate the schedule deviation (SD). It involved using the planned schedule (PS) and actual schedule (AS) data for each of the 25 road intersection projects.

$$SD_i = \left(\frac{AS_i - PS_i}{PS_i} \right) * 100\% \quad (2)$$

From the 25 road intersection projects selected for analysis, a detailed review of contracting documentation and documentation generated during the construction process was conducted to identify the causes of schedule planning deficiencies that resulted in time and cost deviations. Two researchers reviewed each project. This review classified the causes of schedule deficiency following the list of causes identified by Castañeda et al. [41]. For data collection, a Microsoft Excel spreadsheet was designed in which the 25 projects were listed, and a column was generated for each of the causes of schedule deficiency. During the data collection, if a project had a cause of deficiency, it was recorded with a 'Yes', and if not, with a 'No'. At the end of the documentation review, a meeting was held

between the two researchers to compare the information obtained. Discrepancies were identified and addressed during this meeting, and project documents were reviewed again where necessary. Finally, a consensus was reached on the causes that impacted each project.

Four methodological steps were undertaken before the final analysis. First, the findings of Castañeda et al. [41] were analyzed. This work provided a set of 22 causes of scheduling deficiencies, which were derived from a systematic literature review and expert consultation. Second, a preliminary interview instrument was created to explore how these causes manifest in road intersection projects. This instrument was pilot-tested with a group of five professionals to verify the clarity and relevance of the questions and to adjust their format and language as necessary. Third, a final version of the semi-structured interview was developed and conducted with a group of ten experts who have extensive experience in road infrastructure planning. Their responses were used to associate each deficiency with one or more of the five proposed scheduling stages. Finally, the collected data were organized and processed in Microsoft Excel. Each deficiency was recorded for each project as a binary variable (1 = present; 0 = absent) and was further integrated into the Qualitative Comparative Analysis (QCA) using fsQCA 4.1 software. This integration helped identify causal configurations that contribute to schedule and cost deviations.

Based on the data collected during the review of project documentation, a Qualitative Comparative Analysis (QCA) was conducted to identify the combinations of causes leading to schedule and budget deviations in road intersection construction projects. QCA is a technique for systematically analyzing qualitative and quantitative data, combining Boolean logic and set theory aspects with traditional comparative analysis. This method allows researchers to identify patterns and causal relationships between variables in studies with a moderate number of cases. The binary nature of the data collected justifies using the QCA method in this research. In addition, QCA is particularly suitable for studies with moderate sample sizes, where it is essential to understand complex causal configurations and interactions between multiple variables. The QCA began with data preparation, creating a dichotomous table in Microsoft Excel (see Figure 3). Columns included the causes of deficiencies, while rows listed the projects. Each project was marked with a “1” if it was affected by a particular cause and a “0” if not. Two additional columns were created: one for schedule deviation and another for budget deviation. These columns recorded “1” if the project experienced a deviation and “0” if it did not. This table was then exported to the fsQCA software [44,45].

Given that the analyzed data were organized dichotomously, Crisp-Set QCA was used. The output variables were the schedule and budget deviations, while the causal conditions were the causes of deficiencies in the schedule planning of the analyzed projects. A truth table was constructed using the input data to verify the different configurations of cause combinations that could lead to deviations. The QCA was conducted in two stages: one focused on schedule deviations and the other on budget deviations. Additionally, the analysis considered the five stages proposed in stage two, assigning the causes of scheduling deficiencies to each stage as determined by an expert workshop. From the identified configurations in the truth table, coverage and consistency for each configuration were calculated. The number of configurations was determined by the number of grouped causes of deficiency in each analyzed stage n , using the expression 2^n . Coverage (CG) indicates the proportion of cases where the condition and the outcome of interest appear among the cases showing the condition (see Equation (3)). Consistency (CS) indicates the proportion of cases with both the condition and the outcome of interest among the total cases showing the outcome of interest [46] (see Equation (4)).

$$CG_j = \left(\frac{FD_i}{ND} \right) * 100\% \quad (3)$$

$$CS_j = \left(\frac{FD_i}{N_C} \right) * 100\% \quad (4)$$

where N_D represents the total number of projects that exhibited the analyzed deviation (schedule deviation: $N_D = 20$; budget deviation: $N_D = 16$), N_C is the total number of projects that presented the deficiency causes of configuration j . FD_i is the total number of projects that were affected by the deficiency causes of configuration j and also experienced the analyzed deviation (schedule or budget deviation).

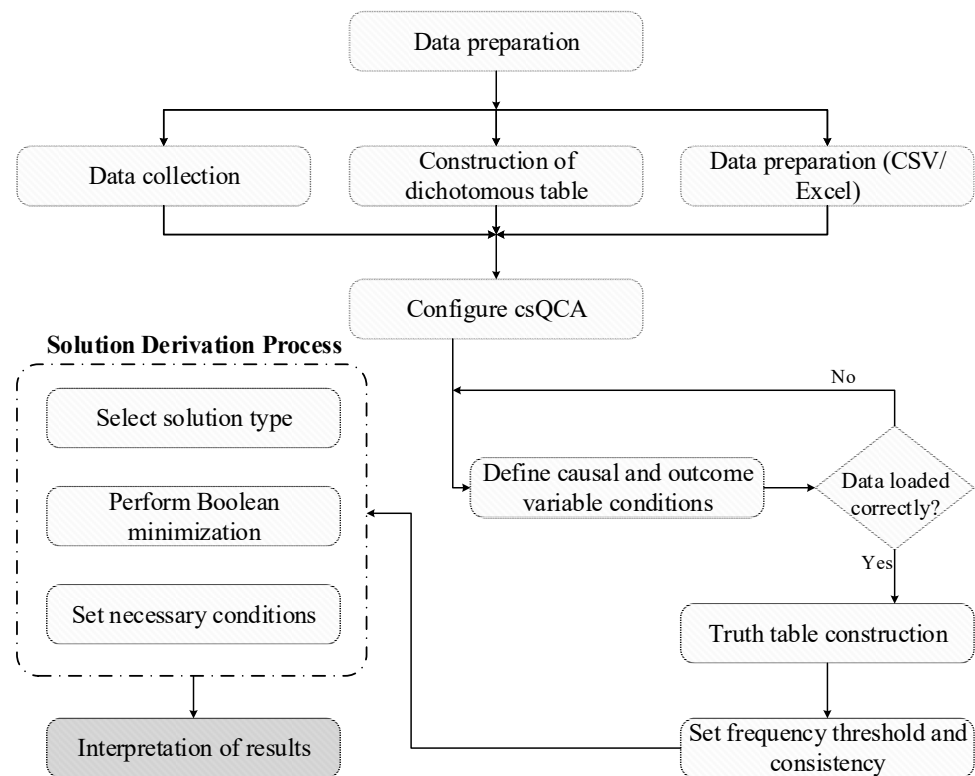


Figure 3. Process flow for QCA adoption.

Based on the results obtained for the consistency and coverage values of each configuration derived from the truth table, configurations with high values for both consistency and coverage were selected. To strengthen the analysis, Boolean operators “AND” and “OR” were applied to examine the various configurations of scheduling deficiencies across different projects, contributing to schedule and budget deviations. This analysis allowed for the identification of configurations where the combination of two or more factors significantly influenced the occurrence of schedule and budget deviations.

