DISSERTATION

QUALITY CONTROL OF FRONT-END PLANNING FOR ELECTRIC POWER CONSTRUCTION: A COLLABORATIVE PROCESS-BASED APPROACH USING SYSTEMS ENGINEERING

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ABSTRACT

QUALITY CONTROL OF FRONT-END PLANNING FOR ELECTRIC POWER CONSTRUCTION: A COLLABORATIVE PROCESS-BASED APPROACH USING SYSTEMS ENGINEERING

Controlling construction costs in the electric power industry will become more important as the nation responds to new energy demands due to the transition from gasoline to electric vehicles and to emerging trends such as artificial intelligence and use of cryptocurrency. However, managing electric utility construction project costs requires that the risk of field change orders (FCOs) during construction be controlled. In the electric power industry, utility companies face increasing risk from FCOs, due to conversion from overhead to underground systems required by security and climate change factors, and subgrade work is more challenging and less predictable than the more visible overhead work. Change orders cause cost overruns and schedule slippages and can occur for reasons such as changes in scope of work, unforeseen jobsite conditions, modifications of plans to meet existing field conditions, and correction of work required by field inspectors to meet safety standards.

The best opportunity to control FCOs comes during front-end planning (FEP) when conditions leading to them can be identified and mitigated. This study utilized systems engineering methodologies to address risk of FCOs in three phases: (1) defining the root causes and identifying severities of FCOs, (2) evaluating stakeholder responsibilities to find and mitigate root causes of FCOs, and (3) developing a process to identify and find solutions for the risk of FCOs.

The first phase involved using a descriptive statistical analysis of the project database of an electric utility company to identify and analyze the magnitude, frequency, and causes of FCOs in overhead and underground electrical construction. The results showed that FCOs with added scopes occurred more frequently in underground projects than in overhead projects. The analysis also indicated that most causes of FCOs could be managed during the FEP process, and it laid a foundation for the next phase, to promote collaboration among stakeholders to allocate responsibility to identify and mitigate risk of FCOs.

In the second phase, the study used Analytical Hierarchy Process methodologies to distribute weights of stakeholder votes to create an integrated metric of front-end planning team confidence that a desired level of quality had been achieved. This study was significant in that it showed how effectiveness of collaborative working relationships across teams during front-end planning could be improved to create a quality control metric to capture risk of FCOs.

In the third phase, the study used results from the first two phases and additional tools based on Swimlane diagrams and logical relationships between tasks and stakeholders to formulate a quality control roadmap model. This model is significant because it creates a roadmap to enhance the effectiveness of interdisciplinary teamwork through a critical path of the FEP process. The roadmap model shows a streamlined process for decision-making in each phase of front-end planning to minimize risk of FCOs through a logical path prior to final design.

While there have been efforts to improve the design process, this study is the first one known to the researcher to address quality control of FEP using a roadmap process for quality control in electric power construction projects. The primary contribution is to enrich the body of knowledge about quality control of FEP by creating a roadmap model based on systems engineering and enhancing the effectiveness of collaborative working relationships in a logical process that captures risk of FCOs early in the FEP process.

Besides the contribution of a method to reduce the risk of FCOs, the study points to another important concern to the construction industry about safety on the jobsite. The contractor normally requires a time extension to complete the work due to an FCO, but to reduce the impact to the project schedule, overtime is normally provided to the construction workers to perform the task. Additional research on this issue is required, but it is apparent that due to the fatigue of long working hours, this overtime may impact the task performance as well as the physical and psychological well-being of the construction workers, and they may lose safety awareness and have higher risk of accidents on the construction site. Thus, reducing the risk of FCOs will lead to less overtime and is an effective way for the construction project team to reduce the risk of construction accidents.

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DEDICATION

I dedicate this to my parents (Tam Lich Nguyen), my children (Jane Nguyen, Sean Nguyen, and Christine Nguyen), and my extended family.

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CHAPTER 1

Introduction

1.1 Background

The electric power industry provides most of the energy used in global commerce (U.S. Department of Energy, 2015), and controlling its capital costs of construction to mitigate rising energy charges is important for households and businesses. These costs consist of original contract amounts and any additions caused by field change orders (FCOs) during the construction process. Controlling total capital costs and energy charges requires effective front-end planning (FEP) to capture the risk of FCOs in the early phase of the project life cycle.

Cost overruns occur in other industries, but the problem stands out in the electric power utility industry (Gharaibeh, 2013) due to the technical complexity of unidentified items or scopes in original contracts caused by issues like existing field conditions, lack of jobsite visits, or poor collaboration between stakeholders during design and planning (Serag et al., 2010, Gharaibeh, 2013, Shrestha, 2018, Alshdiefat et al.,2018, Khalifa et al., 2019, and Senouci et al., 2019). To mitigate these problems, the electric power utilities must understand these risks, provide an effective FEP process, and take other measures and corrective actions to avoid change orders.

This study addresses risks of FCOs through analysis of their causes and development of quality control methods. The methods will be applicable to electric utility construction in overhead and underground systems. The primary focus is on underground systems, which involve more complexity due to the need to bury system components to avoid risk of wildfires and increase security. The overall study has been conducted in three phases. The first phase addresses overhead and underground cases with an analysis of FCOs with respect to their magnitude, frequency, risk factors and causes, as well as how they are affected by planning and design processes in FEP.

Subsequent phases involve only underground systems because of concerns over migration from overhead to underground systems due to security and climate change factors.

1.2 Need for Research

For a higher confidence level about cost and schedule control of any project, it is necessary to identify all the scopes executed and the potential changes at an early phase of the planning and design processes. Academic and industry studies have been conducted of construction change order issues to identify reasons and consequences for diverse types of construction. For example, Mehany et al. (2014) found that road and highway construction projects have unanticipated conditions and changes that cause claims and cost overruns due to diverse causes. The electric utility field is also facing construction change orders issues due to the nature of the construction work, which has many detailed technical scopes and rigorous safety standards. A study by Gharaibeh (2013, p.1) stated that "the problem of cost overrun occurred in several industries; however, among the industries that gain considerable attention during the past few years is the power utility industry." Therefore, in addition to looking at the reasons and consequences of the change orders, it is necessary to focus on preventing and recognizing the potential change orders at an early phase of the project life cycle.

Besides the importance of the study on how electric utility companies can control the risk of FCOs to control project costs, the benefits of this research may extend to another important concern for the construction industry and academia, the safety of the job site. More study is needed of this issue, but overtime work is usually granted to the construction team to avoid delays in the overall project schedule due to the FCOs. In particular, construction workers might experience fatigue from long working hours, impacting their task performance and physical and psychological well-being. The reduction of risk of FCOs could also improve safety at job sites.

1.3 Problem Statement and Research Objectives

Existing low voltage distribution circuits need upgrading to higher load capacity to ease the high demand of the electric usage in many regions, and the cost effectiveness of making changes is a high priority to most utility companies. The nature of upgrades and the expansion of scope of old electrical substations are complicated. The project life cycle must involve a comprehensive management process that includes planning and engineering design, close work with local and public regulators to get permits to construct, active communication between all stakeholders, construction bidding strategy, procurement, and project execution with testing procedures and final project completion.

Studies have focused on cost impacts of construction change orders to the total project cost, but there is a lack of peer-reviewed literature about construction change orders for electric utility projects. The research addresses this gap by conducting a study on the severity of electrical field change orders and development of a quality control roadmap of the FEP process to recognize the potential risk of FCOs in the early phase of the project life cycle. The findings will prove the following hypothesis:

The construction field change order is the "symptom" and not a "norm", and its impacts are significantly reduced by well-prepared initial planning and design processes.

The roadmap should help the electric utility company owner to plan and manage their project costs more effectively. To develop it, the research objectives are:

1. Quantify and analyze the magnitude and frequency of construction FCOs in electrical construction projects.
2. Analyze the risk factors and the causes of FCOs in electrical construction projects.

3. Analyze the interrelationships between the causes of change orders and the phases of the planning and design processes.
4. Develop explanations for how the FEP process mapping model can help to recognize and identify the potential change orders that may happen in the field.
5. Develop a proposed underground quality control FEP roadmap model to provide the possible preventive solutions to the risk of FCOs.
6. Provide recommendations for how utility companies can improve their FEP.

The objectives were pursued in three phases. The first study (Nguyen et al., 2023) focuses on addressing objectives 1 and 2 by using a descriptive statistical analysis of the project database of an electric utility company. It quantifies and analyzes the magnitude, frequency, and causes of FCOs of both overhead and underground electrical construction projects. The result lays the foundation for the next phase to promote collaboration among stakeholders. The results of this study were published in the Electricity Journal/Elsevier (Nguyen et al., 2023).

The second study focuses on objectives 3 and 4. Using the Analytical Hierarchy Process (AHP) methodologies, the weights of stakeholder votes were distributed based on responsibilities for each category of FCOs to obtain an integrated metric of FEP team confidence. The important features of the study are to enhance the effectiveness of collaborative working relationships across teams during the FEP process and to provide a quality control metric to capture risk of FCOs during the initial phase of the project life cycle. The results of the second study were reported in a paper that is currently under review by the Electricity Journal/Elsevier (Nguyen et al., 2024).

The third study focuses on research objective 5, using the results from studies 1 and 2. It maps the tasks to the stakeholder’s responsibilities and establishes a logical relationship between the tasks and stakeholders to develop a proposed quality control roadmap of the FEP process. The significance of the roadmap model is to enhance the effectiveness of interdisciplinary teamwork through a critical path of the FEP process. This last study will be submitted to a journal in summer 2024.

1.4 Main assumptions/boundaries

1. In Chapter 2, when records showed multiple causes with the lump sum of the FCO costs, the assumption was made that costs can be distributed evenly in this study.
2. The study identified nine root causes of FCOs in Chapter 3. However, to simplify the analysis and concentrate on the riskiest ones based on their frequency and cost magnitude, the top five causes were distributed to the stakeholder's responsibility. The top five of FCOs represent 85% of the frequency and 90% of the cost magnitude of the original nine causes.
3. The project management team will own the Proposed Quality Control Process for Front-End Planning as discussed in Chapter 3, and the Proposed Quality Control Roadmap for Front-End Planning Process as discussed in Chapter 4.

1.5 Limitations

1. The dataset of this study was based on the projects completed in 2016-2020 from one utility company. The study indicated the importance of the collaborative working relationship between the stakeholders during the FEP process. The lasting effects of the Covid-19 pandemic, which led industry practitioners to implement a remote or hybrid working model for FEP, may impact the effectiveness of communication and collaborative working relationships among stakeholders in the future. Future research should examine the severity of the frequency and magnitude of FCOs for projects from different utility companies

where FEP occurred during the pandemic to ascertain effects on FCOs. The results may indicate additional needed features in the quality control roadmap methods.

2. This study used expert opinion by one person with over 20 years of experience in the construction industry with frequent participation with stakeholders in construction and power utility companies to do the judgement on the AHP. In practice, the power industry practitioners should gather the input from project team members and team leader from each discipline with sufficient experience to judge the distribution of the relative degree of each stakeholder's responsibility for the causes of FCOs as well as the ranking of each stakeholder in the FEP process.
3. The unknown condition is defined in this study as concealed or unknown physical conditions at the jobsite or bad weather that prevents work at the jobsite. The electric utility companies should record the different type of unknown conditions in the project database such as bored piping variations, old and unrecorded infrastructure, which are not in the existing drawings of record. Such an unknown/unexpected field condition database will help the project team be aware of the possible risk scenarios during the FEP process to minimize the risk of this FCO category.

1.6 Benefits and Research Target Audience

The conducted research provides benefits in three areas.

i) Identifies and quantifies the magnitude and severity of FCOs for electric utility construction.

ii) Demonstrates how to achieve better teamwork and communication among FEP stakeholders to work cooperatively to reduce FCO risks.

iii) Assembles these advances into a proposed quality control roadmap for the FEP process to reduce FCOs during the construction phase.

The findings should benefit electric utility company owners, planners and designers, cost program managers, cost engineers, and investors. These participants in the electric power industry can test the roadmap model with their data and make appropriate changes to fit their situations. The model should help to control costs for consumers, and it can pave the way for other researchers to explore process mapping for the planning and design phase to eliminate the change orders for other fields such as, wastewater, highway, airport, and refinery construction. In addition, the research fills a gap in the literature on how to use the process mapping model method in the planning and design phases for the electric utility construction projects. Finally, the three phases have led the researcher to recognize the potential effects of minimizing FCOs on site safety and have indicated an avenue for possible future research.

1.7 Dissertation Organization

The three phases of the work are presented in five chapters. This first chapter presents the background, need for research, problem statement and research objectives, and methodologies. Chapter 2 quantifies and analyzes the causes and types of FCOs to lay down a foundation the next research phase to promote collaboration among stakeholders. Chapter 3 distributes the weights of stakeholder votes based on responsibilities for each category of FCOs to obtain an integrated metric of FEP team confidence that can be utilized in the quality control roadmap. Chapter 4 proposes a quality control FEP roadmap model to enhance the effectiveness of interdisciplinary teamwork through a critical path of FEP process to reduce the risk of FCOs; and Chapter 5 summarizes the major research findings, solutions and discussions, limitations, and provides recommendations for electric power companies and other construction industry sectors, and future research.

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CHAPTER 2

Electric Utility Construction: Causes and Types of Field Change Orders

2.1 Summary

The electric power industry provides most of the energy for global commerce, and controlling its construction costs is important to provide affordable energy. Controlling original contract costs and any added costs due to change orders requires effective planning and design of projects. While cost overruns due to change orders occur in other industries, the electric power utility industry faces technical complexity, poor understanding of field conditions, lack of jobsite visits, and poor collaboration among stakeholders during design and planning. Although published data exist for costs of change orders in other industries, almost none are available for the electric power sector. To mitigate these problems, project managers must understand these risks, provide better cost forecasts, and take other measures to avoid change orders. Using a descriptive statistical analysis of the project database of an electric utility company, this study addresses the data gap by analyzing the magnitude, frequency, and causes of field change orders of both overhead and underground electrical construction. The results identified nine causes of field change orders (FCOs) during construction. The percentage increases in the electrical construction contract costs appear to be higher than in other industries, which is an alarming finding considering the tendency to bury transmission lines due to fire hazards. The result showed that FCOs with added scopes occurred more frequently in underground projects than in overhead projects. The analysis indicated that most causes of field change orders could be managed during planning and design and through the construction phase. The findings of this study can be used by electric utilities when they convert from overhead to underground systems due to security and climate change factors.

2.2 Introduction

Electric utilities own and operate overhead and underground infrastructure systems. The underground systems are more complex due to the need to bury system components, often in response to threats from natural disasters and fires. Clearly, controlling the construction costs of both types of systems is important to assure the financial viability of utilities and the energy costs to consumers. The costs of the systems include those in the construction contracts and any added costs due to field change orders (FCOs). The FCOs are any additions, deletions, or revisions in scopes of original construction contracts that increase charges by cost overruns, schedule slippages, and other negative effects on project performance (Hanna et al., 2007).

This study draws on the project database of an operating electric utility company to report on an analysis of the magnitude, frequency, risk factors, and causes of FCOs, as well as their dependence on the effectiveness of the planning and design processes in preventing them. The analysis is intended to lay the foundation for a future study on how planning and design processes can be improved to reduce FCOs and control the overall capital cost of construction.

The paper reports on an initial study in a research program aimed at the use of systems engineering to create a quality control program for electric power utility companies. The study began with a literature review of background knowledge about construction FCOs to include their definitions, causations, and impacts, especially for electric power construction. The project database of the electric utility company provided information that was used to assess the magnitude, frequency, risk factors, and root causes of the FCOs that it has experienced. Results were analyzed and presented by a descriptive statistical display to highlight the dimensions of the problem and the principal driving forces. The analysis and statistical display enabled the identification of key factors to reduce FCOs that will be analyzed subsequently to improve planning and design processes.

The findings reported here can help project electrical utility owners and managers understand the main reasons for the occurrence of FCOs during construction and detect potential problems during the initial phases of the project lifecycle. Once these reasons are understood, project owners and managers will be better positioned to minimize them during the construction phase. The findings also contribute to the body of knowledge about cost concerns when electric utilities convert from overhead to underground systems due to security and climate change impacts, such as cold and snow events, wildfires, and intense rainfall and storms (Alonso and Greenwell, 2013; Csanyi, 2017; Public Works, Disaster and Fire Safety and Transportation Commissions, 2018; and Mcarthur, 2022). Such events can cause significant damage, resulting in expensive repair and replacement costs. The U.S. Global Change Research Program (2018) and the U.S. Environmental Protection Agency (2022) have reported that energy disruptions from them harm the economy and require billions of dollars to repair the damaged electricity generation, transmission, and distribution systems. These issues indicate the likelihood that relocating overhead systems to underground systems will increase in frequency (NEI Electric Power Engineering, 2008).

2.3 Background

2.3.1 Definitions of change orders

Definitions of change orders are found in publications of academic and construction professional organizations. For instance, Shrestha et al. (2018, p. 2) defined change orders as “any changes that occur in construction projects after the detailed designs of the projects are completed and accepted by the owners.” These changes create events where the owner and the contractor agree to add, delete, or reduce the scope of work, change the design, revise the project schedule, adjust the project price, or modify any provision of the original construction contract agreement.