One of the main methodological limitations of this study lies in the composition of the participants involved in the semi-structured interviews, as 60% of them were academic researchers. While this composition provides a broad perspective supported by strong theoretical foundations, it may also introduce bias by overrepresenting research-oriented viewpoints and underrepresenting direct experience in project execution. The high proportion of academics may limit the generalizability of the findings to contexts where field-based professional practice is predominant. However, the inclusion of 40% of professionals with more practice-oriented roles partially balances the results, allowing for a contrast between academic perspectives and operational realities. To mitigate this limitation, a methodological triangulation strategy was adopted, combining a systematic literature and project review, semi-structured expert interviews, and a Qualitative Comparative Analysis (QCA) based on empirical data from executed road intersection projects. This

empirical component reinforces the external validity of the study. However, it is acknowledged that future research should expand the diversity of participants by incorporating a higher proportion of civil engineers and practitioners actively engaged in project execution, as well as representatives from public agencies and consulting firms. Such diversity would enhance the validation of the study's findings under varying professional perspectives and help to contextualize the predominately academic views.

3. Results and Analysis

3.1. Processes and Data Inputs in the Planning of Road Schedules

Table 3 presents the processes and data inputs that constitute the planning of road project schedules, identified through a literature review of a final analysis sample of 22 documents. This sample comprised scientific articles and technical manuals from the Scopus search engine and national and international transportation department databases. Identifying the processes and data inputs necessary for schedule planning allows planners and managers to make more informed decisions on allocating resources such as labor, materials, and equipment for schedule development. Detailed knowledge of the planning processes improves project accuracy and control by allowing early identification of potential deviations. With this, planners and the technical team can propose implementing corrective actions to avoid undesirable impacts upon completion. Identifying the processes and the sequence in which they should be developed strengthens risk management by developing robust contingency plans, thus reducing the probability of delays and cost overruns due to poor planning.

Table 3. Processes and data inputs in the planning of road schedules.

Id	Process	Input Files	References
P ₁	Identify factors affecting the construction process	Drawings, design specifications and technical reports, type of contract, characterization of the area, allocated budget, database historical, Traffic Management Plan (TPM)	[37,39,47–53]
P ₂	Define procedures for incorporating additions	Project scope and terms of reference, owner's requirements	[37,39,53,54]
P ₃	Define work milestones	Project scope and terms of reference, owner's requirements, drawings, design specifications, and technical reports	[39,48,49,53,55]
P ₄	Define work zones or phases (Major work item)	Project scope and terms of reference, owner's requirements, drawings, design specifications and technical reports, characterization of the area	[37,47,50–52,55,56]
P ₅	Define schedule planning models	Planning methodologies, tools, database historical (KPI), drawings, design specifications and technical reports, control criteria, rules and regulations	[48,49,54]
P ₆	Define time units	Project scope and terms of reference	[39,51,53]
P ₇	Define parameters and schedule management plan	Project scope and terms of reference, owner's requirements	[47–49]
P ₈	Collect project drawings and specifications	Drawings, design specifications, and technical reports	[39,48–50,53,55]

Table 3. Cont.

Id	Process	Input Files	References
P ₉	Determine work in phases	Project scope and terms of reference, owner's requirements, drawings, design specifications and technical reports, characterization of the area	[47,49,50,52,55,56]
P ₁₀	Define landfills and quarries	Technical and economic feasibility, characterization of the area, control criteria, rules and regulations, landfill capacity and history, database historical	[38,48,51]
P ₁₁	Identify complementary works and similar works	Drawings, design specifications, technical reports, database historical, control criteria, rules and regulations, project phases	[37,47,50,53,55,57,58]
P ₁₂	Define the WBS (Work Package)	Drawings, design specifications and technical reports, project scope and terms of reference, types of work, control criteria, rules and regulations, project phases	[39,49–53,55,58,59]
P ₁₃	Identify general and detailed activities	Project scope and terms of reference, characterization of the area, WBS work packages, drawings, design specifications and technical reports, available resources, control criteria, rules and regulations	[37,39,48–53,55,58,59]
P ₁₄	Define units of measure	Types of work, WBS work packages, general and detailed activities	[39,50,51]
P ₁₅	Identify the internal circulation of the work	Characterization of the area, types of work, work zones or phases, drawings, design specifications and technical reports, project phases, general and detailed activities	[47,48,51,56]
P ₁₆	Identify advances or delays of successor activities	Types of work, WBS work packages, general and detailed activities	[39,50,51,58]
P ₁₇	Define construction methods	Types of work, technology and equipment available, cost and time, training, drawings, design specifications and technical reports, project phases, control criteria, rules and regulations, database (KPI)	[50,52,53,60]
P ₁₈	Identify dependencies and precedence of activities	Types of work, drawings, design specifications and technical reports, types of dependence, project constraints, available resources, project phases, TPM	[39,47–49,51–54,58]
P ₁₉	Define material resources	Drawings, design specifications and technical reports, work zones or phases, general and detailed activities, preliminary work quantities, resource costs, market research, types of work	[37,39,48–53,55,58]
P ₂₀	Define manpower resources		[39,48–53,55]
P ₂₁	Define minor tool		[48–51,53]
P ₂₂	Define construction machinery and equipment		[48–53]
P ₂₃	Identify quantities of work by activity		[37,39,48–53,58,61]
P ₂₄	Identify production rates		[37,39,48–51,53]

Table 3. Cont.

Id	Process	Input Files	References
P ₂₅	Define work schedule and working days	Estimated durations, activity sequences and dependencies, available resources, project schedule, project phases, programming software, general and detailed activities, project constraints	[39,49–53,55,57]
P ₂₆	Develop the schedule		[37,39,48,49,51,53]
P ₂₇	Evaluation of solution schedule		[37,39,47,48,51,53,54]
P ₂₈	Perform cost estimates		[48,49,53]
P ₂₉	Generate documentation	Output stages I, II, III, and IV	[62]

The process flow map in Figure 4 displays the planning of road intersection schedules. It consists of 29 processes identified through a systematic review. It is associated with five stages proposed based on the PMBOK's schedule management planning processes: (1) Road Schedule Management Planning, (2) Definition of Construction Activities, (3) Sequencing Construction Activities, (4) Estimating Duration of Construction Activities, and (5) Road Construction Schedule Development. The process classification in the stages was obtained from a panel of five experts in road construction scheduling. Each stage is represented by a distinct vertical color band, outlining the identified processes and relevant influencing variables. By aligning findings with PMBOK standards, the proposed process flow facilitates the adoption of best practices to enhance the planning and scheduling of road intersection construction projects.

Figure 4 presents the methodological framework proposed for the scheduling of road construction projects, organized into six sequential stages. The flow begins with Stage I, where planning parameters, control criteria, scheduling models, and time units are defined, establishing the foundation for subsequent activities. In Stage II, project drawings and specifications are collected, the Work Breakdown Structure (WBS) is structured, and work zones and measurement units are defined. Stage III addresses the logical sequencing of work through the identification of activity dependencies and the definition of construction methods. In Stage IV, required resources, execution methods, and production rates are estimated, which enables the development of a preliminary schedule. Then, in Stage V, the final schedule is developed, its feasibility is evaluated, feedback is incorporated if necessary, and the corresponding documentation is generated, including cost estimates. Finally, Stage VI involves the execution, monitoring, and control of the schedule during the construction phase. Based on Figure 4, it is possible to coherently integrate technical data, planning decisions, and control tools needed to manage schedules in road projects with a structured and replicable approach.

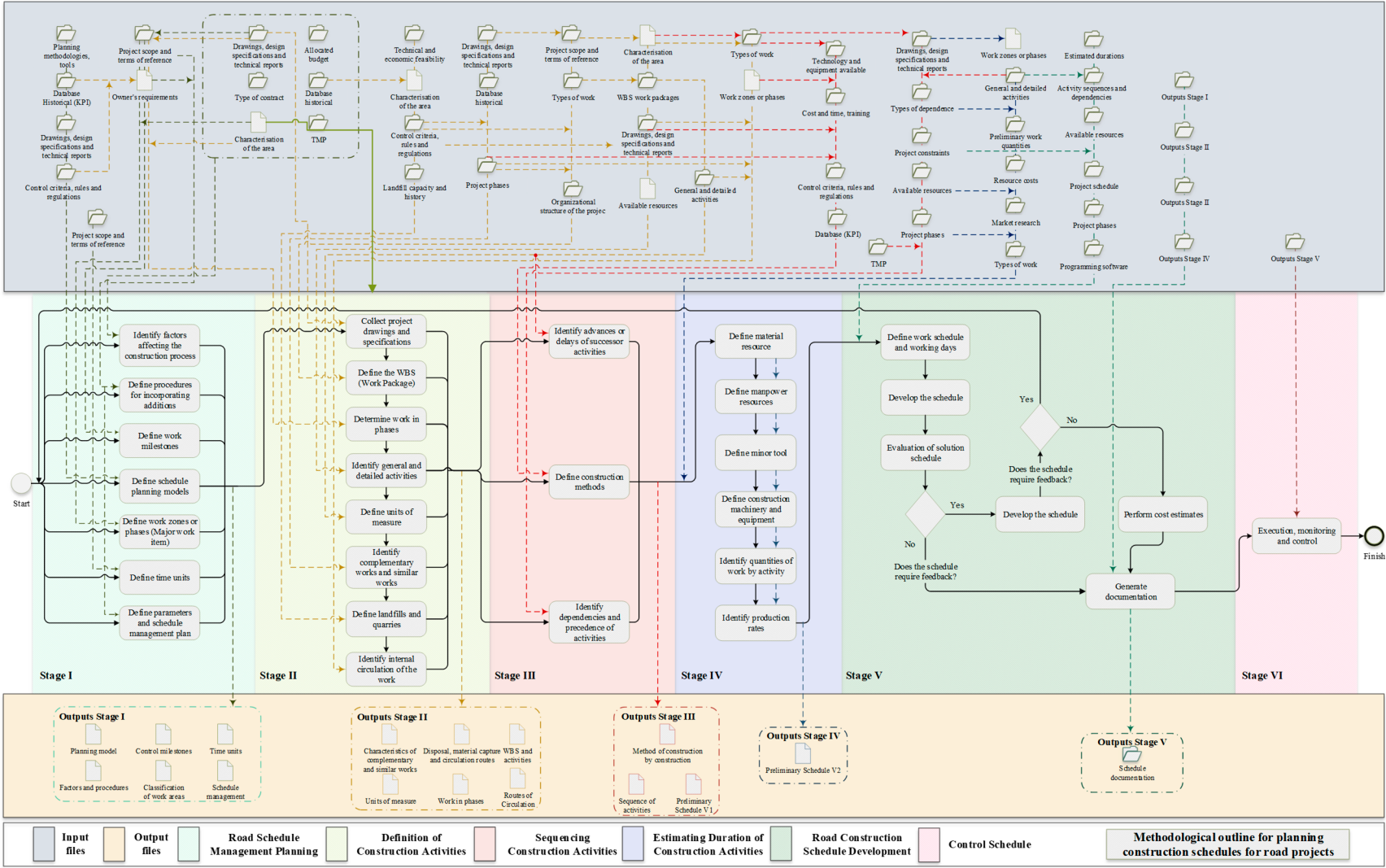


Figure 4. Process flow diagram of road intersection planning timelines, according to planning steps PMBOK [40].

3.1.1. Road Schedule Management Planning

This stage involves defining the processes and data inputs that will be used to manage the schedule throughout the lifecycle of the road infrastructure project. Specifically, Stage I includes seven key processes: (1) identifying factors affecting the construction process, (2) defining procedures for incorporating additions, (3) defining work milestones, (4) defining schedule planning models, (5) defining work zones or phases, (6) defining time units, and (7) establishing schedule parameters and the overall schedule management plan. These processes are supported by various inputs, such as the planning method, project scope and terms of reference, historical databases (KPIs), technical specifications, drawings, and control criteria. The outputs of this stage include a structured planning model, milestone controls, time units, classification of work zones, and a schedule management plan, which together establish the foundation for subsequent scheduling activities. It addresses aspects related to the structure and control of the schedule, establishing the required levels of precision based on the deliverables' characteristics and the project's construction processes. Additionally, the necessary time units for planning and controlling activities are determined, which, in road projects, may include hours, days, weeks, or other units depending on the project's scale. Furthermore, the procedures for incorporating necessary additions and corrective activities for deficiencies detected in the schedule during construction are described. In terms of monitoring, the metrics for measuring schedule performance as construction progresses are established, and the criteria for updating these metrics are based on recorded progress. Depending on the organization and its protocols, the characteristics of reports detailing the schedule status at specific points in the construction process are defined. With this information, the procedures required to manage and control the schedule during the construction phase are documented, providing both the scheduling and control professionals with a clear roadmap for handling events and updates during the construction process. It is recommended that the various project stakeholders be involved in gathering their insights and observations, reducing the likelihood of schedule deficiencies and avoiding schedule and budget deviations.

3.1.2. Definition of Construction Activities

This stage involves gathering project information to identify and define the characteristics of the construction activities necessary to realize the project. During this phase, factors that could affect the construction process are identified, and the areas where the work is recommended to be carried out are planned according to the required sequence and the conditions of vehicular and pedestrian traffic at the site. Ensuring that the activities align with the traffic management plan is essential when planning construction activities for road intersections. This coordination helps to manage the construction process about the traffic conditions at the project site. To define construction activities and the necessary work packages, it is essential to consider the site characteristics that might affect the development of these activities. This involves specifying the quarries for material supply and the disposal sites for excavated or demolition material, focusing on minimizing environmental impact. The locations of these quarries and material sources will condition the activities' structures and the duration of the construction stage. It is also crucial to detail internal site circulation, loading and unloading zones, complementary works required for construction, and suitable construction methods that align with the project's characteristics and components. Reviewing similar previous projects can support the definition of construction processes and help achieve greater efficiency. Using this information, the planning team can establish the main chapters of the work breakdown structure (WBS), breaking down the project into construction activities based on the selected construction processes, characteristics, and

scope. The unit of measure is defined for each construction activity, allowing for scheduling and monitoring progress during the construction phase.

3.1.3. Sequencing Construction Activities

Sequencing construction activities involves identifying and documenting the order in which the project's construction activities should be based on the activities identified during the planning phase. This information helps establish the chronological order of construction activities, ensuring an efficient construction process that aligns with the project's scope. Identifying these relationships also helps pinpoint the constraints activities will face during construction, allowing the contractor to manage the release of constraints on predecessor activities. Furthermore, planners can use this information to estimate the duration and critical path of the project, identifying activities that could delay the project if they are delayed. This approach enables planners to highlight essential construction activities and those with float, where schedule deviations can occur without affecting the project's delivery date. Key types of precedence relationships include finish-to-start (FS), finish-to-finish (FF), start-to-start (SS), and start-to-finish (SF). Additionally, it is crucial to account for leads or lags that may impact the start of successor activities. When defining precedence relationships for road infrastructure construction processes, it is essential to consider the work zones where the construction process will occur. This consideration allows for alternating between different work zones, coordinating the construction process with the project's traffic management plan, minimizing disruptions to road users, and enhancing construction efficiency.