In 2007, the Associated General Contractors of America (AGC, p. 3) and the National Association of State Facilities Administrators (NADFA) defined a change order as “a written order signed by the Owner and the Contractor after execution of this Agreement, indicating changes in the Scope of the Work, the Guaranteed Maximum Price (GMP) and Date of Substantial Completion and/or Date of Final Completion, including substitutions proposed by the Contractor and accepted by the Owner.” The American Institute of Architects (AIA 2007, p. 20) also defined a change order as “a written instrument prepared by the Architect and signed by the Owner, Contractor, and Architect stating their agreement upon all the following.

- The change in the scope of work;
- The amount of the adjustment, if any, in the Contract Sum; and
- The extent of the adjustment, if any, in the Contract Duration/Time.”

Based on these definitions, change orders are defined here as the addition and/or deletion of scopes, accommodation of field conditions, design error, omission from bidding, time extension, and unknown site condition, among others.

2.3.2 Impacts of change orders

How change orders affect construction depends on the contract type (Gunhan et al., 2007). Studies show that change orders can cause cost overruns, schedule slippages, or both, impacting project performance and labor productivity. They also can cause frustration and conflict among stakeholders as the project team identifies responsibilities for their root causes. The frustrations and disputes caused by change orders were also noted by Taylor et al. (2012, p. 1360), who wrote that “change can make life frustrating for project stakeholders, and many projects experience significant performance degradation because of change.” They suggested that the well-documented negative impacts of change orders on project performance incentivize owners to avoid change orders. In 2018, Collins et al. published similar results in a qualitative study of electrical-related change orders of university projects. They found that “change orders are rarely seen in a positive light; considered a necessary evil at best..., as well as the heightened possibility of litigation between project stakeholders” (Collins et al., 2018, p. 649).

The literature on the impacts of change orders indicates that projects with them are usually prone to delays, cost increases, and reduced labor productivity. Owners feel the impacts, as well as contractors. Increased costs require more significant budget contingencies, delayed projects necessitate rescheduling, and conflicts between the parties add to costly disputes.

2.3.3 Causes of Change Orders

Finding the root causes of FCOs can help industry practitioners consider risk factors during the design and planning phases and thus help to control construction costs. Many factors may cause a change order, such as design errors, design changes, additions to the scope, or unknown conditions in the field that entitle contractors to equitable adjustments to base contract prices and schedules (Hanna et al., 2007). Using data from Kentucky highway projects, Taylor et al. (2012) found causes that include contract omissions, owner-induced enhancements, and contract item overruns. Their research contributes to the body of knowledge that the high-risk change orders on roadway construction can be avoided through improved front-end planning. Their study shows not only distinctive trends that were useful for constructability reviews on future projects, but also indicates the need for new directions in front-end planning and project scoping to minimize change orders on highway projects.

In a study of the Jordanian private construction industry, Alshdiefat et al. (2018) listed the causes of change orders in building projects as engineering causes, causes related to the client, and causes due to the circumstances of the project. The engineering causes include design errors, incomplete designs, estimation errors, and inconsistency between contract documents. The causes related to the client include the changes initiated by the client, lack of communication between project parties, and time lags between the design and construction phases. The causes related to the project's circumstances include the different site conditions and shortages of materials.

In a study of construction projects in Saudi Arabia, Khalifa et al. (2019) found that the most frequent causes of change orders from the contractors' view are: the owner's additional works; errors and omissions in design; lack of coordination between construction parties; defective workmanship; and owner's financial difficulties. They found that consultants' views showed the same causes, but with additional attention to differing site conditions. In a study of charter school construction, Senouci et al. (2019) found that the leading causes for change orders were owner-directed changes, unforeseen conditions, design errors/omissions, code requirements, and value engineering.

In 2020, Herrera et al. analyzed frequency and importance of cost overrun causative factors in road infrastructure projects. The authors reported that the ten most important and frequent cost overrun factors were: (1) failures in design, (2) price variation of materials, (3) inadequate project planning, (4) project scope changes, (5) design changes, (6) unrealistic contract duration, (7) inadequate bidding method, (8) legal issues, (9) late decision making by the owner, and (10) political situation. The results show a strong influence of design and planning aspects on the occurrence of cost overruns in road projects, and the authors concluded that the cost overrun phenomenon could be widely mitigated through modifications and greater controls to traditional processes developed in the project’s early stages.

In a study of the key causes and impacts of variation orders in Iraqi construction projects, Ismaeel et al. (2021) reported that the size of variation orders in Iraqi construction projects was high, and found 13 key causative factors led to variation orders are (1) late a contractor in execution, (2) errors and omissions in the design, (3) the consultant's lack of judgment and experience, (4) different site conditions, (5) incomplete design at bidding time, (6) owner financial problems, (7) the consultant lacks historical data for the project, (8) the financial difficulties of the contractor, (9) the contractor's desire to improve his financial condition, (10) lack of skills, (11) change in work quantities, (12) lack of design documentation, (13) not to use a consultant for advanced engineering design programs. The authors concluded that minimizing the variation orders is very important to reduce the cost impacts in the construction projects, and the authority management and project managers must make a plan to address these key causes in future projects to ensure their success. In a more recent study by Amini et al. (2023), the authors reported that poor site management, improper planning, fluctuation of prices of materials, lack of experience, and poor economic conditions are the critical reasons for cost overruns in Iranian construction projects. The findings also indicated that among the studies conducted in Asian countries, the first three factors have the highest frequency. The authors recommend that the project management section should be especially considered and modified for effective and efficient cost control of construction projects. Also, the planning in different stages, material management, resource planning and management, and proper financial management should be emphasized. In addition, all stakeholders should work together to achieve successful projects within the stipulated budget and exceed the anticipated quality standard.

In the study of evaluating the causes and impacts of change orders on the construction projects performance in Oman, Maamari et al. (2021) found that the variations have more impacts on the project and the change orders harm the project most. The research result was revealed that 'Change in specifications', 'Alterations in design and drawing' and 'Time lag in the project implementation' were considered to be the primary causes of change orders. Additionally, the research result was also revealed that 'Change of scope', 'Errors and omissions in design' and 'Insufficient Logistics' were the primary causes of variations affecting the construction projects in Oman. Apparently, an adequate front end planning could help to capture the risks to minimize the impacts of change orders as the authors indicated in their research.

In 2021, Setiawan et al. studied on the risk evaluation causes of contract change order to improve cost performance on railway construction project in Indonesia. The authors reported that the risk factors can be seen from three aspects that consist of technical, legal, and environment aspects. The authors also reported that the high risk variable are as follows: (1) error and omissions in design, (2) inadequate drawings & details, (3) change of scope, (4) accelerated construction, (5) replacement of material, (6) change in specifications, (7) change in design, (8) different site conditions, (9) there is a utility network, (10) land acquisition problems. The authors suggested a risk controlling process is needed to improve the cost performance of railway projects.

Waty et al. (2022) examined the causes for the change orders in road construction in Indonesia: reviewed from the owner. The authors reported that a mismatch between design drawings and field conditions is the main factor causing change orders for the planning and design. The authors suggested that the project team should periodically monitor the pictures and field conditions before implementation. The contractor should pay more attention to the work contract provisions as the executor of the road construction project, and more attention should be paid to the field safety factors.

Tayyab et al. (2023) studied factors influencing cost overrun in high-rise building construction across India. The authors reported that the top ten critical factors influencing cost overruns were frequent change orders during construction by the owner, delay in construction, escalation of material prices, market inflation or deflation, rework, frequent changes in design, inaccurate evaluation of the project timeline, unforeseen ground condition, inaccurate quantity take-off, and delay in progressive payment by the owner. These results were expected to help construction professionals minimize cost overruns, improve cost control measures, and initiate future research.

Drawing from previous studies, Table 2.1 shows a classification of the causes of change orders for electrical overhead and underground projects that were experienced in the electric utility company that was studied. Each cause is assigned a number that correlates with its description. The table provides a framework to organize the findings from the literature review about these types of FCOs. Other electric utilities may experience different types of FCOs.

Table 2.1 The cause and description of field change orders (FCOs) for electrical projects

FCOs Reason No.	**Cause and description**	**Previous studies from the literature**
1	**Cause** - Business Operating Hours. **Description** - Contractors must perform nighttime work to avoid daytime traffic congestion and operations of public offices, businesses, or schools during business hours.	No studies were located.
2	**Cause** - Accommodate Existing Field Condition. **Description** - Construction crews find damaged electrical materials, faulty electrical equipment or unsafe site condition requiring attention before continuing with the original work.	Gunhan et al. (2007), Serag et al. (2010), Alaryan et al. (2014), Shrestha (2016), Alshdiefat et al. (2018), Khalifa et al. (2019), Ismaeel et al. (2021), Setiawan et al. (2021), Waty et al. (2022), Amini et al. (2023), Tayyab et al. (2023).
3	**Cause** - Correction of Work Due to Design Error. **Description** - Construction crews find mistakes in design, requiring the working scope to be corrected before continuing with work.	Gunhan et al. (2007), Hanna et al. (2007), Alaryan et al. (2014), Alshdiefat et al. (2018), Shrestha (2018), Khalifa et al. (2019), Senouci et al. (2019), Herrera et al. (2020), Ismaeel et al. (2021), Maamari et al. (2021), Setiawan et al. (2021), Waty et al. (2022), Tayyab et al. (2023).
4	**Cause** - Project Schedule Constraint. **Description** - The utility company must pay additional premium time for the contractor to meet schedule deadline.	Alaryan et al. (2014), Herrera et al. (2020), Maamari et al. (2021), Setiawan et al. (2021), Tayyab et al. (2023).
5	**Cause** - Change of Construction Methodology. **Description** - Need for shoofly construction or for a helicopter to fly materials to the jobsite.	No studies were located .
6	**Cause** - Omission from Bidding. **Description** - Scopes required not included in the original design	Gunhan et al. (2007), Taylor et al. (2012), Alshdiefat et al. (2018), Khalifa et al. (2019), Senouci et al. (2019), Herrera et al. (2020), Ismaeel et al. (2021), Maamari et al. (2021), Setiawan et al. (2021), Waty et al. (2022).
7	**Cause** - Code Compliance/Permit/Testing. **Description** - The utility company must pay for additional work modification, permit, and testing fees during the construction phase.	Gunhan et al. (2007), Alaryan et al. (2014), Senouci et al. (2019), Herrera et al. (2020), Setiawan et al. (2021), Tayyab et al. (2023).
8	**Cause** - Remove Scopes. **Description** - Scopes not needed are eliminated or reduced.	Gunhan et al. (2007), Shrestha et al. (2018). Herrera et al. (2020), Setiawan et al. (2021).
9	**Cause** - Unknown/Unexpected Field Condition. **Description** - Concealed or unknown physical conditions at the jobsite or bad weather that prevents work at the jobsite.	Hanna et al. (2007), Serag et al. (2010), Alaryan et al. (2014), Senouci et al. (2019), Shrestha (2018), Ismaeel et al. (2021), Setiawan et al. (2021); Waty et al. (2022), Amini et al. (2023).

Most of the FCO types are supported by studies found in the literature, with the exception of business operation hours and change of construction methodology. While no studies of these were located in the power utility construction, the typical FCO causes should be studied for possible addition to industry standards. The business operation hour change represents the cause that contractors must perform nighttime work to avoid traffic congestion and making negative impacts on the operations of public offices, businesses, or schools during standard business hours from 8am to 5pm due to power outages. In the change of construction methodology, the contractor must needs to change the normal construction method to the shoofly construction method, or there is a need for a helicopter to fly materials to the jobsite.

2.3.4 Change order models

Serag (2006) used site data on heavy road construction projects to quantify productivity loss due to change orders. Two models were developed to assess the impact of change orders, one to quantify the percent increase in the contract price and the second to quantify the productivity loss of drainage piping work. The author found that the most common cause for a change order was to account for unforeseen conditions and alterations in the plan, which frequently occur because much of the work occurs underground in heavy construction. The author also found that change order issues might be due to poor design caused by lack of a thorough study of the area before preparing the design.

In a later publication using the same data, Serag et al. (2010) used a regression model to quantify the impact of change orders on project cost for roadwork construction. The authors also found that the change order due to unforeseen conditions was one of the most significant variables when the percentage increase in the contract price exceeds 5%. This finding has significance for underground electrical projects that encounter unforeseen conditions due to geotechnical issues.

In a study of the magnitude of construction cost and schedule overruns in public works projects, Shrestha et al. (2013) found that cost and schedule overruns increased as project sizes and complexity increased. Shrestha (2016) found that the causes of change orders and impacts on road maintenance contracts were due to changes in work scope, errors in the estimate, and failure to verify work site conditions before signing a contract. The solutions suggested were to review specifications, prepare exact estimates, and review design drawings before bidding. In addition, the author developed a change order contingency estimation tool and a schedule-crashing tool to predict cost contingency and to reduce the negative impact on schedule-growth. Shrestha and Zeleke (2018) studied change orders in school building renovation projects and found that unforeseen conditions and design-related change orders had a significant effect on the cost, greater than that of owner-initiated change orders. The authors suggested investigating existing conditions to design projects with fewer change orders and effects on costs and schedules.

Chen (2015) developed a model to predict the number of change orders for building, infrastructure, heavy industry, and manufacturing projects. While the model allows users to explore different input values and their effects, change order issues should be detected and addressed early in projects and the potential risk should be identified and reduced through more effective planning and design.

2.3.5 Change Orders in Electrical Utility Projects

Only a few studies of cost overruns in power transmission and infrastructure projects have been published. For instance, in a study of power transmission projects, Gharaibeh (2013) identified internal and external factors that created complexity. These include government involvement, project execution strategy, corporate rate culture, organizational processes, corporate information systems and tools, and human behavior. The author suggested that project teams improve individual, group, and organizational learning skills. Sovacool et al. (2014) also studied construction cost overruns for electricity infrastructure and made an international comparison. They found that the construction of electricity infrastructure has a substantial risk of cost overruns and suggested that investors, electric utilities, public officials, and energy analysts should reevaluate the methodologies they use to predict construction timetables and calculate budgets. In another study of electric power projects, Kim et al. (2018) assessed construction cost overruns in transmission grid projects in Vietnam. They used factor analysis and identified seven key factors: management of human and construction resources; competence of stakeholders; policies of the Government; construction policies; relationships among main contractors, subcontractors, the workforce; cost of materials and equipment; and adverse objective attributes (like natural disasters). The attributes causing the highest cost overruns were the incompetence of the project manager, the incompetence of construction supervision consultants and design consultants, unstable interest rates, and unstable construction policies.

2.3.6 Conclusions from the literature of construction change orders

Despite the studies cited about the causes and effects of change orders, a comprehensive understanding of the root causes of change orders in the electrical utility sector is still lacking because the literature includes no comprehensive studies about them. Modeling studies like those by Serag (2006), Chen (2015), and Shrestha (2016) do not indicate comprehensive approaches to solutions. A more comprehensive study is needed to capture the risk of change orders from the front-end planning and design processes to reduce the impacts of change orders in construction for electrical utility companies and their customers. To fill that need, this study is a first step to analyze the magnitude and frequency of FCOs, examine their causes and risk factors, and make preliminary observations about the roles of planning and design processes in reducing them. It lays the groundwork for further research on enhancing planning and design processes using systems engineering tools like the V-model, stakeholder map, and functional modeling (U.S. Department of Transportation - FHWA, 2007; Walsh, 2023; and UC Berkeley | ITS/PATH, 2023). Tools such as these can help model and evaluate project management functions, promote collaboration among stakeholders, and identify issues and solutions early in the project lifecycle (Kossiakoff et al., 2011).

2.4 Research Methodology

This section presents the framework, methods, and data collection and analysis procedures during this initial study. The steps in the research process are:

1. Extract original unit price contract cost and final payment cost data. The difference is the field change order cost.
2. Classify field change orders by types. The categories are general and not specified as underlying reasons or root causes of the changes.
3. Review narratives of the changes from project records to identify their root causes.
4. Quantify and analyze the magnitude and frequency of overhead and underground construction field change orders during the construction phase.
5. Analyze risk factors related to causes of field change orders in the construction contracts. The causes and their frequency percentages are identified and analyzed respectively in this step.
6. Perform preliminary analysis of interrelationships between causes of change orders and the planning and design processes based on the descriptive statistics and risk analysis. This will serve as a basis for the next phase of the research.
7. Provide results and recommendations.

2.4.1 Data Source and Tools

The data are of instances of change orders from the database of an operational electric power utility. The utility's pseudonym is the ABC Electric Company, which maintains the anonymity of the operating utility. Cost data were extracted from a database using SAP software for overhead and underground projects completed in 2016-2020**,** in which existing old and low voltage distribution circuits needed expanding and upgrading to higher load capacities to meet demands. The data include the project description, location, narrative of the change, number of additions and/or deletions of FCOs, and project initial and final costs. The analysis used the Minitab Statistical Analysis from Minitab Company (Academic Sector Solutions, 2023).

2.4.2 Profile of the Projects in the Analysis

The dataset comprises 301 total projects, with 179 overhead and 122 underground projects. Each type was analyzed separately, but the comparisons and analyses were aligned so industry practitioners could see the differences. In general, the projects in the database have a duration of two years: six months for preliminary engineering design; six months for final engineering design; five months for permitting; two months for bidding and construction; and five months for construction and testing. The overhead and underground project sizes are between \$2.5M to \$5.0M and \$3.0M to \$5.5M, respectively.

A total of 53 (30%) of the overhead construction projects and 18 (15%) of the underground construction projects had zero cost of field change orders. These were retained in the database because projects without change orders should yield helpful information about planning and design methods for later phases of the research. Three overhead projects and one underground project were removed from the dataset because they were considered outliers with percentage changes exceeding 190%. As a result, 176 overhead and 121 underground projects, or a total of 297 projects, were included in the analysis.

2.5 Results and discussion

2.5.1 Magnitude of FCOs

Tables 2.2 and 2.3 show statistics for the construction costs of all overhead and underground projects, including those with zero FCOs (Table 2.2) and all projects except those with zero FCOs (Table 2.3). Percentage change is based on the final minus initial cost divided by the initial cost. The inclusion of projects with zero FCO modifies the mean values, as shown in Table 2.2.

Table 2.2 Percentage change in construction contract costs for all projects

Type	Min	Max	Mean	Median	Standard Deviation
Overhead	-87.3%	163.7%	14.5%	6.1%	27.8%
Underground	-44.6%	165.0%	31.9%	20.2%	37.1%

The dataset includes 176 overhead projects and 121 underground projects.

Table 2.3 Percentage change in construction contract costs with FCOs

Type	Min	Max	Mean	Median	Standard Deviation
Overhead	-87.3%	163.7%	20.8%	17.9%	31.2%
Underground	-44.6%	165.0%	37.4%	27.9%	37.6%

Without the projects with zero cost of FCOs, the dataset includes 123 overhead projects and 103 underground projects.

2.5.1.1 Overhead construction projects

Figure 2.1 shows the distribution of the percentage change in the cost of all overhead projects, including those with zero FCOs. The results show a positive skew with more projects with positive changes than with negative changes. Positive changes indicate added costs due to added scopes or services, while projects with negative changes indicate reduced scopes or services from the original construction contracts. As shown by the added bell curve, if the projects with zero change order cost were removed, the distribution would be closer to normal, but the mean value would be shifted to the right to show a mean of 20.8% for all projects with field change orders as referenced in Table 2.3.

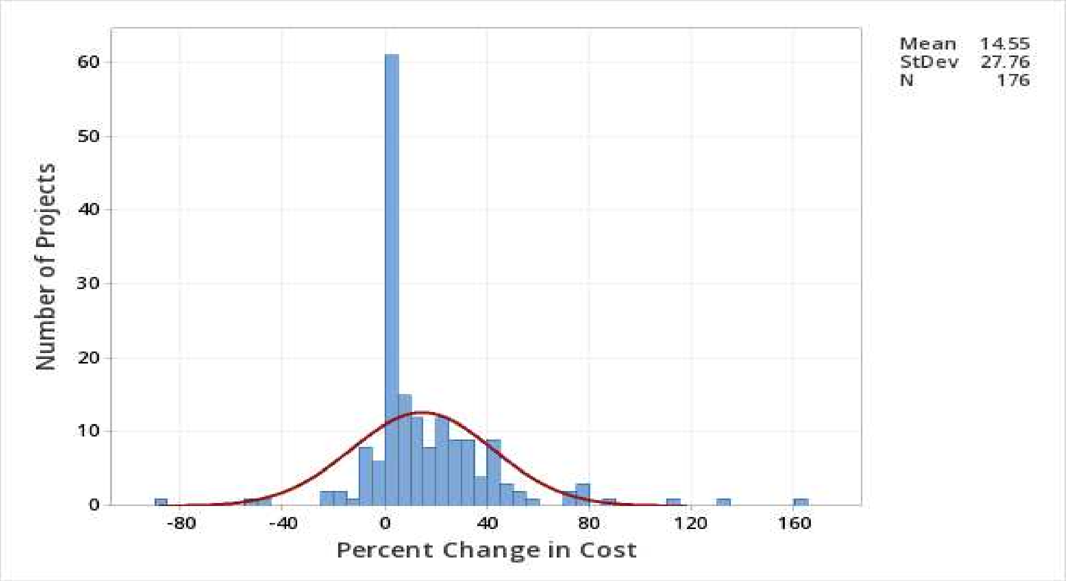

Figure 2.1 Histogram of overhead electrical construction percentage change in cost

2.5.1.2 Underground Electrical Projects

Figure 2.2 shows the distribution of the percentage change in the cost of underground electrical construction projects. The results also have a positive skew with more projects with added costs than reduced costs. As shown by the added bell curve, if the projects with zero change order costs were removed, the normal distribution also does not work. There is still a positive skew, but the mean value would be shifted to the right to show a mean of 37.4% for all projects with field change orders, as referenced in Table 2.3. The scatter shown by the histogram indicates the uncertainties inherent in underground projects (Serag, 2006; Serag et al., 2010; and Sovacool et al., 2014).

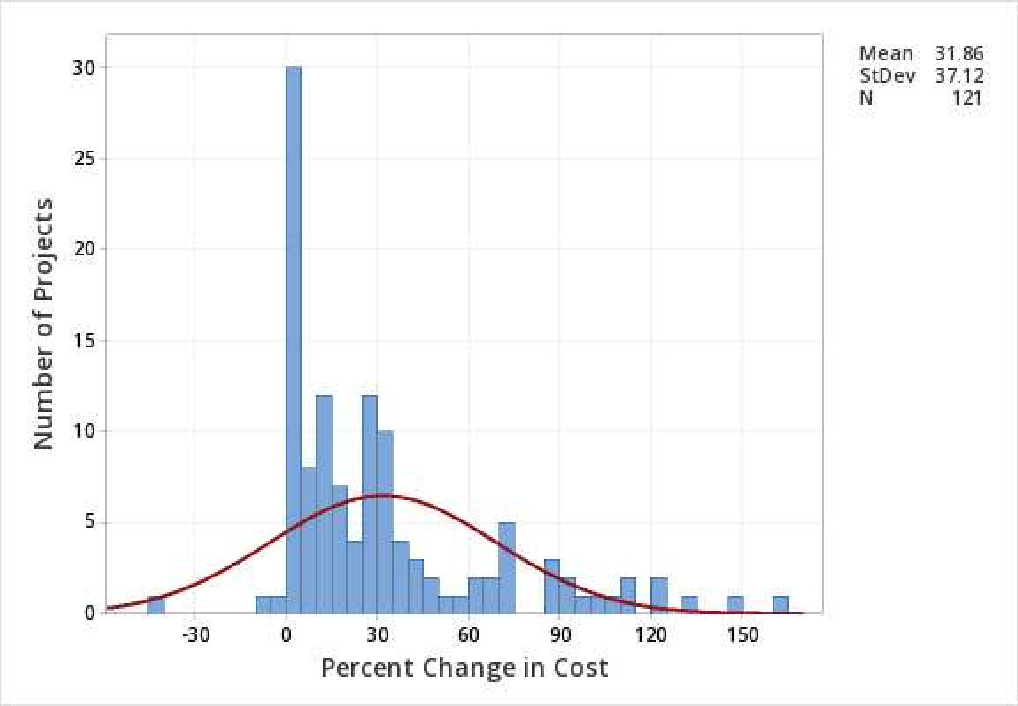

Figure 2.2 Histogram of underground electrical construction percentage change in cost.

2.5.1.3 Discussion of Magnitude of FCOs

Since there is a lack of literature on electric utility project costs, the results cannot be compared with other utilities. Still, the percentage increases in the electrical construction contract costs appear to be higher than in other industries. For example, Chen (2015) found an average construction percentage change of 6.95% for building, infrastructure, heavy industry, and light industry construction projects. Anees et al. (2013) reported average cost overruns due to change orders between 11% and 15% of the original contract value in large building construction. Alaryan et al. (2014) reported change order increases in Kuwait's public and private construction projects as an average of 6% to 10% of the contract value. In one study of university projects, Collins et al. (2018) reported electrical change orders were disproportionately high (11%-16%) as compared to general contracting (5%-10%) or mechanical (5%-8%) construction-related change orders.

The higher percentage (31.9%) of change orders in underground electrical projects compared to overhead electrical projects (14.5%) is apparently caused by their greater challenges due to invisible site conditions and requirements for more field investigations during the planning and design phases (Serag, 2006; Hanna et al., 2007; Serag et al., 2010; Taylor et al., 2012; Shrestha, 2016; and Senouci et al., 2019). Lack of field condition information will lead to inevitable design errors or missing scopes, which result in more field change orders during construction.

The high positive percentage changes in both overhead and underground electrical projects clearly indicate that costs can be reduced if the planning and design processes are improved to reduce the frequency of field change orders (Serag et al., 2010; Taylor et al., 2012; Gharaibeh, 2013; Shrestha et al., 2013; Alshdiefat et al., 2018; and Shrestha, 2018).

2.5.2 Frequency of FCOs

2.5.2.1 Overhead and Underground Electrical Projects

A project can have varying numbers of scope changes, where the work to be done is either increased (added scope) or decreased (deleted scope). Table 2.4 shows descriptive statistics of four scenarios of combinations of field change orders. Table 2.5 shows statistics for added scopes when the number of occurrences increase. Table 2.6 shows similar statistics for deleted scopes. Notes for clarification are shown below the tables.

Table 2.4 Statistics of FCO combinations
for overhead (OH) and underground (UG) electrical construction

Field change order scenario	OH number of projects	OH distribution (%)	UG number of projects	UG distribution (%)
Projects have FCOs with both added and deleted scopes	18	10.2%	12	9.9%
Projects have FCOs with added scopes only	87	49.4%	89	73.6%
Project have FCOs with deleted scopes only	18	10.2%	2	1.7%
Projects have no FCOs	53	30.2%	18	14.8%
Total	**176**	**100.0%**	**121**	**100.0%**

Table 2.5 Summary statistics of the number of field change order occurrences of added scopes for overhead and underground electrical construction

Number of FCO occurrences of added scopes	OH number of projects	OH distribution (%)	UG number of projects	UG distribution (%)
1 to 2	82	46.6%	82	67.8%
3 to 4	13	7.4%	16	13.2%
5 to 6	4	2.3%	2	1.7%
> 6	6	3.4%	1	0.8%
Referenced notes below	18[1]	10.2%	2[3]	1.7%
	53[2]	30.1%	18[4]	14.8%
Total[5]	**176**	**100.0%**	**121**	**100.0%**

Notes: 1. 18 OH projects have deleted scopes only; 2. 53 OH projects have no FCOs; 3. 2 UG projects have deleted scopes only; 4. 18 UG projects have no FCOs; 5. The 18 OH and 12 UG projects with both added and deleted scopes are shown with the data on FCO type, see Table 2.4.

Table 2.6 Summary statistics of the number of field change order occurrences of deleted scopes for overhead and underground electrical construction

Number of FCO occurrences of deleted scopes	OH number of projects	OH distribution (%)	UG number of projects	UG distribution (%)
1	29	16.5%	10	8.3%
2	5	2.8%	4	3.3%
3	1	0.6%	0	0.0%
> 3	1	0.6%	0	0.0%
Referenced notes below	87[1]	49.4%	89[3]	73.6%
	53[2]	30.1%	18[4]	14.8%
Total[5]	**176**	**100.0%**	**121**	**100.0%**

Notes: 1. 87 OH projects that have added scopes FCOs only; 2. 53 OH projects that do not have FCOs; 3. 89 UG projects that have added scopes FCOs only; 4. 18 UG projects that do not have FCOs; 5. The 18 OH and 12 UG projects with both added and deleted scopes are shown with the data on FCO type, see Table 2.4.

2.5.2.2 Discussion of Frequency of FCOs

The data in the tables show that most overhead and underground projects have one to two FCOs with added scopes (Table 2.5). Overhead projects have relatively more FCOs with deleted or zero scope changes, as compared to underground projects (Table 2.6). Most underground projects have added scopes only, which indicates that their increases complexity and costs, as compared to overhead projects (Serag, 2006; Serag et al., 2010; and Sovacool et al., 2014).

While added scopes occur more frequently than deleted scopes for both types of projects, they occur more frequently in underground projects than overhead projects. The indication is that underground work is more challenging than overhead work, and this should alert utility companies to spend more time in the design and planning phase to minimize FCOs during the construction phase (Serag et al., 2010 and Shrestha, 2016).

2.5.3 Risk Factors and Causes of FCOs

Knowledge of risk factors and causes of the FCOs can provide a foundation to improve the planning and design processes. The causes were classified in Table 2.1 in the background section for nine instances of field change orders for both overhead and underground projects.

Table 2.7 shows the frequency percentage of overhead and underground electrical projects due to each change description. Each project can have more than one field change order and each field change order can be due to more than one cause of change. For example, the project can have one or more than one field change, and the FCOs can be due to several causes, such as adding cost payment due to business operating hours, adding scope to accommodate the current field condition, and adding scope for correction of work due to design error.

Table 2.7 Frequency percentage of causes of field change orders for overhead and underground electrical construction

FCOs Reason No.	The change descriptions	OH frequency percentage	UG frequency percentage
1	Business Operating Hours	14.1%	10.0%
2	Accommodate Current Existing Field Condition	24.6%	36.8%
3	Correction of Work Due to Design Error	12.9%	5.0%
4	Project Schedule Constraint	11.3%	24.1%
5	Change of Construction Methodology	5.2%	4.6%
6	Omission from Bidding	10.1%	5.4%
7	Permit/Testing	1.6%	1.9%
8	Remove Scopes	13.3%	3.1%
9	Unknown/Unexpected Field Condition	6.9%	9.1%

As displayed in Table 2.7, the top five change descriptions for overhead projects with the highest frequency percentages are: (1) accommodation of current existing field condition with 24.6%, (2) business operating hours with 14.1%, (3) remove scopes with 13.3%, (4) correction of work due to design error with 12.9%, (5) project schedule constraint with 11.3%, respectively. Similarly, the top five change descriptions for underground projects with the highest frequency percentages are (1) accommodation current existing field condition at 36.8%, (2) project schedule constraint at 24.1%, (3) business operating hours at 10.0%, (4) unknown/unexpected field condition with 9.1%, (5) omission from bidding at 5.4%, respectively.

FCOs, due to business operation hours, frequently happen in both overhead and underground electrical construction, and utility practitioners can plan for night shifts when power cannot be off during the daytime. This cause of change orders can be added to industry standards. Correction of work due to design errors, omission from bidding, and removed scopes of overhead electrical construction also show the importance of initial planning and design. The removed scopes are not necessarily beneficial for the utility because they indicate that the scopes are not properly planned, and they add cost and time to manage the FCOs for the utility and contractor.

The project schedule constraints also present significant concerns because electrical construction is a practical field that requires effective scheduling to avoid delays and paying for premium time to complete the scopes and meet deadlines. The underground electrical work appears to occur frequently FCOs due to project schedule constraints, which indicates that underground work is more complicated than the overhead electrical work, as discussed previously.

2.5.4 Possible Interrelationships Between Change Orders and Planning and Design Processes

The causes of the nine types of change orders (Table 2.1) can be recognized during the initial planning and design processes (Serag et al., 2010; Taylor et al., 2012; Gharaibeh, 2013, Shrestha et al., 2013; Alshdiefat et al., 2018; and Shrestha, 2018). For instance, business operating hours as a cause of a FCO can be recognized in the permitting phase then the city or county informs the utility about areas where power outages impact commercial buildings or public offices. In addition, accommodation to current existing field conditions can be recognized and reduced by an effective front-end process, especially with jobsite visits and investigations for both overhead and underground electrical construction work (Gharaibeh, 2013 and Shrestha, 2016). The correction of work due to the design errors cause is directly related to the planning and design processes. The overhead electrical construction has a higher design error than the underground electrical construction. It can be mainly due to the large number of existing overhead electrical distribution lines and the complex configuration of distribution networks. Project schedule constraints, change of construction methodology, omission from bidding, and permit/testing causes of FCOs can be reduced by an effective project management plan that recognizes them prior to issuing the construction contracts.

Removal of scopes is also directly related to the planning and design processes. Recognizing unknown/unexpected field conditions may be challenging, but an effective front end of planning and design will be the best solution (Serag et al., 2010; Taylor et al., 2012; Gokulkarthi et al., 2015; and Alshdiefat et al., 2018).

Lack of field condition information inevitably leads to design errors or missing scopes, resulting in more field change orders during construction (Hanna et al., 2007; Alshdiefat et al., 2018; Khalifa et al., 2019). Additionally, the high positive percentage changes in both overhead and underground electrical projects raise a serious concern that the planning and design processes should be improved to reduce field change orders. The job walks between the power utility company and the contractor during the planning and design phase are highly recommended to ensure both parties have a mutual agreement and responsibility on both scopes and costs of the planning projects. This agreement can help to avoid field change orders in the construction phase.

2.6 Conclusion

This study supports electric power utilities work in controlling capital construction costs and reducing the impact of cost overruns from field change orders (FCOs). The results show that underground projects have higher risk of FCOs in both magnitude and frequency than overhead projects. This important finding alerts practitioners as conversion from overhead to underground electric systems proceeds due to security and climate change. Underground systems are exceedingly complex, and the scatter shown by Figure 2.2 is evidence of the uncertainties inherent in such projects. Furthermore, the higher percentage change in the costs of underground electrical projects compared to overhead electrical projects is apparently caused by their more significant challenges due to their invisible systems and requirements for more field investigations during planning and design. Since there is a lack of literature on electric utility project costs, the results cannot be compared with other utilities. Still, the percentage increases in the electrical construction contract costs appear to be higher than in other industries.