3.1.4. Estimating Duration of Construction Activities

This stage involves estimating the duration of construction activities by calculating the labor time needed for each activity defined in Stage 2. The schedule accuracy depends heavily on precise duration estimates for each activity. Therefore, it is crucial to analyze the requirements and constraints of each activity to make realistic estimates based on potential scenarios during road construction. It also involves defining the resources needed, including machinery, materials, and personnel. Estimating machinery and personnel performance is crucial due to the high degree of mechanization in road construction projects. This estimation should be conducted rigorously, using previous estimates and experiences to achieve high equipment and personnel productivity accuracy. Additionally, precise estimation of the quantities for each activity, based on the unit of measurement defined in earlier stages, is vital. In the absence of historical performance data, alternative techniques such as scenario-based estimation or breaking down activities into sub-activities and estimating the duration of each sub-activity can be employed. It is necessary to analyze the risks and obstacles that may impact the duration of activities and to account for the time needed for contingency activities to mitigate such risks. Site and weather conditions must also be considered, with particular attention to traffic conditions, which will influence the duration of construction activities based on the zoning established for the construction process. The availability of equipment, such as heavy machinery, should be considered, as the number of available units will affect the duration of activities depending on the contractor's resources.

3.1.5. Road Construction Schedule Development

This stage involves creating the project schedule based on information gathered in earlier phases. Various tools and methods, such as precedence diagrams, critical path methods (CPM), and Gantt charts, can be used for the schedule development process. It is crucial to define the work calendar for scheduling tasks according to work hours and calendar constraints, including holidays and legal restrictions. This calendar helps identify

the time slots during which work can be scheduled. Assigning labor tasks within these available time slots enables the identification of the project's critical path. Analyzing this critical path allows for estimating the project's duration based on the duration of activities within it. After creating the initial schedule, alternative analyses can be conducted to compress the timeline by adjusting the allocation of resources to each construction activity. Graphic methods facilitate identifying opportunities for planning parallel execution of activities, which can reduce the project's duration without compromising its scope. Linear scheduling methods can benefit road construction projects due to the repetitive construction activities. Road projects often involve distributing construction processes across different zones, where various activities must be repeated to build the pavement layers in each zone. The application of line-of-balance techniques helps identify incompatibilities between construction activities. Once each activity's start and end dates are defined, a baseline can be established to measure the project's progress and performance during construction.

3.2. Causes of Schedule Deficiencies Related to Planning Stages

Table 4 presents the relationship between 22 causes of schedule planning deficiency obtained from the study conducted by Castañeda et al. [41] and the five stages of schedule management planning proposed for this study: (1) Road Schedule Management Planning, (2) Definition of Construction Activities, (3) Sequencing Construction Activities, (4) Estimating Duration of Construction Activities, (5) Road Construction Schedule Development. Each intersection marked with a 'tick' (✓) indicates that the cause is highly associated with that stage, according to the interviews conducted with the ten industry professionals. This analysis is adopted to identify and prioritize the stages that present deficiencies and require improvement, which could facilitate the implementation of specific strategies to enhance the planning of road project schedules.

Table 4. Relationship between stages and causes of deficiency in the planning of road project schedules.

Id	Deficiencies in Road Project Schedule Planning					
		Road Schedule Management Planning	Definition of Construction Activities	Sequencing Construction Activities	Estimating Duration of Construction	Road Construction Schedule Development
C ₁	Poor estimation of workforce performance				✓	
C ₂	Poor estimation of workforce quantity				✓	✓
C ₃	Deficient coordination with public utilities (water, sanitary, electrical, and other surface or subway networks)	✓				
C ₄	Inadequate estimation of permit acquisition durations				✓	
C ₅	Inadequate weather forecasting					✓
C ₆	Deficient estimation of material quantities		✓		✓	✓
C ₇	Inadequate estimation of construction document approval times				✓	

Table 4. Cont.

Id	Deficiencies in Road Project Schedule Planning	Road Schedule Management Planning	Definition of Construction Activities	Sequencing Construction Activities	Estimating Duration of Construction	Road Construction Schedule Development
C ₈	Request for project start time extensions (applies in cases of rescheduling requests)	✓				
C ₉	Inadequate exploration of existing site conditions		✓			
C ₁₀	Lack of experience of the planner		✓	✓	✓	✓
C ₁₁	Failures in the definition of successor and predecessor relationships between activities			✓		
C ₁₂	Failures in the configuration of the work schedule (working days, holidays, working hours, seasons of the year)					✓
C ₁₃	Omission or deficiency in the definition of work packages (WBS)		✓			
C ₁₄	Inadequacy of planning software adopted	✓				
C ₁₅	Lack of planning of storage and parking sites		✓		✓	
C ₁₆	Omission of road markings in planning	✓	✓			
C ₁₇	Poor zoning of the construction process based on traffic conditions			✓		
C ₁₈	Failures in on-site traffic estimation	✓		✓		
C ₁₉	Poor planning of machinery routes				✓	
C ₂₀	Lack of verification during the schedule preparation					✓
C ₂₁	Inadequate estimation and consideration of waiting times (setting time or other waiting times between activities)				✓	
C ₂₂	High complexity of construction work	✓	✓			

The relationship between causes of deficiency and planning stages shows that each stage can be affected by one or more specific causes. These results reinforce the need for project planners to adopt methodologies and strategies according to the particularities of each stage to address the problems inherent in road intersection planning. Knowing the causes associated with each stage makes it possible to plan actions and implement tools to mitigate these causes, improving the planning process's accuracy. In addition, it addresses the fundamental importance of managing clear and precise information in aspects such as objectives, roles and responsibilities, tasks, dependencies between activities, resource estimation, and integration of activities, among others. An incorrect development in any of these areas can result in uncoordinated planning, unrealistic schedules, and inefficient use of resources, which inevitably leads to delays and cost overruns. Thus, schedule planning requires professionals who correctly execute each process and can integrate and coordinate all activities coherently aligned with the project objectives.

3.3. Deviation Magnitudes by Causes of Deficiency

Relevant information content in Appendices A and B about analyzed projects is needed for this section. Appendix A consists of a table that contains technical information for the 25 projects analyzed. The ID column represents the contract number as registered in SECOP I or SECOP II. Additional columns include type, contracting entity, planned cost, real cost, cost variation, planned duration, real duration, and time schedule variation. Appendix B consists of a table presenting the relationship between the causes found for each project.

Table 5 shows the average percentages of schedule deviations (SD) and cost deviations (CD) for projects affected and unaffected by the most frequently occurring planning deficiencies identified in the analyzed projects. First, the lack of experience of the planner (C₁₀) was identified in 15 road intersection projects, resulting in an average increase of 128% in project duration and 26.2% in initial cost for the affected projects. To identify this cause, a thorough review of the initial project documentation was conducted, revealing that the contractor requested a review shortly after the contract award. This led to significant design changes and the inclusion of unforeseen but necessary activities. Unaffected projects exhibited smaller variations, highlighting the considerable influence of this cause. Second, deficient estimation of material quantities (C₆) caused more significant average variations in schedule and cost than the previous cause, with 136% and 27.9%, respectively. Although this cause affects fewer projects, its impact is more substantial, as evidenced by the comparison between affected and unaffected projects. This cause relates to the need for more planner experience, as both are present in most analyzed projects. The third identified cause is the omission of road markings in planning (C₁₆). Analysis of project budgets revealed that projects with strict control over signage exhibited lower variations in schedule and cost, with an increase of 151.8% in schedule and 23.9% in cost compared to the first two causes. Projects unaffected by this cause showed smaller average variations. Finally, the omission or deficiency in the definition of work packages (WBS) (C₁₃) was identified by analyzing incidents during the construction phase. Affected projects commonly added unforeseen activities, necessitating meetings to approve them and define their costs. These projects experienced average variations of 122.4% in time and 30.1% in cost. These four main causes show a considerable difference in magnitude between affected and unaffected projects. Therefore, Table 5 highlights the cases where a direct relationship was identified between the average variations of affected and unaffected projects for each cause with a “*”.