The study also indicated that both overhead and underground electrical construction have a much higher frequency of positive changes than negative changes. These results should alert the power utility companies to spend more time in the front-end design phase to ensure the scope of work is being designed and tasked accurately to avoid FCOs during the construction phase. The job walks between the project team and the contractor during the planning and design phase are highly recommended to ensure both parties have a mutual agreement and responsibility on both scopes and costs to avoid variations in the execution phase.

Within the classification of nine causes of FCOs found from this study, the top five for overhead projects were accommodation of existing field conditions, business operating hours, removal of scopes, correction of work due to a design error, and project schedule constraint. Similarly, the top five change order descriptions for underground projects were accommodation of existing field conditions, project schedule constraints, business operating hours, unknown/unexpected field conditions, and omission from bidding.

Additionally, underground FCOs, due to the accommodation of existing field conditions, showed the highest percentage among the causes, mainly due to existing damaged electrical materials, faulty electrical equipment, or unsafe site conditions. Therefore, industry practitioners should be aware of this cause and clearly understand conditions below the subgrade during the planning and design stages to mitigate risk for underground distribution systems and/or conversion from overhead to electrical underground systems.

Furthermore, the underground project schedule constraints are a noticeable concern to the project management team. Since electrical construction is a practical field, it requires adequate planning and scheduling of the projects to avoid delays; otherwise, utility companies must pay extra costs for contractors to meet deadlines. The scheduling task is also crucial in planning and designing processes to ensure the projects are completed within budget and schedule.

To reduce the number of construction FCOs for power utility company owners, future research should focus on exploring the link between the causes of FCOs and the planning and design processes. This will identify which project stakeholders are associated with the root causes of FCOs. Systems engineering methods, such as V-model, stakeholder map, and functional modeling, can be used to analyze solutions to FCO issues.

This study provides valuable implications for both professional practice and scholarly research. In professional practice, the study identified and analyzed the root causes of FCOs in terms of magnitude and frequency helping the practitioners be aware of the risks during the planning and design phase to avoid FCOs, especially the comparison between the overhead and underground electricity projects allows the practitioners having a comprehensive vision about the factors causing the cost overruns as well as the concerns about costs when electric utilities convert from overhead to underground systems due to security and climate change factors. This study lays the foundation for the next phase of research on quality control in the front-end planning process, promoting collaboration among stakeholders, and identifies issues and solutions early on in the project lifecycle.

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CHAPTER 3

A Proposed Quality Control Process for Front-End Planning to Minimize Risk of Field Change Orders in Underground Electrical Construction

3.1 Summary

Controlling capital costs and cost overruns due to construction field change orders (FCOs) is essential for the electric power industry to provide affordable energy services. Conversion from overhead to underground systems due to security and climate change factors will increase the risk of FCOs due to site conditions. The failure in collaboration by front-end planning (FEP) teams can increase risk of FCOs due to missing scopes, errors in design, lack of existing field condition evaluation, constraints on the project schedule, or unexpected field conditions, among other causes. This study involved development of a quality control process that enables members of the FEP team to vote their confidence levels about risk control of FCOs before proceeding to final design. The proposed process utilized Analytical Hierarchy Process (AHP) methodologies to distribute the weights of stakeholder votes based on responsibilities for each category of FCOs to obtain an integrated metric of FEP team confidence. Data from an operational electric power utility was used to provide a case scenario approach and to illustrate the method. Three actual projects were analyzed to assess how well the process would have worked for them. The novelty of the proposed model is to enhance the effectiveness of collaborative working relationships across teams during the FEP process and to provide a quality control metric to capture risk of FCOs in the early phase to minimize cost overruns in the project execution phase.

3.2 Introduction

Front-end planning (FEP) is a critical phase of infrastructure project lifecycles where comprehensive plans leading to construction are prepared (Yussef et al. 2020). While there is no fixed set of steps or procedures, FEP generally includes tasks such as jobsite visits, scope of work development, design and technical specifications, evaluation, approval of design, permitting, strategy development for contractor selection, and coordination between stakeholders (National Academies Press, 2001). For this study, FEP is considered to encompass all steps leading up to making the decision to proceed with final design. FEP requires effective collaboration and participation from stakeholders to minimize the occurrence of field change orders (FCOs) during construction (Doloi, 2013; Collin et al., 2018; and Herrera et al., 2020).

The need to emphasize effectiveness of the FEP process to minimize change orders and maximize project performance has been explained by several investigators (Serag et al., 2010; Taylor et al., 2012; CII 2014; West et al., 2018) and the effects of inadequate preparation and collaboration on risks of FCOs have been explained by Maamari et al. (2020) and Waty et al. (2022). However, despite findings that industry professionals should emphasize the FEP process to reduce FCOs, the construction industry still faces cost overruns and schedule slippages (Serag et al., 2010; Taylor et al., 2012; Gharaibeh, 2013; Shrestha et al., 2013; Alshdiefat et al., 2018; and Shrestha, 2018). These previous studies show that, although FEP processes have been studied extensively for industrial and commercial projects, further research is needed to assess the roles and responsibilities of stakeholders to minimize FCOs. The studies show that the root causes of FCOs in projects in the electric power industry have not been studied much, which indicates a need for this study because the industry is confronting rapid change, especially the need to convert overhead to underground systems.

In this study, the development of a quality control process for FEP is demonstrated and the roles and responsibilities of stakeholders are specified to enable a voting process to assess when quality is high enough to minimize FCOs. The study focuses on collaboration among FEP stakeholders and builds on an earlier one by Nguyen et al. (2023) in which causes and frequencies of FCOs were determined using data from an electric power utility. The results of that study showed that underground projects have a higher risk of FCOs in both magnitude and frequency than overhead projects, which causes cost concerns due to conversion to underground systems due to security and climate requirements.

The paper begins with a literature review about construction FCOs and the FEP process. Then, it illustrates the use of systems engineering methods to integrate disciplines by laying out the cross-functional responsibilities of stakeholders in a proposed FEP quality evaluation model. The methods include the use of expert judgment (Saaty et al. 2015), a Fishbone Diagram (Rosenfeld, 2014 and Senouci et al., 2019) to rank elements, the Analytical Hierarchy Process (AHP) method to distribute responsibilities, and the extensive use of matrix displays and spreadsheets to quantify degrees of responsibility and risk. The AHP method is often used to compare alternatives in decision-making, but can also be used to distribute data by weights to support decision-making tool approaches (Ihimekpen et al., 2017; Kim et al., 2017; Wang et al., 2017; Alshdiefat et al., 2018; and Gunduz et al. 2019). Explaining use of these tools requires details that are included in Appendix A.

The degree of responsibility of each stakeholder in the FEP process for causes of FCOs was mapped using the Fishbone method to display stakeholder responsibilities. The responsibilities of stakeholders to prevent FCOs were distributed using Analytic Hierarchy Process (AHP) methods. Using the results of these tasks, the FEP quality control process was applied to enable stakeholders on the project team to vote on whether confidence in reducing FCO risk is high enough to proceed with the final design. Expert judgment was used to test and illustrate how to implement the proposed quality control method. In addition, three underground construction projects were analyzed to test the procedure, understand the possible outcomes, and develop conclusions.

3.3 Background

This section reports on peer reviewed literature about FEP collaboration among stakeholders and impacts on FCOs. Recommendations and solutions to reduce FCOs are also addressed.

3.3.1 The importance of Front-End Planning (FEP) in construction projects

FEP is an essential project process that enables owners to address risk and make decisions to maximize the potential for successful projects. Other names for FEP are pre-project planning, conceptual engineering or design, pre-conceptual planning, feasibility analysis, developing the brief, preliminary design, programming/schematic design/design development, and front-end loading (Gibson, 2019). The importance of proper scoping in FEP was recognized by the Construction Industry Institute (CII, 1996) in the release of its Project Definition Rating Index (PDRI). Such project definition rating index tools were studied by Elzomor et al. (2018), who found that small and large infrastructure projects require similar levels of project definition during FEP. Rahat et al. (2022) compared 59 Envision^{TM} credits and 46 PDRI elements to develop Envision-PDRI frameworks for small and large infrastructure projects. The work showed that linking Envision^{TM} credits with FEP can support stakeholders to improve the decision-making process for infrastructure projects.

Late starts of the risk management process can cause problems and create additional costs because the highest risks are incurred in the front-end process and the highest impacts occur in the back-end process (Rad et al., 2017). In addition, Elsayegh (2021) explained the need for collaborative planning to confront the challenges and suggested studies to address it. He also developed a prediction model for project cost and schedule performance in relation to collaborative planning risks.

3.3.2 *The impacts of FEP on change orders*

In a study of Kentucky Highway projects, Taylor et al. (2012) reported that the high risk of change orders on roadway construction can be avoided through improved FEP. They also suggested the need for new directions in FEP and project scoping to minimize change orders on highway projects. Shrestha (2016) also studied the causes of change orders and their impacts on road maintenance contracts. The indicated needs to improve FEP by reviewing specifications, preparing better estimates, and reviewing design drawings before bidding. Herrera et al. (2020) also identified cost overrun causative factors in road infrastructure projects and found that problems could be mitigated through modifications to traditional processes in the early stages of projects. Waty et al. (2022) found similar results for change orders in road construction in Indonesia and suggested that project teams should monitor field conditions before implementation, pay attention to work contract provisions, and emphasize field safety factors.

In a study of commercial construction projects, Olsen et al. (2012) identified the causes of FCOs and the importance of finding design errors by improved FEP. Some of their solutions align with Gunhan et al. (2007), who identified solutions for public school construction, such as pre-contract services, training of school administrators, precise scoping, constructability reviews, and value engineering. Doloi (2013) studied the roles of key stakeholders in residential, commercial, and industrial construction projects in Australia. The study showed that planning and scheduling deficiencies have the highest impact on cost performance. Maamari et al. (2021) studied change orders on construction projects in Oman and reported on work variations due to FEP problems caused by change order impacts. Tayyab et al. (2023) studied cost overruns in high-rise building construction across India and identified the top ten critical factors to help construction professionals minimize cost overruns, improve cost control measures, and initiate research to reduce cost overruns through an effective FEP process.

Most previous studies focused on road and building construction, but in the last decade more attention to electrical construction projects has been given. In a study of Canadian power transmission projects, Gharaibeh (2013) suggested that project teams should focus on the effectiveness of inter-organizational collaboration to minimize FCO issues. Sovacool et al. (2014) also studied construction cost overruns for electricity infrastructure worldwide and made an international comparison. They reported that the construction of electricity infrastructure has a substantial risk of cost overruns and suggested that investors, electric utilities, public officials, and energy analysts should reevaluate the methodologies they use to predict construction timetables and calculate budgets. Collin et al. (2018) studied the effects of electrical-related change orders on university projects in the United States. They found that "many electrical change orders were related to work items accounted for by the project team during preconstruction, but not contracted for during the initial tendering stage" (Collins et al., 2018, p. 649). In another study of electric power projects, Kim et al. (2018) assessed construction cost overruns in transmission grid projects in Vietnam. They used factor analysis and identified seven key factors that can be captured from the early phase of an effective management planning process. More recently, Nguyen et al. (2023) found causes and frequencies of FCOs from an electric power utility based in the United States, demonstrating that underground projects have a higher risk of FCOs in both magnitude and frequency than overhead projects.

3.3.3 Construction project life cycle and the importance of early collaboration

FEP occurs early in the project life cycle, where each phase culminates with a project deliverable. A common explanation of the five phases shows: 1) Project Initiation, 2) Project Planning, 3) Project Execution, 4) Project Monitoring and Control, and 5) Project Closure (Hendrickson et al., 2008; Messner, 2022; Carnegie Mellon University, 2023; and Donato, 2023). Regardless of the phases, the owner holds the key to the construction performance because any decision made at the beginning stage of the project life cycle has greater influence than those made at the later stages (Sinha et al., 2007).

As construction becomes more complex, effective collaboration becomes more of a key factor in completing quality projects on time and within budget. Collaboration promotes innovation, time and cost-saving, added value for the client, reduced errors, and avoidance of unnecessary rework. It should begin in the early planning stages where bringing in major players on a project, owner, architect, engineers, general contractor, and key subcontractors can lead to better design and decision-making by the FEP stakeholders (Jones, 2021).

Effective team collaboration should be established as soon as possible in the planning and design process to achieve maximum results. A core design team should be assembled early in the life cycle to articulate and define the client's program and evaluate the project's feasibility (Stonemark Construction Management, 2023).

3.3.4 Systems engineering and project management

Systems engineering offers project management tools for improving quality (UC Berkeley | ITS/PATH, 2023). The approach was applied in the Connected Corridors program for transportation engineering to lay out the life cycle of a project up front to minimize the risk to budget, scope, and schedule. The US Federal Highway Administration applied systems engineering core concepts to their Intelligent Transportation Systems project management processes to detect defects early in the project cycle (US DOT, 2007).

The Fishbone diagram used here to display causes and effects and identify stakeholder responsibilities for FCOs is an application used within system engineering to examine causes and effects of quality control issues (Six Sigma, 2017; Senouci et al., 2019; Wong, 2021; and Creighton, 2022). Another system engineering tool is the AHP methodology, which was used in this study to distribute the responsibilities of stakeholders in FEP for causes of FCOs.

Quality control requires cohesive collaboration between the project management stakeholder team to resolve issues and maximize project performance (Olsen et al., 2012; Molwus, 2014; Lofgren, 2020; Elsayegh, 2021; Jones, 2021; Cho et al., 2022; and Stonemark Construction Management, 2023). The quality control process proposed here is based on this philosophy and considers all types of FCOs from most to least important to each stakeholder.

3.3.5 Conclusions about the literature on construction change orders

Despite studies that show how failures of FEP lead to change orders and how solutions can be provided, the interrelationships between the root causes of field change orders and the project FEP stakeholders are not well understood. This is especially the case for the electrical utility sector, where few studies have been conducted, as compared to road and building construction. Previous studies shed light on the FEP process (CII, 1996; Elsayegh, 2021; Elzomor, 2018; Cho et al., 2022, Rahat et al. 2022), but they do not indicate comprehensive solutions for cross-functional collaboration between the stakeholders during FEP. Therefore, a more comprehensive study is needed to capture the risk of change orders related to interrelationships among FEP stakeholders to reduce the impacts of FCOs, especially for electric utility companies where few studies have been conducted.

3.4 Research Methodology

3.4.1 Data and analysis tools

The study used change order information from the database of an operational electric power utility in the U.S. The utility is identified as the ABC Electric Company to establish anonymity. Cost data were extracted from the utility's database using SAP software for overhead and underground projects completed in 2016-2020. In both cases**,** existing old and low voltage distribution circuits needed expanding and upgrading to higher load capacities to meet demands. The database includes the project description, location, narrative of the change, number of additions and/or deletions of FCOs, and project initial and final costs. The analysis used the Minitab Statistical Analysis software from the Minitab company, part of Academic Sector Solutions.

The 122 underground projects in the data set generally have a duration of two years: six months for conceptual/preliminary engineering design in which the project team can perform the proposed FEP quality control evaluation to minimize the risk of FCOs; six months for final engineering design; five months for permitting; two months for bidding; and five months for construction and testing. One project was removed because it was considered an outlier with percentage changes exceeding 190%, leaving 121 underground projects. Project sizes were between \$3.0M to \$5.5M. A total of 18 (15%) of the underground construction projects had zero cost of FCOs. These were retained in the database because projects without change orders should yield helpful information about FEP methods for later phases of the research.

3.4.2 Framework and methods for data collection and analysis

The framework for the development of the proposed quality control model is illustrated by Figure 3.1. The sequence begins with identification of the unique FCO types experienced by a specific utility. The stakeholders in the FEP process within that utility are identified and their responsibilities for FEP and for individual FCO risks are analyzed and distributed. Results are used in the voting process among stakeholders to determine when risk is low enough to proceed to final design and construction.