Table 5. Cost and schedule deviations magnitudes by causes of deficiency.

Causes of Deficiency		Frequency n = 25	Affected		Unaffected	
			SD	CD	SD	CD
C ₁₀	Lack of experience of the planner	15 (60.0%)	128.0%	26.2%	47.8% *	6.5% *
C ₆	Deficient estimation of material quantities	14 (56.0%)	136.0%	27.9%	52.4% *	7.2% *
C ₁₆	Omission of road markings in planning	14 (56.0%)	151.8%	23.9%	36.5% *	11.3% *
C ₁₃	Omission or deficiency in the definition of work packages (WBS)	12 (48.0%)	122.4%	30.1%	97.4% *	10.8% *
C ₃	Deficient coordination with public utilities (water, sanitary, electrical, and other surface or subway networks)	10 (40.0%)	79.0%	15.4%	184.6%	33.7%
C ₉	Inadequate exploration of existing site conditions	10 (40.0%)	127.1%	15.8%	136.6%	33.3%
C ₂₂	High complexity of construction work	10 (40.0%)	73.9%	29.2%	189.8%	20.0% *
C ₄	Inadequate estimation of permit acquisition durations	8 (32.0%)	104.1%	16.2%	225.5%	45.3%

The fifth identified cause, deficient coordination with public utilities (water, sanitary, electrical, and other surface or subway networks) (C₃), affected fewer projects. The analysis of project documents revealed a need for more information gathering on existing networks. During the construction phase, unforeseen networks were encountered, leading to deviations in schedule and cost. The sixth identified cause, inadequate exploration of existing

site conditions (C_9), is closely related to the previous one and is present in almost all the same projects. Its average schedule deviation was 127.1% and 15.8% in cost. This cause was identified through reports mentioning unexpected elements or conditions not noted during field visits. The seventh cause, the high complexity of construction work (C_{22}), primarily impacted projects due to the difficulties encountered during execution. Although this cause can be mitigated during the planning stage, the inherent complexity of the projects led to unforeseen limitations or conditions not experienced in other projects. These difficulties resulted in average variations for affected projects of 73.9% in schedule and 29.2% in cost. Lastly, the cause of inadequate estimation of permit acquisition durations (C_4) was the most prevalent in the analyzed projects. Affected projects reported an average schedule deviation of 104.1% and 16.2% in cost. These last four causes do not show a direct relationship in the magnitude of schedule and cost variations between affected and unaffected projects. This is because most projects, although presenting more than one cause, share different causes. Therefore, while these individual causes generate significant variations in affected projects, other causes or combinations of causes can result in even more important variations in unaffected projects. These combinations will be analyzed in the following section.

3.4. Qualitative Comparative Analysis

Table 6 presents the results of the Qualitative Comparative Analysis (QCA) conducted to identify causal patterns leading to cost and schedule deviations in road intersection projects across the five proposed planning and scheduling stages. The QCA utilized (1) the five planning stages proposed, (2) deficiency causes identified in the 25 analyzed projects, (3) relationships between deficiency causes and stages identified through interviews with a panel of 10 experts, and (4) classification of whether each of the 25 projects experienced cost or schedule deviations. The first column details the different stages of the planning and scheduling process. The second column displays the results of condition combinations, along with their respective consistency and coverage metrics (CG), associated with expected cost overruns. Additionally, it presents the combinations, consistency (CS), and coverage (CG) metrics corresponding to expected delays in project execution. The values highlighted in red indicate acceptable consistency and coverage levels, supporting the identified configurations' empirical and logical validity. These combinations help determine how deficiencies in schedule planning contribute to cost and schedule deviations in road intersection projects.

The Qualitative Comparative Analysis (QCA) results revealed that the cause of 'Deficient estimation of material quantities' (C_6) has a consistency value of 0.625 in the presence of cost overruns for Stages 2, 4, and 5 of the planning process. This indicates that in 62.5% of the projects, this cause was present when cost overruns were observed. In Stage 2, which corresponds to the 'Definition of Construction Activities', C_6 is identified as a critical and necessary cause for the presence of cost overruns in road intersection projects. In 81.3% of the cases, the presence of C_6 , or its combination with C_{10} ($C_6 + C_{10}$) or C_{16} ($C_6 + C_{16}$), was necessary for cost overruns to be evident. In addition, the combination of C_6 with C_{13} ($C_6 + C_{13}$) or C_{22} ($C_6 + C_{22}$) was necessary in 75.0% of the cases for cost overruns to be evident. For C_6 , the coverage is 0.714, which indicates that 71.4% of the projects that present this cause also present cost overruns. In step 4, 'Estimating Duration of Construction', C_6 presents the second highest consistency among the causes analyzed. The presence of C_6 , or alternatively C_{10} ($C_6 + C_{10}$), or C_4 , or C_7 ($C_4 + C_6 + C_{10} + C_7$), or C_2 ($C_2 + C_4 + C_6 + C_{10}$) is necessary in 81.3% of the cases for cost overruns to be evident. Unlike Stage 2, in Stage 4, C_6 presents a delay consistency of 0.65, being the highest of the stage, which indicates that this cause is found in 65.0% of the projects that present delay. Finally, in Stage 5, 'Road Construction Schedule Development', the presence of C_6 or,

alternatively, C_{10} ($C_6 + C_{10}$) is necessary in 81.3% of the cases for cost overruns to be evident, as in Stage 2. The combinations ($C_6 + C_{10}$) and ($C_6 + C_4$) with a consistency of 0.75 and 0.70, respectively, show how adding causes to a critical cause can reinforce cost overruns in road intersection projects. Thus, the underestimation of material quantities impacts direct costs and generates uncertainty and constant adjustments, affecting the project's development under compliance with the initial contractual conditions. This highlights the importance of accurate estimation of quantities of work from the initial stages, as early errors can trigger significant financial problems during the construction stage. C_6 when combined with other causes such as: 'Omission or deficiency in the definition of work packages (WBS)' (C_{13}), 'Lack of experience of the planner' (C_{10}), 'Omission of road markings in planning' (C_{16}), and 'High complexity of construction work' (C_{22}), can increase the presence of undesired scenarios at different stages and potential cost overruns in projects. Lack of experience can lead to inaccurate estimates of materials, time, and resources needed, while C_{13} and C_{16} result in incomplete and disorganized planning, requiring continuous adjustments and causing workflow disruptions. In addition, C_{22} adds an additional difficulty level, increasing the likelihood of errors and the need for revisions and corrections.