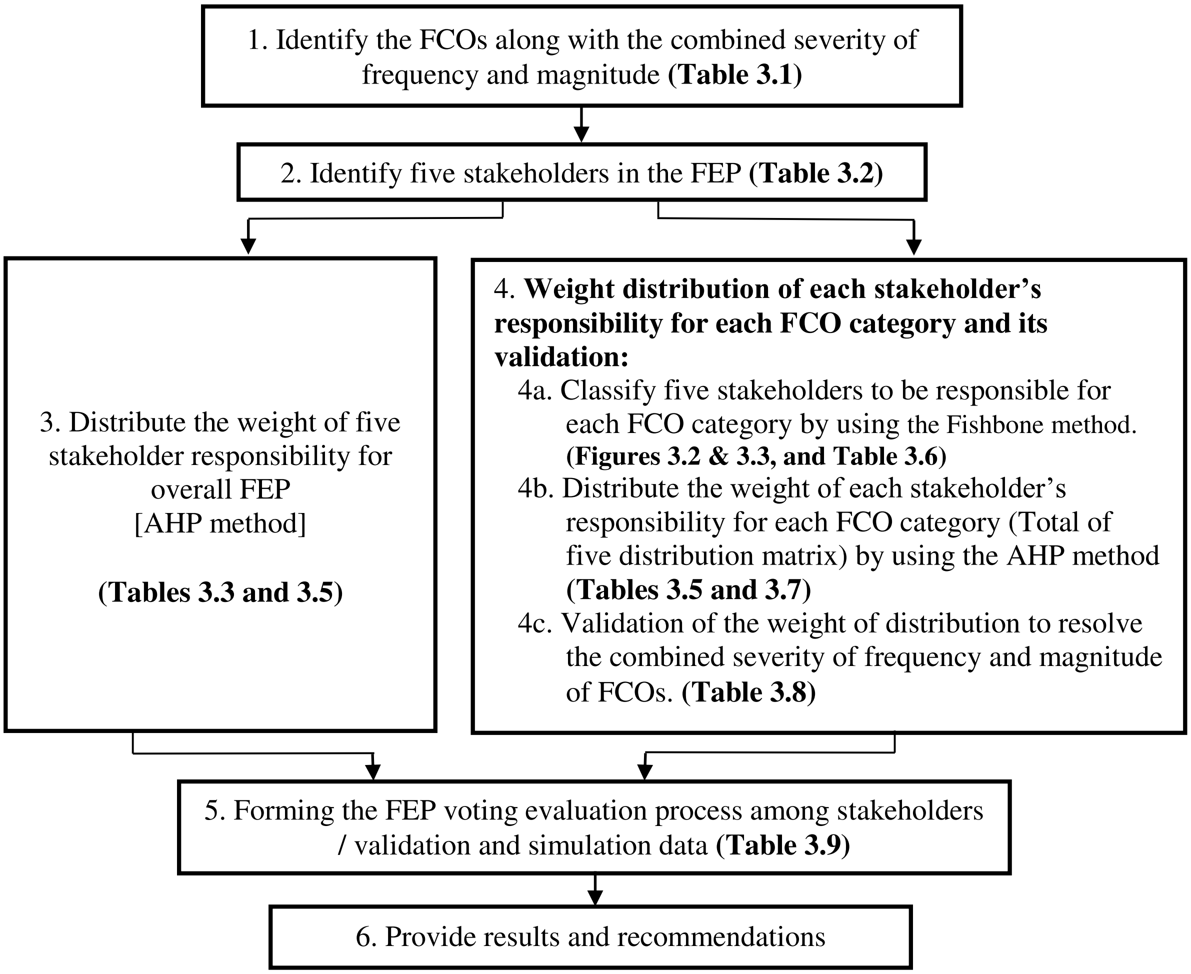


Figure 3.1 Proposed process for quality control during FEP

Details of the steps and methods are described next.

3.4.2.1 Identify the FCO causes

It is assumed that each utility identifies FCO causes from its construction project records. For this analysis, nine root causes of FCOs from Nguyen et al. (2023) were identified and then reduced to five to simplify the analysis and concentrate on the riskiest ones based on their frequency and cost magnitude. This reduced the project dataset from 121 to 113 underground projects. Frequencies of FCOs were determined in the previous study, and the magnitude of cost was added here to develop a combined metric for severity of FCO impacts. When records show multiple causes, the assumption was made that costs can be distributed evenly. The top five causes of FCOs represent 85% of the frequency and 90% of the cost magnitude of the original nine causes.

Table 3.1 shows the top five FCO types with descriptive titles that are used in the analysis. Frequency data from the previous study are in Columns 3, and Column 4 adds data of cost impacts. Columns 5 and 6 provide indices and a ranking of the combined impacts computed as the product of frequency and cost magnitude. The ranking provides a severity metric that is used in another step to validate the distributions of stakeholder responsibilities for assessing FCO risks. The combined severity ranking is the same as the individual severities of frequency and cost magnitude.

Table 3.1 Frequency, magnitude and combined ranking of causes of field change orders for 113 underground electrical projects

FCOs Reason No. (Column 1)	**The change descriptions** (Column 2)	**UG projects frequency percentage [A1]** (Column 3)	**UG projects magnitude percentage [A2]** (Column 4)	**Combined impacts UG projects of frequency & magnitude [A1 x A2]** (Column 5)	**Combined ranking of severity of frequency & magnitude** (Column 6)
1	Accommodate Current Existing Field Condition	43.24%	40.82%	17.65%	1
2	Project Schedule Constraint	28.32%	31.00%	8.78%	2
3	Business Operating Hours	11.75%	16.47%	1.94%	3
4	Unknown/Unexpected Field Condition	10.81%	7.14%	0.77%	4
5	Correction of Work Due to Design Error	5.88%	4.57%	0.27%	5

3.4.2.2 Identify stakeholders

Each utility company will identify its own stakeholders in FEP because organizational structures and roles may differ. Eleven stakeholders were identified for this study, but to reduce complexity of the analysis, only the most influential five were retained. Table 3.2 illustrates the five used here, along with descriptions of their responsibilities and relative importance in FEP.

Column 3 includes numerical rankings from 1 to 9 (less to more important) based on the AHP method, which will be explained in the next section. Some utilities may include outside consultants within stakeholder groups.

Table 3.2 Stakeholders in the FEP process

Stakeholders	Responsibilities	Relative Importance in FEP
Procurement Team	Negotiate contract agreements of costs and schedules with contractors.	The least importance among five stakeholders in FEP, score of 1.
Project Management Team	Coordinate with stakeholders and monitor and execute the project.	Equal to moderate importance as it coordinates with all stakeholders during the FEP, score of 2.
Field Engineering Team	Study project sites to support scoping and design.	Strong to very strong importance for site investigation, score of 6.
Civil Team	Prepare for underground work by boring test holes, subgrade preparation, and trenching.	Very strong importance to extreme importance as it studies site conditions and subgrade to ensure constructability, score of 8.
Design/Planning Team	Define and design project scopes with collaboration from other teams.	The main team in FEP with extreme importance, score of 9.

3.4.2.3 Distribute FEP responsibility among stakeholders

The descriptive information in Table 3.2 was used to develop Table 3.3, which provides an example of distributing stakeholder responsibilities for FEP. The distributions involve use of the AHP methodology which is explained in more detail in Appendix A. Figure A-1 provides additional detail related to Table 3.3.

The AHP methodology uses an Intensity Scale to guide the judgment of the analyst in distributing relative weights. Table A-1, page A3 in the Appendix, provides additional information about its use in determining pairwise comparisons of relative stakeholder responsibilities. See page A4 in Appendix A for details on how the numbers were determined.

Table 3.3 Sample of pairwise comparison of the stakeholder responsibility for overall FEP

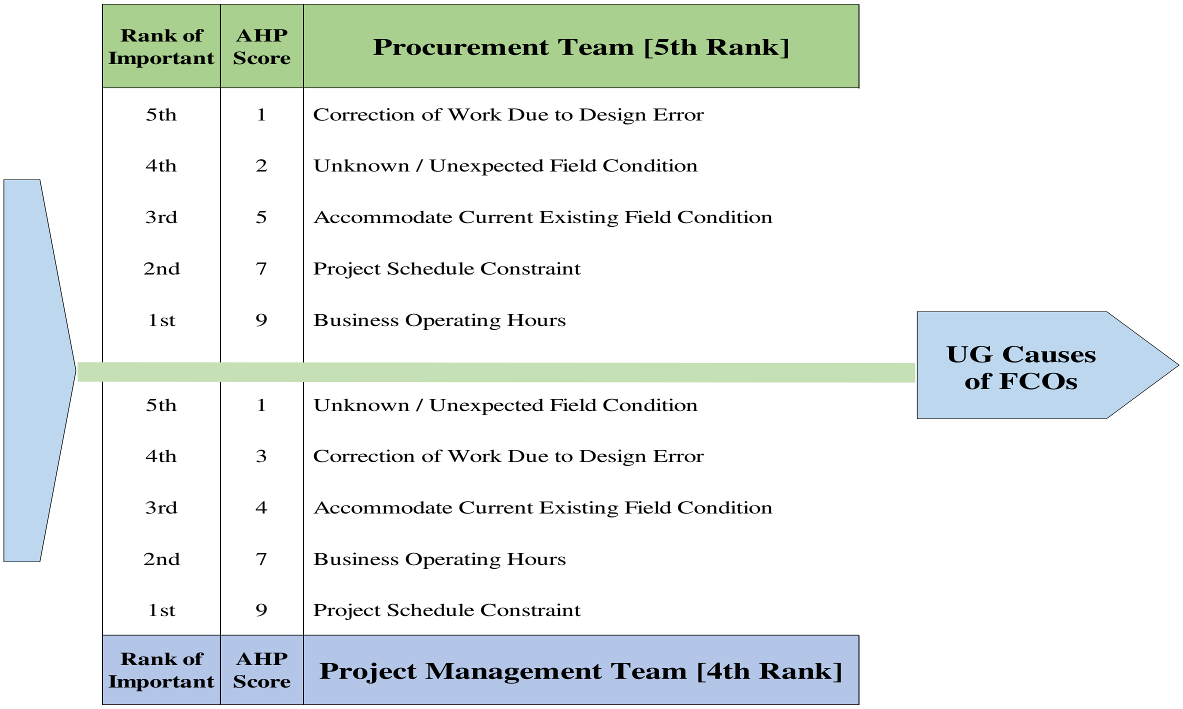
Stakeholders [Column 1]	**Procurement Team [Column 2]**	**Project Management Team [Column 3]**
Procurement Team	1.00	0.50
Project Management Team	2.00	1.00
Field Engineering Team	6.00	5.00
Civil Team	8.00	7.00
Design/Planning Team	9.00	8.00

Table 3.3 is identical with Table A-2 in Appendix A, which is used for a more detailed explanation. The scaling illustrated in Table 3.3 requires judgments about how each stakeholder contributes to the FEP process. Such judgements can be made by surveying stakeholders or using expert opinion. The use of expert opinion has been reported as superior to a survey in several reports (Molwus 2014, Saaty et al. 2015, Schmidt et al. 2015, Gokulkarthi et al. 2015, and Alshdiefat et al. 2018). This study used expert opinion by a judge who has reviewed and negotiated FCOs and claims and has over 20 years of experience in the construction industry with frequent participation with stakeholders in construction and power utility companies.

3.4.2.4 Distribute weight of each stakeholder's responsibility for each FCO category and its validation

This step is divided into three sub-steps 3.2.4a, 3.2.4b, and 3.2.4c. In step 4a, the Fishbone diagram shown in Figure 3.2 is used to develop an initial classification of the relative degree of each stakeholder's responsibility for the causes of FCOs. Two stakeholder teams are shown for purposes of illustration. In a subsequent step, the AHP method is used to make a further pairwise comparison for each stakeholder category for each FCO cause. The classification using the Fishbone Diagram (Figure 3.2) is displayed by rank of importance from the first (1st) to the fifth

(5th), where the AHP Intensity Scale was used in a scheme to assign the first order a score of 9.00 as the highest and the fifth order a score of 1.00 as the lowest importance.



Rank of Important	AHP Score	Procurement Team [5th Rank]
5th	1	Correction of Work Due to Design Error
4th	2	Unknown / Unexpected Field Condition
3rd	5	Accommodate Current Existing Field Condition
2nd	7	Project Schedule Constraint
1st	9	Business Operating Hours

Rank of Important	AHP Score	Project Management Team [4th Rank]
5th	1	Unknown / Unexpected Field Condition
4th	3	Correction of Work Due to Design Error
3rd	4	Accommodate Current Existing Field Condition
2nd	7	Business Operating Hours
1st	9	Project Schedule Constraint

Figure 3.2 Fishbone Diagram to classify stakeholder responsibilities for each FCO category

In step 4b, five pairwise comparisons of the FCO categories are required, one for each stakeholder. Table 3.4 provides an example of distributing the Procurement team's responsibility for each FCO category. Drawing from the Fishbone Diagram, the AHP scores shown represent the judge's opinion of the relative responsibility of a given team for all FCO causes. The table shows rank of importance, with the first order assigned a score of 9 as the highest and the fifth order assigned a score of 1 as the lowest importance, consistent with the AHP Intensity Scale.

The judgments for the other scores in the table are explained on page A5 of Appendix A.

Table 3.4 Sample of pairwise comparison of stakeholder responsibility for each FCO categories

Procurement Team FCO Responsibility [Column 1]	Correction of Work Due to Design Error [Column 2]	Unknown / Unexpected Field Condition [Colum 3]
Correction of Work Due to Design Error	1.00	0.50
Unknown / Unexpected Field Condition	2.00	1.00
Accommodate Current Existing Field Condition	5.00	4.00
Project Schedule Constraint	7.00	6.00
Business Operating Hours	9.00	8.00

Step 4c is the validation of the consistency of the original severity rankings in Table 3.1 and the distributions of the weights of stakeholders and of each stakeholder's responsibility for each FCO category. In this step, the distribution of weights from steps 4a and 4b are checked against the severity rankings from step 1 to assess if they meet the consistency requirements of the AHP method. If the distributions are inconsistent with the severity rankings, they will be repeated until they are consistent.

The consistency test is explained in Appendix A. The AHP requirement is that the consistency ratio (CR) must be less than 0.1 (10%). The CR is defined as the ratio of a consistency index and a random consistency index.

3.4.2.5 Organizing the FEP voting evaluation process among stakeholders

This step of the study enables the project team to assess the stakeholder confidence scores based on their responsibilities during FEP before proceeding with the final design.

The next section explains the functioning of the process with a series of tables, ending with a consolidated table (Table 3.9) to show the results of stakeholder voting about their confidence that FCO risks are minimized. The sequence of the presentation of results is shown in Table 3.9 is:

Table 3.5: Results for the pairwise comparison of the five stakeholders' responsibility for overall FEP, with the consistency check.

Table 3.6: Judgements of responsibilities of each stakeholder for each FCO category.

Table 3.7: Example of distribution of procurement team responsibility for each FCO category (four other tables are shown in Appendix A).

Table 3.8: Distribution of the weight of each stakeholder's responsibility for each FCO category with five pairwise comparisons of the FCO categories and distribution validation for pairwise comparisons.

3.5 Quality Control Process: Results

3.5.1 The distribution of the stakeholder responsibility for overall FEP

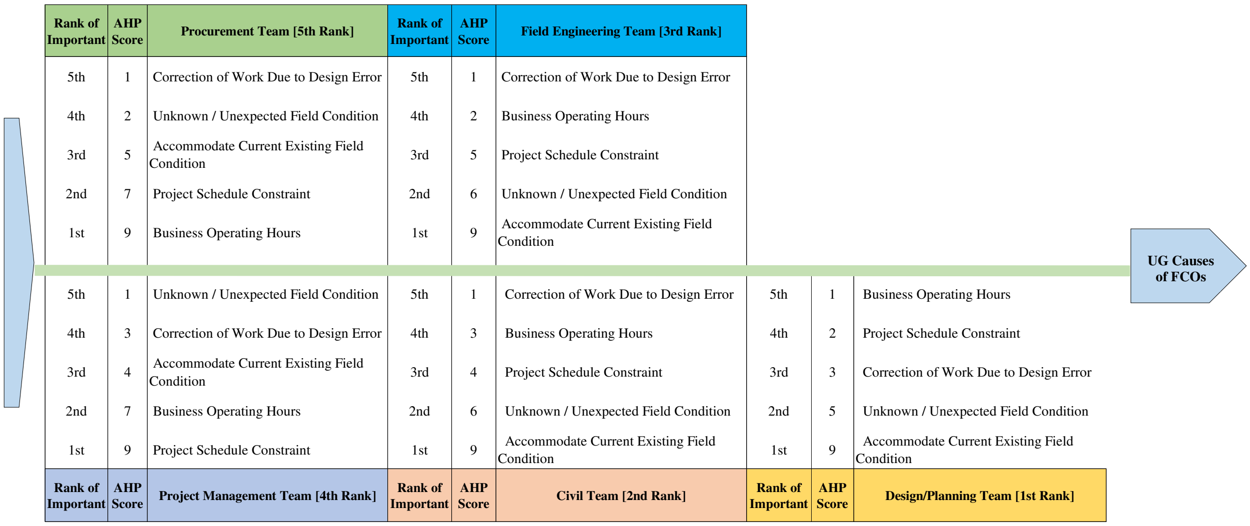
Table 3.5 presents the results for the pairwise comparison of the five stakeholders' responsibility for overall FEP. The consistency ratio of the pairwise comparison is computed at 0.04, which is smaller than the AHP requirement of 0.1, indicating the distribution is acceptable. The weight vectors are the eigenvectors to show the relative weights between each stakeholder, as shown in the rank column. Their normalized values shown in the next column were used to calculate scores in the evaluation model in Table 3.9.

Table 3.5 Pairwise comparison of the five stakeholder's responsibility for overall FEP

Stakeholders [Row 1 / Column 1]	Procurement Team [Column 2]	Project Management Team [Column 3]	Field Engineering Team [Column 4]	Civil Team [Column 5]	Design/ Planning Team [Column 6]	Weight Vector (W.V.) [Column 7]	Normalized Weight Vector (N.W.V.) [Column 8]	Rank [Column 9]
Procurement Team [Row 2]	1.00	0.50	0.17	0.13	0.11	0.26	0.03	5
Project Management Team [Row 3]	2.00	1.00	0.20	0.14	0.13	0.37	0.05	4
Field Engineering Team [Row 4]	6.00	5.00	1.00	0.33	0.25	1.20	0.15	3
Civil Team [Row 5]	8.00	7.00	3.00	1.00	0.50	2.43	0.31	2
Design/Planning Team [Row 6]	9.00	8.00	4.00	2.00	1.00	3.57	0.46	1
Column Total [Row 7]	**26.00**	**21.50**	**8.37**	**3.60**	**1.99**	**7.82**	**1.00**	
(Column Total) x Relative (N.W.V.) [Row 8]	0.86	1.02	1.28	1.12	0.91			
Lambda max (λmax) = Sum [(Column Total) x Relative (N.W.V.)] [Row 9]	5.19							
Consistency Index (CI) = [(λmax -n) / (n-1)] [Row 10]	0.05							
Consistency Ratio (CR) = (CI/RI) [Row 11]	0.04	CR = 0.04 < 0.1, which indicates the distribution is acceptable. The RI of 5 (n) comparisons is 1.12 by Satty (1980).						

3.5.2 Classification of stakeholders responsible for each FCO category

The Fishbone Diagram in Figure 3.3 expands the information that was presented on Figure 3.2 to illustrate the relative responsibilities of each stakeholder group for each FCO category. The results are summarized in Table 3.6 and used in the AHP method to distribute the weight of stakeholder responsibilities for each UG electrical FCO category.



Rank of Important	AHP Score	Procurement Team [5th Rank]	Rank of Important	AHP Score	Field Engineering Team [3rd Rank]
5th	1	Correction of Work Due to Design Error	5th	1	Correction of Work Due to Design Error
4th	2	Unknown / Unexpected Field Condition	4th	2	Business Operating Hours
3rd	5	Accommodate Current Existing Field Condition	3rd	5	Project Schedule Constraint
2nd	7	Project Schedule Constraint	2nd	6	Unknown / Unexpected Field Condition
1st	9	Business Operating Hours	1st	9	Accommodate Current Existing Field Condition

Rank of Important	AHP Score	Project Management Team [4th Rank]	Rank of Important	AHP Score	Civil Team [2nd Rank]	Rank of Important	AHP Score	Design/Planning Team [1st Rank]
5th	1	Unknown / Unexpected Field Condition	5th	1	Correction of Work Due to Design Error	5th	1	Business Operating Hours
4th	3	Correction of Work Due to Design Error	4th	3	Business Operating Hours	4th	2	Project Schedule Constraint
3rd	4	Accommodate Current Existing Field Condition	3rd	4	Project Schedule Constraint	3rd	3	Correction of Work Due to Design Error
2nd	7	Business Operating Hours	2nd	6	Unknown / Unexpected Field Condition	2nd	5	Unknown / Unexpected Field Condition
1st	9	Project Schedule Constraint	1st	9	Accommodate Current Existing Field Condition	1st	9	Accommodate Current Existing Field Condition

Figure 3.3 The Underground (UG) Electrical causes with FCOs associated with the stakeholders

Table 3.6 The judgements of responsibilities of each stakeholder for each FCO category for UG electrical Projects

Stakeholders	**FCOs**				
	Accommodate Current Existing Field Conditions	Project Schedule Constraint	Business Operation Hours	Unknown/unexpected Field Conditions	Correction of Work due to Design Error
Design/Planning Team	9	2	1	5	3
Civil Team	9	4	3	6	1
Field Engineering Team	9	5	2	6	1
Project Management Team	4	9	7	1	3
Procurement Team	5	7	9	2	1

3.5.3 The distribution of the weight of the stakeholder's responsibility for each UG electrical FCO category

Table 3.7 is an expansion of Table 3.4 to present pairwise comparisons of one stakeholder's responsibilities for FCO categories. The Procurement team is shown again, and tables for the other stakeholders are not shown to avoid excessive detail. The consistency ratio is 0.06, which is smaller than the AHP requirement of 0.1, indicating that the distribution is acceptable. The normalized weight vector value is used again in the same way to calculate the score of the evaluation model.

Table 3.7 Distribution of Procurement Team responsibility for each FCO category

Procurement Team FCO Responsibility	**Correction of Work Due to Design Error**	**Unknown / Unexpected Field Condition**	**Accommodate Current Existing Field Condition**	**Project Schedule Constraint**	**Business Operating Hours**	**Weight Vector (W.V.)**	**Normalized Weight Vector (N.W.V.)**	**Rank**
Correction of Work Due to Design Error	1.00	0.50	0.20	0.14	0.11	0.28	0.03	5
Unknown / Unexpected Field Condition	2.00	1.00	0.25	0.17	0.13	0.40	0.05	4
Accommodate Current Existing Field Condition	5.00	4.00	1.00	0.33	0.20	1.06	0.13	3
Project Schedule Constraint	7.00	6.00	3.00	1.00	0.33	2.11	0.27	2
Business Operating Hours	9.00	8.00	5.00	3.00	1.00	4.04	0.51	1
Column Total	**24.00**	**19.50**	**9.45**	**4.64**	**1.77**	**7.89**	**1.00**	
(Column Total) x Relative (N.W.V.)	0.84	0.99	1.27	1.24	0.91	5.25		
Lambda max (λmax) = Sum [(Column Total) x Relative (N.W.V.)]	5.25							
Consistency Index (CI) = [(λmax -n) / (n-1)]	0.06							
Consistency Ratio (CR) = (CI/RI)	0.06	CR = 0.06 < 0.1, which indicates the distribution is acceptable. The RI of 5 comparisons is 1.12 by Satty (1980).						

3.5.4 Overall validation of consistency

The consistency ratios were computed previously for all pairwise comparisons. Using those computations, the normalized weight vectors for each stakeholder's responsibility for each FCO category are shown in Table 3.8. By averaging the normalized weight vectors, the overall responsibilities for FCO categories can be ranked, and results show consistency with the initial ranking of frequency and magnitude that was shown in Table 3.1. This indicates success where the proposed quality control model is able to assess the risk of FCOs. Note that the rank of each FCO category relative to each stakeholder is different than the rank of its average normalized weight vector.

Table 3.8 Responsibility distribution validation

Responsibility Distribution Validation	**Design/Planning Team Normalized Weight Vector**	**Civil Team Normalized Weight Vector**	**Field Engineering Team Normalized Weight Vector**	**Project Management Team Normalized Weight Vector**	**Procurement Team Normalized Weight Vector**	**Average Normalized Weight Vector**		**Average Normalized Weight Vector Rank [A1]**	**Combined Severity of Frequency & Magnitude Rank [A2]**	**Variance [A1 - A2]**	**Satisfaction**
Accommodate Current Existing Field Condition	0.60	0.56	0.55	0.10	0.13	0.39		1	1	0	✓
Project Schedule Constraint	0.06	0.11	0.15	0.52	0.27	0.22		2	2	0	✓
Business Operating Hours	0.04	0.07	0.05	0.28	0.51	0.19		3	3	0	✓
Unknown / Unexpected Field Condition	0.20	0.23	0.22	0.03	0.05	0.15		4	4	0	✓
Correction of Work Due to Design Error	0.10	0.04	0.04	0.07	0.03	0.05		5	5	0	✓
Total	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**					

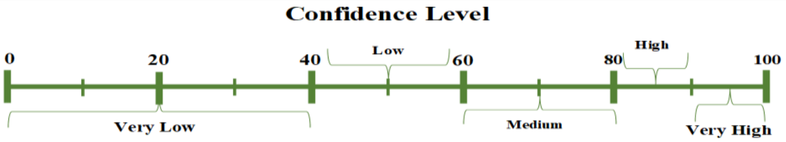
3.5.5 FEP voting evaluation process and simulation data among stakeholders

Table 3.9 illustrates the overall quality control process with three sections. The first section shows stakeholders and causes of FCOs as normalized weight vector from steps 3 and 4b. The second section is used for the project team to perform the evaluation. In it, each stakeholder provides a confidence evaluation with a score from 0 to 100. This is illustrated as simulation data in the table. The higher confidence range level indicates that the project team should have a lower risk of FCOs. Each stakeholder group can decide how to determine its vote. The third section of the table shows the combined results after the stakeholders vote on the confidence level scores. The combined result is calculated by considering each stakeholder's responsibility for the FCO categories assessed. The power utility company decides the passing score that permits the project team to move to the design phase.

Table 3.9 Front-End Planning FCOs Quality Control Model

Front-End Planning FCOs Quality Control Model

1. Stakeholders and Causes of FCOs	Design/ Planning Team [Weight = 0.46]	Civil Team [Weight = 0.31]	Field Engineering Team [Weight = 0.15]	Project Management Team [Weight = 0.05]	Procurement Team [Weight = 0.03]
Accommodate Current Existing Field Condition	0.60	0.56	0.55	0.10	0.13
Project Schedule Constraint	0.06	0.11	0.15	0.52	0.27
Business Operating Hours	0.04	0.07	0.05	0.28	0.51
Unknown / Unexpected Field Condition	0.20	0.23	0.22	0.03	0.05
Correction of Work Due to Design Error	0.10	0.04	0.04	0.07	0.03
Total	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**



Evaluation Result

92.87

2. Confidence Level Evaluation	Simulation Data				
Accommodate Current Existing Field Condition	95	95	95	95	85
Project Schedule Constraint	90	90	90	90	85
Business Operating Hours	95	80	90	90	85
Unknown / Unexpected Field Condition	95	95	95	90	75
Correction of Work Due to Design Error	85	80	95	90	70

3. Results of Confidence Level Scores					
Accommodate Current Existing Field Condition	12.75	51.82	56.61	9.73	47.20
Project Schedule Constraint	24.09	13.17	5.60	46.86	9.28
Business Operating Hours	48.67	4.24	3.65	24.76	6.08
Unknown / Unexpected Field Condition	4.83	20.80	19.43	3.05	17.17
Correction of Work Due to Design Error	2.97	2.90	9.20	6.11	2.46
Sum of Result of Confidence Level [A1]	**93.31**	**92.93**	**94.49**	**90.51**	**82.18**
Stakeholders Weight [A2]	**0.46**	**0.31**	**0.15**	**0.05**	**0.03**
FEP Evaluation Result [A1 x A2]	**42.53**	**28.82**	**14.51**	**4.31**	**2.72**

The overall score of stakeholders should be high enough before proceeding to the final design phase to ensure all the FCO risks can be minimized during the construction phase. The simulated data was scored in the second section. The result shows an overall evaluation score of 92.87. This score is in the very high range of the confidence level, so the project team should have a low risk of FCOs.

For the voting task, this study suggests the individual in each stakeholder category should have at least 15 years of experience in the field of responsibility and hold a senior manager position to provide the voting to ensure the proper communication and quality of the voting. In practice, the senior manager should get the input from his or her project team members to ensure the team thoroughly completes the risk evaluation of FCOs to ensure the accuracy of the voting input. Thus, the top five senior managers from the five stakeholders will be held accountable for the voting task in the FEP quality control process.

3.6 Quality Control Process: Discussion of three case studies

The proposed quality control method was tested by retroactive analysis of three completed projects, A, B, and C, with the low, medium, and high impacts of the FCOs, respectively. Projects A, B, and C were required to expand and upgrade the existing old and low-voltage distribution circuits to higher load capacities to enhance reliability and safety to meet capacity demands. The scopes of these projects included rerouting duct bank conduits and installation of underground cables, electrical devices, and underground civil structures. Projects A, B, and C had three, four, and six months of construction and testing, respectively.

The overall assessment of these three projects showed that FCO severity was high due to the Accommodate Current Existing Field Condition and the Project Schedule Constraint causes, and low due to Business Operating Hours and other causes.

Project A had a one percent change in the cost, and the FCOs were due to Unknown/Unexpected Field Condition and Project Schedule Constraint. The percentage change is based on the final minus initial cost divided by the initial cost. This indicated that the project team had done thorough preparation work prior to proceeding with the final design and awarding the construction contracts. If the project team performed the proposed FEP quality control evaluation as described in section 4.5, the score would be in a very high range of the confidence level, indicating that the project team would have a low risk of FCOs. The Unknown/Unexpected Field Condition cause triggered the Project Schedule Constraint cause to avoid the delay to the project schedule in this project. Recognizing Unknown/Unexpected Field Conditions may be challenging, but an effective front- end of planning and design will be the best solution (Serag et al., 2010; Taylor et al., 2012; Gokulkarthi et al., 2015; and Alshdiefat et al., 2018).

Project B had a thirty percent change in the cost and the FCOs were due to Accommodate Current Existing Field Condition and Project Schedule Constraint causes. This indicated that the project team had not done thorough preparation work prior to proceeding with the final design and awarding the construction contracts. If the project team performed the proposed FEP quality control evaluation as described in section 4.5, the score would be in the low to medium range of the confidence level, which indicates the risk level of FCOs in this project. The Accommodate Current Existing Field Condition cause triggered the Project Schedule Constraint cause to avoid the delay to the project schedule in this project.

Project C had a forty-eight percent change in the cost and the FCOs were due to Accommodate Current Existing Field Condition, Project Schedule Constraint, Business Operating Hours, Unknown/Unexpected Field Condition, and Correction of Work Due to Design Error. This indicated that the project team had not done thorough preparation work prior to proceeding with the final design and awarding the construction contracts. If the project team performed the proposed FEP quality control evaluation as described in section 4.5, the score would be in a low range of the confidence level, which indicates that the project team would have a high risk level of FCOs in this project. Similar to project B, the Accommodate Current Existing Field Condition cause also triggered the Project Schedule Constraint cause to avoid the delay to the project schedule in this project.

Overall, the assessment showed that both Accommodate Current Existing Field Condition and Unknown/Unexpected Field Condition causes would trigger additional premium time to be paid for the contractor to meet the schedule deadline. This is consistent with the finding from the study that these two FCO causes created the highest impact of cost overrun to the project. Thus, to minimize the risk of this FCO, the Design/Planning team, Civil team, and Field Engineering team should collaboratively evaluate the existing project field condition to ensure all scopes are included in the early stages of design. The Project Management team can facilitate this by coordinating with all stakeholders during FEP to ensure the tasks are being done in a timely and effective manner. Even though the Procurement team has the lowest score of importance among the stakeholders, it is very important in coordinating the construction bid packages. Thus, the Procurement team should establish an effective strategy in the FEP to ensure the project team and contractor have a mutual agreement on both the scopes and costs of the projects.

The proposed quality control process sets a high responsibility rank for the Field Engineering team, Design/Planning team, and Civil team to assess the Accommodate Existing Field Conditions cause as well as the Project Management team for the Project Schedule Constraint cause. With the proposed cross-functional collaboration solution to the existing FCOs issue, the stakeholders should be able to recognize the risk of these FCO causes through the referenced FEP quality control process. Although FEP is defined as the project preparation phase prior to the start of the final design, this study recommends the project team perform the quality evaluation at any given stage when needed in the project life cycle to minimize the risk of FCOs during the construction phase.

3.7 Conclusion

Using methods from systems engineering, the study developed a quality control process for FEP that can enable electric utility companies to assess the risk of FCOs prior to final design. This will be important when, due to climate and safety factors, conversion from overhead to underground electrical systems triggers more cost overruns because of the complexity of the subgrade work. By reducing cost overruns due to FCOs, utility companies can be better positioned to keep energy costs affordable for households and businesses.

To improve quality control, utilities should emphasize cross-functional collaboration between stakeholders during the FEP process. Any decision made at the beginning stage of the project life cycle has far greater influence than those made at the later stages. Late starts of risk management will create additional costs in the project execution phase.

For the case study utility, the top five main stakeholders in FEP were the Design/Planning team, the Civil team, the Field engineering team, the Project management team, and the Procurement team. The Fishbone and the AHP methodologies enabled the distribution of the weight of responsibility for FEP of the stakeholders within the project team. They also enabled assessment of the interrelationships between the project stakeholders and the root causes of FCOs. These led to an FEP evaluation model that allows the project team to vote and decide when the quality is high enough to proceed with the final design to minimize the cost impacts of FCOs.

The study indicated that the Design/Planning team, Civil team, and Field Engineering team are most responsible for the top FCO category, Accommodate Current Existing Field Condition cause. The Procurement and the Project Management stakeholders have high responsibility for the Business Operating Hours and Project Schedule Constraint causes. In addition, the Procurement team is responsible for negotiating with the contractors about scopes and prices for contracts.

Hence, they should work collaboratively with multiple stakeholders to have a complete and verified construction bid package prior to negotiating and issuing the construction contract to avoid scope creep which may trigger FCOs.

Overall, this study provides power industry practitioners with a quality control process for FEP using the Fishbone and AHP methodologies. Future research can focus on mapping the quality control process. This type of roadmap can integrate project activities linked to stakeholder responsibilities to optimize project performance and ensure that risk of FCOs is captured early in FEP.

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CHAPTER 4

A Proposed Quality Control Roadmap for Front-End Planning Process to Minimize the Risk of Field Change Orders in Underground Electrical Construction

4.1 Summary

It is essential for the electric power industry to control capital costs and cost overruns due to field change orders to provide affordable energy for households and businesses. The risk of field change orders is mainly due to poor preparation during the front-end planning process. A key issue in front-end planning is collaboration between stakeholders and few guides are available for the electric power sector, despite their availability in other sectors. This study addressed this gap with a proposed quality control roadmap model with four phases for front-end planning. The project team stakeholders will perform assigned tasks and assess the risk of field change orders during the first three phases, and fourth phase is for them to vote on risk evaluation to decide if confidence in reducing change order risk is high enough to proceed with final design. A case study of an actual project is used to simulate a test of the model and scheduling software demonstrates the logical relationships between the tasks. The novelty of the proposed roadmap model is to use systems engineering methods to enhance the effectiveness of interdisciplinary teamwork among stakeholders through a critical path of the front-end planning process.