Consistency of the cause 'Lack of experience of the planner' (C_{10}) for cost overrun and delay is 0.750 and 0.650, respectively. This indicates that this cause is present in 75.0% of the projects with cost overruns and 65.0% of the projects with delays. The presence of C_{10} , or alternatively its combination with C_{13} ($C_{10} + C_{13}$), is necessary in 75% of the cases for cost overruns to be evident. In comparison, its combination with C_{16} ($C_{10} + C_{16}$) is necessary in 93.8% of the cases and with C_{22} ($C_{10} + C_{22}$) in 81.3% of the cases. In addition, the coverage of the combinations of C_{10} with C_4 ($C_{10} + C_4$) or C_4 with C_6 ($C_4 + C_6 + C_{10}$) indicates that 70.0% and 80.0% of the projects that present the cause also present delay. 'Omission or deficiency in the definition of work packages (WBS)' (C_{13}) is mainly identified in the stage 'Definition of Construction Activities', with a consistency of 0.625, indicating that this cause is found in 62.5% of the projects that present cost overruns. The combination of C_{13} with C_{22} ($C_{22} + C_{13}$) has a consistency of 0.813, indicating that it is necessary in 81.3% of the cases for cost overruns to become evident. Individually, C_{13} is less necessary for delays to be evidenced with a consistency of 0.20. Combinations of causes in addition to the planner's lack of experience, such as 'Omission or deficiency in the definition of work packages (WBS)' (C_{13}), 'Omission of road markings in planning' (C_{16}), 'High complexity of construction work' (C_{22}), and 'Inadequate estimation of permit acquisition durations' (C_4) provide critical determinant scenarios in the appearance of cost overruns and delays in road projects. An inadequate WBS aggravates the lack of experience due to the impact on costs and time generated by omissions of critical activities. These omissions may be reflected in cause C_{16} since the omission of road markings may require adjustments during the construction process that could affect the development of the schedule.

The cause of deficiency, 'Omission of road markings in planning' (C_{16}), is mainly present in the stages of the 'Road Schedule Management Planning' and 'Definition of Construction Activities'. The proportion of projects with both a C_{16} cause of deficiency and the presence of cost overrun among the total number of projects with cost overrun is represented by 56.3% and for delay by 60.0%. Combinations of C_{16} with C_3 ($C_3 + C_{16}$) or C_{22} ($C_{16} + C_{22}$) increase the consistency to 75.0% and 81.3%, respectively, for cost overruns with a coverage of 66.7% and 65.0%, respectively. For delay, the consistency and coverage of these combinations do not vary significantly, being the most representative cause of deficiency in Stage 1. 'Deficient coordination with public utilities (water, sanitary, electrical and other surface or subway networks)' (C_3) and 'High complexity of construction work' (C_{22}) add an additional layer of complexity, as works must continually adjust to avoid or correct interference with existing infrastructure, which is further exacerbated in a complex project, as they are inherently more prone to face coordination challenges.

Table 6. Consistency and coverage metrics for cause combinations according to csQCA.

Stage	Cost Deviation (CD)			Schedule Deviation (SD)		
	Combinations	CS	CG	Combinations	CS	CG
Road Schedule Management Planning	C ₃	0.438	0.700	C ₃	0.450	0.900
	C ₈	0.188	1.000	C ₈	0.150	1.000
	C ₁₆	0.563	0.643	C ₁₆	0.600	0.857
	C ₁₈	0.125	1.000	C ₁₈	0.100	1.000
	C ₂₂	0.500	0.800	C ₂₂	0.400	0.800
	C ₃ + C ₁₆	0.750	0.667	C ₃ + C ₁₆	0.750	0.833
	C ₃ + C ₂₂	0.625	0.667	C ₃ + C ₂₂	0.650	0.867
	C ₁₆ + C ₂₂	0.813	0.650	C ₁₆ + C ₂₂	0.800	0.800
Definition of Construction Activities				C ₃ + C ₁₆ + C ₂₂	0.900	0.818
	C ₆	0.625	0.714	C ₆	0.200	0.071
	C ₉	0.438	0.700	C ₉	0.200	0.100
	C ₁₀	0.750	0.800	C ₁₀	0.400	0.133
	C ₁₃	0.625	0.833	C ₁₃	0.200	0.083
	C ₁₅	0.063	0.333	C ₁₅	0.000	0.000
	C ₁₆	0.563	0.643	C ₁₆	0.400	0.143
	C ₂₂	0.500	0.800	C ₂₂	0.400	0.200
	C ₆ + C ₁₀	0.813	0.722			
	C ₆ + C ₁₃	0.750	0.750			
	C ₆ + C ₁₆	0.813	0.684			
	C ₆ + C ₂₂	0.750	0.706			
	C ₁₀ + C ₁₃	0.750	0.750			
	C ₁₀ + C ₁₆	0.938	0.682			
	C ₁₀ + C ₂₂	0.813	0.813			
	C ₁₃ + C ₁₆	0.813	0.684			
	C ₁₆ + C ₂₂	0.813	0.650			
	C ₂₂ + C ₁₃	0.813	0.813			
Sequencing Construction Activities	C ₁₀	0.750	0.800	C ₁₀	0.650	0.867
	C ₁₁	0.063	1.000	C ₁₁	0.050	1.000
	C ₁₇	0.125	1.000	C ₁₇	0.100	1.000
	C ₁₈	0.125	1.000	C ₁₈	0.100	1.000
	C ₁₀ + C ₁₇	0.813	0.813			
	C ₁₀ + C ₁₈	0.813	0.813			
Estimating Duration of Construction	C ₁	0.188	0.750	C ₁	0.200	1.000
	C ₂	0.250	0.800	C ₂	0.250	1.000
	C ₄	0.375	0.750	C ₄	0.360	0.875
	C ₆	0.625	0.714	C ₆	0.650	0.929
	C ₇	0.250	1.000	C ₇	0.150	0.750
	C ₁₀	0.750	0.800	C ₁₀	0.650	0.867
	C ₁₅	0.063	0.333	C ₁₅	0.150	1.000
	C ₁₉	0.125	1.000	C ₁₉	0.100	1.000
	C ₂₁	0.063	1.000	C ₂₁	0.050	1.000
	C ₆ + C ₁₀	0.813	0.722	C ₆ + C ₁₀	0.750	0.833
	C ₄ + C ₇	0.438	0.778	C ₆ + C ₄	0.700	0.875
	C ₄ + C ₆ + C ₁₀ + C ₇	0.813	0.684	C ₄ + C ₁₀	0.700	0.875
	C ₂ + C ₄ + C ₇	0.563	0.750	C ₄ + C ₆ + C ₁₀	0.800	0.842
	C ₂ + C ₄ + C ₆ + C ₁₀	0.813	0.650			
Road Construction Schedule Development	C ₂	0.250	0.800	C ₂	0.250	1.000
	C ₅	0.188	0.600	C ₅	0.250	1.000
	C ₆	0.625	0.714	C ₆	0.650	0.929
	C ₁₀	0.750	0.800	C ₁₀	0.650	0.867
	C ₁₂	0.000	0.000	C ₁₂	0.050	1.000
	C ₂₀	0.125	1.000	C ₂₀	0.100	1.000
	C ₆ + C ₁₀	0.813	0.722	C ₆ + C ₁₀	0.750	0.833
	C ₂ + C ₅ + C ₂₀	0.375	0.667			

4. Discussion

4.1. Impact of the Causes of Deficiency on Deviations

Table 7 presents a classification of the planning deficiency causes according to their level of impact on schedule delays (Schedule Delay— $\overline{SD}$) and cost deviations (Cost Deviation— $\overline{CD}$), expressed through their average effect and relative ranking in each dimension. This table allows for the distinction between causes that predominantly affect time, those that mainly impact costs, and others that generate a dual effect. This differentiation is essential for understanding the nature of each cause and for proposing mitigation strategies with greater precision based on the type of impact they produce.

Table 7. Classification of deficiency causes according to their impact on schedule delays ($\overline{SD}$) and cost deviations ($\overline{CD}$).