4.2 Introduction

Controlling construction costs in the electric power industry will become more important as the nation responds to new energy demands due to electric vehicles and emerging trends such as artificial intelligence and sue of cryptocurrency. Moreover, natural disasters are causing utilities to undertake projects to bury overhead lines to avoid disastrous effects. One of the main issues in cost control is excessive field change orders (FCOs), which must be controlled to avoid cost overruns.

This paper explains the development of a quality control process for front-end planning (FEP), which offers to power utilities the best opportunity to control FCOs. The focus is on underground electrical construction, which tends to be more complex than overhead construction due to greater complexity and difficulty to assess geotechnical issues. The metric used for quality is the number of FCOs. The goal of the process is to minimize the number and severity of FCOs by improving coordination and work among project team stakeholders in FEP until they agree that final design can begin.

The proposed roadmap uses a process model like those required in construction projects to keep tasks and resources aligned without communication gaps. A process consists of all of activities and interactions required to accomplish a project effectively (Pestana el al., 2012, Pima County, 2015, Hijazi et al., 2018, Pakdaman et al., 2019, Sam, 2021, Imran et al., 2022, and Zacharias, 2023). Using a specific tool for FEP is helpful in increasing the efficiency and control of the process to assure project performance outcomes (Safa et al., 2013 and West et al., 2018).

The discussion begins with background and an explanation of previous work that leads to the current work to develop the process. Then, the development of the process methodology is explained, including how it works for different quality control steps. A demonstration of the process is conducted by including the relevant project stakeholders, and a case study of an underground electrical construction project with high impacts of FCOs is presented to assess how well the proposed FEP quality control roadmap would have worked for it. The discussion section presents an assessment of the process and identifies work needed to continue its development and transfer it to practice by utilities.

Data used to demonstrate the methods are from an actual electric utility but provided a fictitious name to preserve anonymity. For the demonstration of the roadmap, FEP stakeholders and types of FCOs experienced for that utility are used to provide actual data. The case study presented later examines one of the utility's completed projects.

The novelty of the work is found in its use of systems engineering methods and tools to develop the logical quality control process and exploit project data to identify causes and impacts of historical FCOs that have been experienced.

4.3 Background

The quality control process roadmap explained here was preceded by two previous studies, one to identify and analyze FCO types (Nguyen et al., 2023) and the other to use the analytic hierarchy process (AHP) method to distribute the responsibilities of stakeholders and the importance of FCOs (Nguyen et al., 2024, in review). This section briefly reviews this previous work to provide tools needed for the process roadmap.

*4.3.1 Data and analysis tools [**previous work**]*

The change order data are from an operational electric power utility in the U.S., which is named ABC Electric Company, to establish anonymity. Types and numbers of FCOs and cost data were extracted from the utility database for overhead and underground projects in 2016-2020. The database includes the project description, location, narrative of the change, number of additions and/or deletions of FCOs, and project initial and final costs.

Most of the 122 underground projects in the data set used here have a duration of about two years: six months for conceptual/preliminary engineering design, where the project stakeholders would follow the roadmap to perform the FEP quality control evaluation to minimize the risk of FCOs; six months for final engineering design; five months for permitting; two months for bidding and construction; and five months for construction and testing. One project was removed because it was considered an outlier with percentage changes exceeding 190%, leaving 121 underground projects. Project sizes were between $3.0M to $5.5M.

*4.3.2 Identify stakeholders and their main tasks in the FEP [**previous work**]*

To use the quality control roadmap process, each utility company will identify its stakeholders in FEP because organizational structures and roles may differ. Table 4.1 illustrates the categories and descriptions of the eleven stakeholders identified for the ABC Electric Company. The top five stakeholders, based on relative importance in FEP, were identified in the previous study to participate in voting evaluation for FEP quality control, and the other six stakeholders are involved in understanding the project for the execution phase.

Table 4.1 Eleven Stakeholders and Responsibilities

Stakeholders	Responsibilities
1. Design/Planning Team	Define and design project scopes with collaboration from other teams.
2. Civil Team	Prepare for underground work by boring test holes, subgrade preparation, and trenching.
3. Field Engineering Team	Study project sites to support scoping and design.
4. Project Management Team	Coordinate with stakeholders and monitor and execute the project.
5. Procurement Team	Negotiate contract agreements of costs and schedules with contractors.
6. Pre-Construction Planning Team	Layout the construction planning and methodology.
7. Contractor	Perform the construction work.
8. Permit Team	Prepare for project permits, right of way, and environmental requirements.
9. Project Cost Estimating Team	Estimate the project costs.
10. Project Cost Control Team	Monitor the project cost payments and project cost forecasting.
11. Project Scheduling Team	Schedule the work tasks and monitor the progress of the construction.

*4.3.3 Identify combined ranking of severity of frequency & magnitude **[previous work]***

Table 4.2 shows the top five FCO types from (Nguyen et al., 2023, and 2024 (in review)) with a severity metric based on frequency and cost.

Table 4.2 Frequency, magnitude, and combined ranking of causes of field change orders for underground electrical projects

FCOs Reason No. (Column 1)	**The change descriptions** (Column 2)	**Combined ranking of severity of frequency & magnitude** (Column 3)
1	Accommodate Current Existing Field	1
2	Project Schedule Constraint	2
3	Business Operating Hours	3
4	Unknown/Unexpected Field Condition	4
5	Correction of Work Due to Design Error	5

*4.3.4 Stakeholders responsibility distribution **[previous work]***

Table 4.3 shows the responsibility distribution validation, developed by Nguyen et al. (2024). The results indicate that the project management and procurement teams are more responsible for the risk of FCOs due to Project Schedule Constraints and Business Operating Hours. The Design/Planning, Civil, and Field Engineering teams are more responsible for the risk of FCOs due to Accommodating Current Existing Field Conditions, Unknown/Unexpected Field Conditions, and Correction of Work Due to Design Error. This information will be used later to map the responsibility of each stakeholder to each type of risk of FCO accordingly.

Table 4.3 Responsibility distribution validation

Responsibility Distribution Validation	**Design/Planning Team Normalized Weight Vector**	**Civil Team Normalized Weight Vector**	**Field Engineering Team Normalized Weight Vector**	**Project Management Team Normalized Weight Vector**	**Procurement Team Normalized Weight Vector**	**Average Normalized Weight Vector**	**Average Normalized Weight Vector Rank [A1]**	**Combined Severity of Frequency & Magnitude Rank [A2]**	**Variance [A1 - A2]**	**Satisfaction**
Accommodate Current Existing Field Condition	0.60	0.56	0.55	0.10	0.13	0.39	1	1	0	✓
Project Schedule Constraint	0.06	0.11	0.15	0.52	0.27	0.22	2	2	0	✓
Business Operating Hours	0.04	0.07	0.05	0.28	0.51	0.19	3	3	0	✓
Unknown / Unexpected Field Condition	0.20	0.23	0.22	0.03	0.05	0.15	4	4	0	✓
Correction of Work Due to Design Error	0.10	0.04	0.04	0.07	0.03	0.05	5	5	0	✓
Total	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**				

4.3.5 Phases and tasks of FEP in the project life cycle

Of the many approaches to FEP, this study followed the model identified by the Construction Industry Institute (CII, 1995) with added tasks proposed by Hansen et al. (2018). The detail of each phase in the FEP is described in Table 4.4 as follows:

Table 4.4 Front-end planning phases and activities

Phase	**Description**
Phase 1: Organize for pre-project planning/ Prefeasibility	• Project initiation • Analyzing the current situation in construction sector and its environment and assessing needs
Phase 2: Select project alternative option(s)/ Feasibility	• Organizing project team • Analyzing current technologies and sites • Prepare conceptual scopes • Evaluate project options
Phase 3: Develop a project definition package/Concept and detailed scope	• Initial development of project scopes and design • Develop project execution approach, control guidelines, and project definition package
Phase 4: Decision Making	• Making decision whether to proceed with to invest in the project or not, approving project execution plans

To accommodate underground projects, more tasks were added, primarily to assess whether confidence in reducing FCO risk is high enough to proceed with the final design in phase four (shown as Task 2 in Phase 4). As a result of these changes, the proposed tasks and phases are presented in Table 4.5.

Table 4.5 Four phases and tasks of FEP in the project life cycle

Phase ->	**1. Organize for pre-project planning/Prefeasibility**	**2. Select project alternative option(s)/Feasibility**	**3. Develop a project definition package/Concept and detailed scope**	**4. Perform FCO Evaluation and decide whether to proceed with final design**
Task 1	Project initiation and jobsite visit (CII 1995, Hansen et al. 2018, and this study).	Analyzing existing technology (CII, 1995 and this Study)	Document project scope and design (CII, 1995 and this study)	Perform risk of FCOs voting (This study)
Task 2	Analyzing the current situation in construction sector and its environment and assessing needs (Hansen et al. 2018, and this study).	Local government regulations and requirements (This study)	Analyzing risk FCOs due to (1) accommodate current existing field condition and (2) unknown/unexpected field condition (This study)	**Make decision (CII, 1995 and this study)** A1. Not meet confidence level: Return to tasks 3 and 4 of phase 1; and tasks 2 and 3 of phase 3 A2. Meet confidence level: Authorize to start final design process
Task 3	Analyzing risk of FCOs due to constraints on daytime traffic congestion and operations of public offices, businesses, or schools during business hours. (This study)	Field condition evaluation and analysis (CII, 1995 and this study)	Analyzing risk FCOs due to design error (This study)	
Task 4	Analyzing risk of FCOs due to project schedule constraint. (This study)	Underground Soil Boring Test (This study)	Define project execution and approach (CII, 1995 and this study)	
Task 5	Prepare pre-project planning plan (CII, 1995 and this study)	Prepare conceptual scopes and estimates (CII, 1995 and this study)	Establish project control guidelines (CII, 1995 and this study)	
Task 6	Complete phase 1 milestone	Evaluate alternative option(s) (CII, 1995 and this study)	Compile project definition package (CII, 1995 and this study)	
Task 7		Complete phase 2 milestone	Complete phase 3 milestone	

4.3.6 Critical path method (CPM)

The critical path method (CPM) was developed in the late 1950s by James Kelley and Morgan Walker. It is a vital project management tool that represents the logical sequence of tasks that must be accomplished to ensure the completion of the entire project timely. The critical path is the longest path through a project, which determines the shortest possible duration and any delay in completing tasks on the critical path will delay the overall project completion (Wang et al., 2015, Kumar et al., 2016, Atin et al., 2019, Institute Project Management, 2022).

The CPM is widely used in the architecture, engineering, and construction industry, among others. For instance, Atin et al. (2019) concluded that the critical path was an effective tool to monitor and determine the project completion period. Another example of applying the critical path can be found in the healthcare industry by Kumar et al. (2016) in which they applied the CPM in the management and coordination of the research activities for the clinical trial project, determining which activities can lead to the project delay. They also concluded that the project is effectively monitored, and realistic schedules can be maintained with the CPM. Additionally, Wang et al. (2021) conducted a study on a lesson learned for the Burn Mass Casualty Incidents in Taiwan using CPM, the authors concluded that the emergency response would be effectively and timely with the logical interrelations of every activity through the CPM network diagram.

4.3.7 Swimlane diagrams and roadmap processes in construction projects

An early variation of the flow process charts was known in the 1940s. The flow process charts were called Swimlane diagrams by Geary Rummler and Alan Brache in their book Improving Processes in 1990. Swimlane diagrams are also known as cross-functional maps, are used to show who does what in a process. Swimlane diagrams help stakeholders understand workflows and how they relate to and interact with other management processes (Waterhouse, 2015 and 2021, SixSigma, 2021, Mckendrick, 2023, and Lucidchart, 2023).

Process mapping consists of a collection of tools and methods used to improve the collaborative understanding of an organization and its processes. Those tools allow project team to document, analyze, improve, streamline and redesign business processes to enhance organizational efficiencies (Halseth, 2008, Anjard, 1998, Hussain et al., 2017, Hijazi et al., 2018., California Department of Transportation, 2020, Imran et al., 2022, and Zacharias, 2023).

To solve the conveying of the information issue between the stakeholders in the submittal process of a mixed-use design-bid-build construction project in Southern California, Pestana et al. (2012) conducted a study on the mapping process and developed the Swimlane diagrams to show the interactions between different project participants in the submittal process. They found that the submittal activities with the mapping process in place could improve the communication and workflow for decision-making between the stakeholders. They concluded that close collaboration between parties results in faster review and approval cycles with a mapping process.

Pakdaman et al. (2019) conducted a study on developing a roadmap for the project management framework and processes. The authors reported that the roadmap is an important tool allowing organizations to keep track of project management milestones on a timeline. The roadmap can help organizations ensure that project management processes are aligned with business environments and succeed in portfolio portfolios.

In addition, Jazzar et al. (2020) studied a roadmap to shaping the future of construction. The authors indicated the need of integration throughout the project lifecycle in a roadmap. They proposed an integration and connectivity with one another in a roadmap to meet with the increase in complexity and sophistication of construction projects.

Salem et al. (2021) to further analyze the process mapping of stakeholders in transportation safety management. To solve the complexity of the work processes in the California Department of Transportation, the authors developed different process mapping levels for the transportation safety management, including relationship maps, cross-functional maps using swim lane diagram, and flowchart maps. The author reported that the process mapping with Swimlane diagrams could improve on the communication, roles and responsibilities, and relationships between entities of the state transportation agencies.

Budayan et al. (2022) conducted a study about the roadmap for the implementation of total quality management (TQM) in ISO (International Organization for Standardization) 9001-certified construction companies: Evidence from Turkey. They reported that the management needs a roadmap that they can follow to prioritize their tasks. The roadmap highlights which key areas of the organization should be improved to effectively implement total quality management (TQM).

4.3.8 Conclusions about the literature review

The previous studies indicate the important of the CPM and roadmap process in the professional practices where it could improve the collaboration and workflow for decision-making between the stakeholders. Especially, Swimlane diagram is an effective tool to enhance the visualization of cross-functional tasks and phases in the process mapping model. Despite studies that show how important of the CPM and roadmap process can help the project team to reduce the project risk management and maximize the project performance outcome, it is still lacking of studies on the FEP quality control roadmap process to resolve the risk of FCOs. Therefore, a more comprehensive study is needed to capture the risk of FCOs through a FEP quality control roadmap process, especially for the underground electrical construction projects at utility companies where a very limitation of studies has been conducted.

4.4 Research Methodology

4.4.1 Framework and methods for data collection and analysis

The framework for the proposed quality control roadmap for FEP process is illustrated by Figure 4.1. The sequence begins with the identification of the FEP stakeholders of the utility using the process. The four phases and tasks identified earlier (Table 4.5) are used to control the process (Box 5 in Figure 4.1). A Swimlane flow diagram is created to map the logical relationships among stakeholders, and scheduling software is used to show the process sequence as a roadmap model. The process includes an FEP quality control evaluation task for stakeholders to assess when the risk of FCOs is low enough to proceed with the final design.

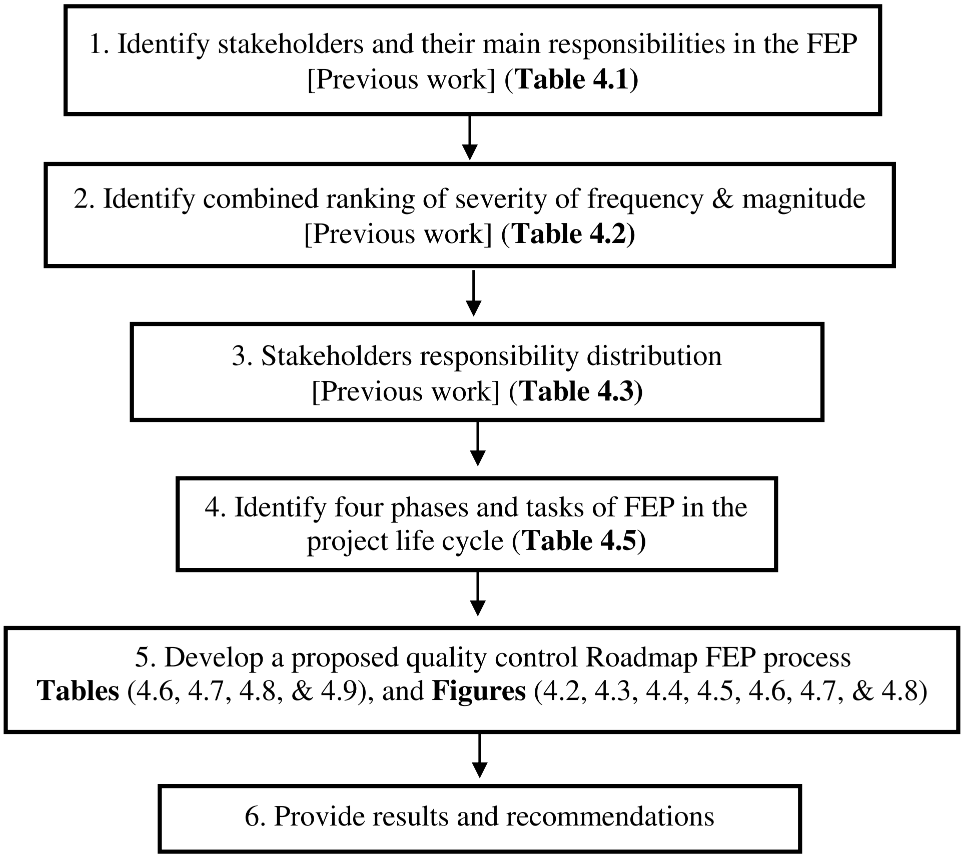


Figure 4.1 Proposed process for quality control roadmap FEP process

The activities in boxes 1-3 in Figure 4.1 were explained in the previous work (Nguyen et al., 2023, and 2024 (in review)), and the four phases and tasks were discussed just above. For Box 5, the process is described next.