Causes of Deficiency		Affected		Rank SD	Rank CD
		$\overline{SD}$	$\overline{CD}$		
C ₁₆	Omission of road markings in planning	151.80%	23.90%	1	5
C ₆	Deficient estimation of material quantities	136.00%	27.90%	2	3
C ₁₀	Lack of experience of the planner	128.00%	26.20%	3	4
C ₉	Inadequate exploration of existing site conditions	127.10%	15.80%	4	7
C ₁₃	Omission or deficiency in the definition of work packages (WBS)	122.40%	30.10%	5	1
C ₄	Inadequate estimation of permit acquisition durations	104.10%	16.20%	6	6
C ₃	Deficient coordination with public utilities (water, sanitary, electrical, and other surface or subway networks)	79.00%	15.40%	7	8
C ₂₂	High complexity of construction work	73.90%	29.20%	8	2

The analysis of the causes of deficiency reveals significant differences in the extent to which each one impacts delays and cost overruns in road project scheduling. The cause of the Omission of road markings in planning (C₁₆) ranks as the most critical in terms of schedule delays (Rank SD = 1), while its impact on cost deviations is notably lower (Rank CD = 5). This indicates that its effect is primarily associated with interruptions or miscoordination during execution rather than direct budget increases. In turn, Deficient estimation of material quantities (C₆) and Lack of experience of the planner (C₁₀), ranked second and third in schedule delays, respectively, also occupy high positions in cost deviation (Rank CD = 3 and 4, respectively), suggesting that both simultaneously affect time and budget. In contrast, Omission or deficiency in the definition of work packages (WBS) (C₁₃) and High complexity of construction work (C₂₂) stand out due to their greater influence on cost overruns (Rank CD = 1 and 2), despite being ranked lower for schedule delays (Rank SD = 5 and 8). This suggests that their impact is mainly reflected in the need for technical, administrative, or contractual adjustments. Additionally, causes such as Deficient coordination with public utilities (C₃) and Inadequate estimation of permit acquisition durations (C₄) show moderate impacts on both dimensions, indicating that their effects tend to be localized and manageable if addressed in a timely manner.

4.2. Causes Identified in Road Intersection Projects and Relationship with Previous Studies

Related studies about the causes of deficiencies in construction projects have identified that using advanced technologies with adequate expertise led to accurately estimating the quantity of materials [63,64]. This corresponds with the causes associated with lack of experience and the use of inadequate software in the planning of road intersection projects (C₆, C₁₀). In addition, planning based on traffic during construction conditions improves the comprehension of the process and provides a tool for estimating incidences that cause overtime [65], which represents a relation between C₁₈, C₁₇, and references about

construction projects. Using BIM 5D for cost and schedule management in the construction industry allows the modeling of different scenarios for efficient quantity estimation, improving cost and time management during the life cycle of a project [66–68]. The use of BIM in road intersection planning can mitigate C_1 and C_2 , as shown in the mentioned studies. Design based on site conditions allows a better estimation of the activities required at the different stages of construction. It also allows for anticipating possible issues not identified in the studies performed [69–73]. Causes related to schedule variation on roadway projects can be mitigated by identifying factors associated with traffic and work zone conditions [24,60,74,75]. As can be observed, the studies related to the construction industry are closely associated with the causes of time and cost variations found in road intersection projects. Other causes also occur in building projects or infrastructure projects different from intersections [31,76–79].

4.3. Practical Benefits of the Research Method

The methodology presented offers practical benefits by identifying the critical deficiencies in the construction scheduling process. By integrating expert interviews with Qualitative Comparative Analysis (QCA), this approach highlights the problem areas and specific combinations of deficiencies that can lead to increased risks in both schedules and budgets. These findings are useful for project managers and planners, who can utilize actionable information to develop targeted interventions. For example, recognizing that a “Lack of planner experience” (C_{10}) often worsens issues related to “Poor estimation of material quantities” allows stakeholders to prioritize capacity-building initiatives or seek external consultation to improve the accuracy of quantity take-offs. Additionally, the proposed methodology aligns with the stages outlined in the PMBOK framework, providing a roadmap for integrating process improvements. Construction teams can utilize this structured guide to reassess their activities, from initial planning and task sequencing to detailed duration estimates. This approach safeguards that important factors are not overlooked, such as traffic management constraints and approval times. The definition of planning phases also enhances accountability among project participants, promoting more transparent communication and better resource allocation. Thus, the practical utility of this method extends beyond academic contexts; it serves as a framework for road infrastructure projects. It can be adapted to various contract types and regional contexts, improving project outcomes by addressing schedule and cost overruns. Finally, a practical analysis of Project #1 (Appendix B) shows causes C_3 , C_4 , C_6 , C_7 , C_8 , C_{10} , C_{13} , C_{16} and C_{22} . A detailed review of the documentation confirms that C_{10} was the cause that generated the most variations in the schedule and costs. Design mistakes identified in the planning process led to new designs, which generated new activities and changes in the construction process. These, combined with delays in permit approvals and other shortcomings by the contractor, caused a time variation of 48.4% and cost variations of 29.1%, as shown in Appendix A.

5. Conclusions

This study provides four theoretical contributions that advance the understanding of schedule planning in road intersection construction projects. First, it offers a structured identification of 29 planning processes and their primary data inputs obtained through a systematic literature review of 22 documents. Second, it proposes a theoretical framework that organizes these processes into five planning stages, aligned with the PMBOK structure and validated by a panel of five industry experts, thus contributing to the formalization of scheduling practices. Third, it introduces an original analytical model that associates 22 causes of planning deficiencies with the five stages, based on insights gathered from semi-structured interviews with ten professionals. Fourth, it presents an empirical validation

of the model by analyzing 25 road intersection projects, using Qualitative Comparative Analysis (fsQCA) to identify causal patterns linked to schedule and cost deviations. The study highlights those certain deficiencies, such as deficient material estimation, lack of planner experience, omission of WBS, and insufficient consideration of road markings, consistently contribute to negative project outcomes. These findings deepen the theoretical foundation of construction planning by linking structured planning stages, deficiency causes, and their measurable impacts on project performance.

This analysis is structured in two parts to contribute new insights into the relationship between planning deficiencies and project performance. The first part quantitatively compares cost deviations (CD) and schedule deviations (SD) in projects affected and unaffected by specific deficiencies, identifying measurable impacts. The second part applies fuzzy-set Qualitative Comparative Analysis (fsQCA) to explore how combinations of deficiency influence these deviations. The results demonstrate that certain deficiencies, specifically, deficient estimation of material quantities (C₆), lack of experience of the planner (C₁₀), omission or deficiency in the definition of work packages (C₁₃), and omission of road markings in planning (C₁₆), emerge as necessary conditions with high consistency scores for producing cost overruns and delays. This dual-level analysis contributes to the academic literature by offering empirical evidence that links specific deficiencies to quantifiable project outcomes. It advances theoretical understanding by identifying critical configurations of planning shortcomings that systematically affect performance. Furthermore, the study offers a predictive framework for anticipating how deficiencies in schedule planning contribute to negative outcomes, thus bridging the gap between theoretical planning models and the realities of project execution.

The practical applications of the theoretical contributions of this study offer significant improvements in scheduling planning for road projects. Professionals can gain a clear understanding of critical processes that require attention to minimize delays and cost overruns in road intersection projects. By identifying and associating planning processes with specific deficiency causes, project managers can implement targeted mitigation strategies to enhance schedule execution and improve the accuracy of time and cost estimates. This evidence-based practical approach facilitates decision-making that is aligned with PMBOK standards, which is crucial for the success of road infrastructure projects in complex and dynamic contexts. Analyzing the consequences of deficiency causes in 25 road intersection projects identified in public contracts holds practical value for road construction industry professionals. By thoroughly examining the minutes and technical documents generated during the execution of these projects, the study provides a precise and well-founded understanding of how and why delays and cost overruns occur. This document review allows for identifying recurring patterns and specific factors contributing to deficiencies in the planning and execution of road projects. Consequently, project managers can use this knowledge to anticipate and mitigate similar problems in future projects. Furthermore, documenting these real cases offers a reference framework for justifying decisions and implementing continuous improvements in scheduling planning and management processes. This comprehensive analysis enhances current practices and contributes to developing more robust and effective strategies for future road intersection projects, ultimately leading to more successful project outcomes.

The limitations identified in this study present opportunities for future research in road project scheduling planning. First, the identified processes focus solely on the planning stage, and the design, monitoring, and control phases of road intersection project planning must be analyzed. Developing a detailed framework for these stages could provide professionals with standardized methodologies to improve project execution and minimize undesired delays and cost overruns. Second, the current study focuses only on

road intersection projects, so expanding the identification of scheduling processes to other types of projects could reveal variations in process flow and their applications. Third, the consequences of delays and cost overruns due to deficiency causes were identified from a limited sample of 25 projects. Increasing the sample size could provide additional information to strengthen the discussion on safety, sustainability, and economic growth. Lastly, this study is limited to analyzing processes, data inputs, and consequences stemming from deficiency causes. Still, improvements need to be proposed to mitigate these deficiencies in the planning of road intersection projects.

Future research could focus on developing and evaluating alternative methodological frameworks for schedule planning that address and reduce the causes of deficiencies leading to delays and cost overruns in road intersection projects. These frameworks could incorporate collaborative planning strategies and digital tools such as BIM, aiming to improve the definition of work packages, the estimation of resources, and the sequencing of construction activities. The potential application of approaches such as the Last Planner System may contribute to enhancing the reliability of scheduling commitments and coordination among stakeholders. Furthermore, future studies may explore the design of training programs to strengthen the technical competencies of planning professionals, particularly during the early stages of schedule development.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/app15094614/s1>. Search input data in SECOP I and SECOP II.

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

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

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

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Abbreviations

AI	Artificial Intelligence
BIM	Building Information Modeling
CD	Cost Deviation
CPM	Critical Path Method
CS	Consistency
fsQCA	Fuzzy-set Qualitative Comparative Analysis
KPI	Key Performance Indicator
PC	Planned Cost
PMBOK	Project Management Body of Knowledge
PS	Planned Schedule
QCA	Qualitative Comparative Analysis
SD	Schedule Deviation
SECOP I	Colombian Public Procurement Platform (version I)
SECOP II	Colombian Public Procurement Platform (version II)
TMP	Traffic Management Plan
WBS	Work Breakdown Structure

Appendix A. Technical Information About Road Projects Analyzed

#	ID	Year	Website SECOP	Type	Entity	Planned Cost (COP)	Planned Cost USD	Real Cost (COP)	Cost Variation	Planned Duration (Months)	Real Duration (Months)	Time Variation
1	LP-DO-067-2015	2015	I	Public bidding	INVIAS	30,933,112,654.00	12,208,238.51	39,933,112,654.00	29.1%	31	46	48.4%
2	LP-DO-SRN-038-2016	2016	I	Public bidding	INVIAS	9,075,396,655.00	2,937,354.28	14,211,314,737.00	56.6%	18	35	94.4%
3	LP-SGT-SRN-020-2013	2013	I	Public bidding	INVIAS	1,734,744,480.00	909,309.60	1,668,882,757.00	−3.8%	5	5.53	10.6%
4	2021-001	2021	I	Public bidding	INVIAS	20,368,828,636.00	5,482,447.79	29,997,366,624.00	47.3%	6	20.4	240.0%
5	LP-SV-01450-2021	2020	II	Public bidding	NdeS Government	8,370,000,000.00	2,250,713.94	10,946,725,153.00	30.8%	10	19.8	98.0%
6	2609-2012	2012	I	Direct Adjudication	Jardin Municipality / Antioquia	758,900,000.00	413,840.11	1,670,036,551.00	120.1%	11	77	600.0%
7	LP-DT-CAQ-018-2016	2016	I	Public bidding	INVIAS	7,028,052,185.00	2,274,708.20	7,028,052,185.00	0.0%	20	25.2	26.0%
8	LP-DT-SPA-078-2014	2014	I	Public bidding	INVIAS	967,619,398.00	509,101.88	1,451,429,097.00	50.0%	4	16.7	317.5%
9	SA-MC-DT-ANT-007-2017	2017	I	Minor Cost Selection	INVIAS	726,649,729.00	248,767.45	726,649,729.00	0.0%	2	3	50.0%
10	OB-120-2023	2023	I	Special Contract	Antioquia Government	4,155,658,089.20	937,206.53	4,155,658,089.20	0.0%	7	9.5	35.7%
11	019-2021-IP	2021	I	Special Contract	Chocó Government	4,947,763,837.00	1,331,733.77	5,795,477,344.00	17.1%	4.6	9.9	116.8%
12	LP-DO-075-2015	2015	I	Public bidding	INVIAS	191,855,672,734.00	75,718,853.08	273,435,860,825.00	42.5%	48	107.7	124.4%
13	CDI-089-2021	2021	II	Special Contract	DNP	8,792,315,443.00	2,366,528.35	8,792,315,443.00	0.0%	18	32.7	81.7%
14	DAJ-LP-005-2020	2021	II	Public bidding	Armenia Municipality	906,012,558.00	243,861.18	613,694,375.00	−32.3%	4	18.2	355.0%
15	002-L.P.2021	2021	II	Public bidding	Pasto Municipality	5,682,838,571.00	1,529,585.54	6,244,101,410.00	9.9%	7	11.5	64.3%
16	LP-013-2021	2021	II	Public bidding	Manizales Municipality	25,324,780,604.00	6,816,385.47	40,765,706,827.00	61.0%	24	36.5	52.1%
17	LP-019-2021	2021	II	Public bidding	Zipaquirá Municipality	3,371,434,797.00	907,451.07	3,489,501,704.00	3.5%	6	17.2	186.7%
18	LP-007-2022	2022	II	Public bidding	Manizales Municipality	1,412,177,608.00	373,936.22	1,411,532,841.00	0.0%	5	2.8	−44.0%
19	LP-013-2022	2022	II	Public bidding	Vilavicencio Municipality	2,639,145,442.00	698,829.99	3,775,562,959.00	43.1%	6	10.5	75.0%
20	IA-001-2023	2023	II	Special Contract	Soacha Municipality	12,379,038,691.00	2,791,787.87	12,478,870,093.00	0.8%	23	23	0.0%
21	DAJ-SAMC-008-2024	2024	II	Minor Cost Selection	Armenia Municipality	470,094,127.00	121,757.02	488,457,749.15	3.9%	1.5	1.5	0.0%
22	20001188 H4 DE 2020	2020	II	Public bidding	AEROCIVIL	60,425,858,014.00	16,248,664.37	60,425,858,014.00	0.0%	16	24	50.0%
23	IDU-LP-SGI-017-2022	2022	II	Public bidding	IDU	477,834,784,322.00	126,527,804.52	493,099,593,582.00	3.2%	36	36	0.0%
24	IDU-LP-SGI-038-2021	2021	II	Public bidding	IDU	181,740,991,864.00	48,917,172.29	181,740,991,864.00	0.0%	41	41	0.0%
25	IDU-LP-SGI-012-2018	2018	II	Public bidding	IDU	79,198,370,092.00	27,410,729.89	86,236,640,112.00	8.9%	21	32.4	54.3%

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