4.4.2 Develop a proposed quality control roadmap for FEP process

The process has three steps that will be applied during all four phases of the FEP.

Step 1 is to map tasks to stakeholder responsibilities.

Step 2 is to develop a logical relationship between the tasks and analyze the critical path of the four phases in FEP.

Step 3 is to develop the Swimlane quality control roadmap for FEP process.

***Step 1**. Mapping tasks to stakeholder responsibilities*

In this step, the process tasks are mapped to stakeholder responsibilities to ensure the risks of FCOs are considered early in FEP. Some tasks involve shared responsibilities to enhance collaboration. This study classifies the project stakeholders into two groups: Project Engineering and Project Management. The stakeholder groups will vary from one utility to another. For the demonstration in the next section, the stakeholder groups are shown for the case study utility.

Table 4.5 showed the tasks to be completed for the four phases of the quality control roadmap for FEP process. Table 4.6 is an example of phase 1 mapping. Some of the FCO types from the case study that will presented later are included to demonstrate details of the tasks.

Table 4.6 Sample of mapping tasks to stakeholder responsibilities

Phase ->	**1. Organize for pre-project planning/Prefeasibility**
Task 1	Project initiation and jobsite visit.
Task 2	Analyzing current situation.
Task 3	Analyzing risk of selected FCOs due to daily traffic congestion and business operating hours.
Task 4	Analyzing risk of selected FCOs due to additional premium time/cost for the contractor to meet project schedule constraint.
Task 5	Prepare pre-project plan.
Task 6	Complete phase 1 milestone.
Team Task Mapping	
1. Project engineering stakeholder(s)	Tasks (1, 2, 5)
2. Project management stakeholder(s)	Tasks (1, 2, 3, 4, 6)
3. Both project engineering and management stakeholders	Tasks (1, 2)

Step 2. *Develop logical relationships between the tasks in each phase, and analyze the critical path of the four phases in FEP*

The tasks must follow a logical critical path to obtain an effective process mapping model. This study used four logical relationships to develop the roadmap path for each phase before proceeding with the final design [Start to Start (SS), Finish to Start (FS), Finish to Finish (FF), and Start to Finish (SF) relationships]. Figure 4.2 shows an example of the logical relationship between the tasks within phase 1 of the FEP roadmap model. Some tasks show FCO categories of the case utility to provide examples.

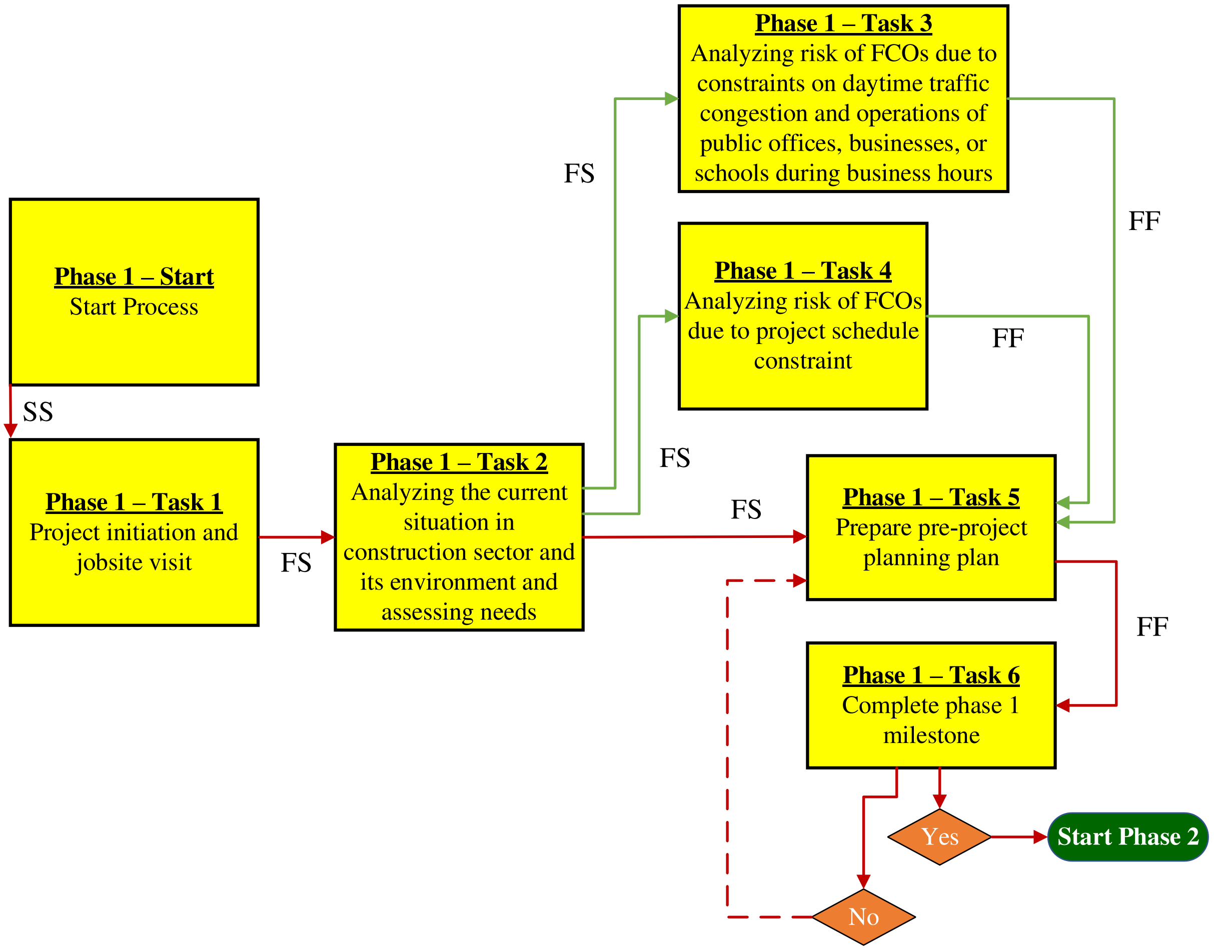


Figure 4.2 Proposed logical path of phase 1 in the FEP roadmap process

The logical sequence shown for Phase 1 (*Organize for pre-project planning /Prefeasibility)* begins with the box shown as "Start." Then, there is an SS relationship between "Start" and Task 1. After the jobsite visit during Task 1, Task 2 can begin, and the two tasks have a FS relationship. Tasks 3, 4, and 5 also have a FS relationship with Task 2. Especially, to be sure all the risks of FCOs from Tasks 3 and 4 are being evaluated, Task 5 requires the completion of these tasks before it can be completed with the FF relationship with Tasks 3 and 4. Task 6 is the completion milestone of phase 1 and have FF relationship with Task 5.

This study judges that it takes a longer duration to perform Task 5 than Tasks 3 and 4. Using the logical sequences, Figure 4.2 shows that the critical path of this phase is from the **Start**

Process to **Task 1** to **Task 2** to **Task 5** to **Task 6** and to **Start Phase 2** because this is the longest path to complete all the tasks in phase 1. In the case that Task 5 has the same or less duration than Tasks 3 and 4, then Tasks 3 and 4 become the critical tasks, and all the Tasks in phase 1 are on the critical path.

***Step 3**. Develop a proposed Swimlane quality control roadmap for FEP process*

The results from steps 1 and 2 are used to link the tasks in each phase to the stakeholder responsibilities to create the roadmap model. The critical path shows the logical sequence of tasks and the completion milestones.

4.5 Quality Control Roadmap for FEP Process: Results, Demonstration, and Primavera (P6)

The results are discussed in sections 4.1, 4.2, and 4.3. The demonstration of the proposed quality control FEP roadmap and the application of Primavera scheduling software (P6) in the logical roadmap model for FEP are discussed in sections 4.4 and 4.5, respectively.

*4.5.1 Mapping tasks to the stakeholder's responsibility (**Step 1**)*

Table 4.7 extends the task mapping that was explained in Table 4.5 for all four phases of the process mapping model. Collaborative working relationships are facilitated by distributing roles of the project engineering and project management stakeholders across all four phases. The project management stakeholders will evaluate the daytime traffic and business operation risks. The risks due to Accommodating Current Existing Field Conditions, Unknown/Unexpected Field Conditions, and Correction of Work Due to Design Error will be evaluated by the project engineering stakeholders.

Table 4.7 Four phases of the proposed logical process mapping

Phase ->	**1. Organize for pre-project planning/Prefeasibility**	**2. Select project alternative option(s)/Feasibility**	**3. Develop a project definition package/Concept and detailed scope**	**4. Perform FCO Evaluation and decide whether to proceed with the final design**
Team Task Mapping				
1. Project engineering stakeholder(s)	Tasks (1, 2, 5)	Tasks (1, 2, 3, 4, 5, 6)	Tasks (1, 2, 3, 4, 5, 6)	Tasks [1, 2A2, 2A1 (Tasks 2 and 3) of phase 3 if not meet the evaluation voting]
2. Project management stakeholder(s)	Tasks (1, 2, 3, 4, 6)	Task (7)	Tasks (7)	Tasks [1, 2A2, 2A1 (3 and 4) of phase 1 if not meet the evaluation voting]
3. Both project engineering and management stakeholders	Tasks (1,2)			Tasks [1, 2A2, 2A1 (Tasks 2 and 3) of phase 3 for project engineering and Tasks (3 and 4) of phase 1 if not meet the evaluation voting]

*4.5.2 Logical relationship between the tasks and analyze the critical path of the four phases in FEP (**Step 2**)*

The logical relationships between tasks for phase 1 were shown in Figure 4.2. The critical path of this phase is from the **Start Process** to **Task 1** to **Task 2** to **Task 5** to **Task 6** and to **Start Phase 2** because this is the longest path to complete all the tasks in phase 1. This path is to ensure all the tasks being performed and completed on time to assure the quality to avoid the risk of FCOs and delay to the FEP process.

*4.5.3 The proposed Swimlane quality control roadmap FEP process (**Step 3**)*

Figure 4.3 is the FEP Swimlane diagram to show the result of the proposed roadmap model from Figure 4.2 mapped onto the project engineering and project management stakeholders for

Phase 1. Tasks 3 and 4 are especially important during this phase as the FCO risks will be assessed. Similarly, tasks (2 and 3) are critical in phase 3.

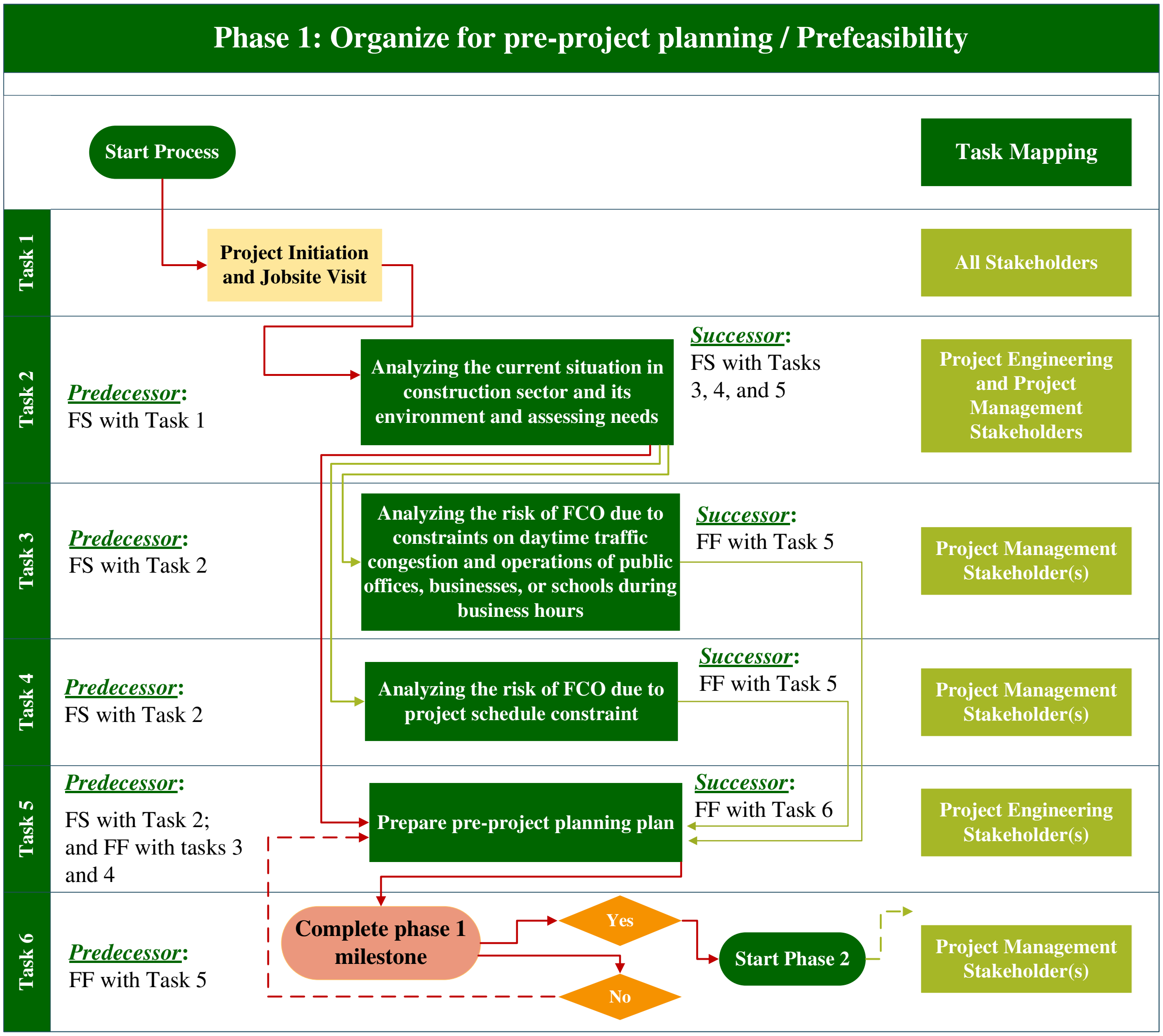


Figure 4.3 Proposed logical FEP Swimlane roadmap between the stakeholders and their tasks for phase 1

4.5.4 Demonstration of the roadmap with the relevant project data

To demonstrate how to use the quality control roadmap, this study used the findings of the eleven stakeholders (Table 4.1), the top five risks of FCOs (Table 4.2), the stakeholder's responsibility distribution (Table 4.3) from the previous work along with the steps (1 and 2) in section 3.2 of this study to form the proposed FEP roadmap model. The project engineering role is also distributed to design/planning, civil, and field Engineering stakeholders. Similarly, the project management role is distributed to project management, project management, pre-construction, procurement, pre-construction, contractor, permit, estimating, cost controls, estimating, scheduling, and cost control stakeholders.

Step 1'. *Mapping tasks to stakeholder responsibilities [**Demonstration**]*

Table 4.8 is the demonstration of the mapping tasks to stakeholder's responsibility for four phases as follows:

The task mapping for the top five stakeholders are distributed among the four phases. However, the other six stakeholders are mapped to the task 1 of phase 1 only as an early involvement to understand about the project when it reaches to the construction phase. They are not mapping to other steps in the further FEP process since their roles are not highly impacted in the FEP phase. Similar to the mapping tasks for phase 1, the mapping tasks for phases (2, 3, and 4) were also performed and results are shown in Table 4.8.

Table 4.8 Four phases of proposed logical process mapping

Phase ->	**1. Organize for pre-project planning/Prefeasibility**	**2. Select project alternative option(s)/Feasibility**	**3. Develop a project definition package/Concept and detailed scope**	**4. Perform FCO Evaluation and decide whether to proceed with the final design**
Team Task Mapping				
1. Design / Planning	Tasks (1, 2, 5)	Tasks (1, 2, 3, 4, 5, 6)	Tasks (1, 2, 3, 4, 5, 6)	Tasks [1, 2A2, (2 and 3) of phase 3 if not meet the evaluation voting]
2. Civil	Tasks (1, 2)	Tasks (2, 3, 4, 6)	Tasks (2, 3, 4)	Tasks [1, (2 and 3) of phase 3 if not meet the evaluation voting]
3. Field Engineering	Tasks (1, 2)	Tasks (2, 3, 4, 6)	Tasks (2, 3, 4)	Tasks [1, (2 and 3) of phase 3 if not meet the evaluation voting]
4. Project Management	Tasks (1, 2, 3, 4, 6)	Task (7)	Task (7)	Tasks [1, 2A2, (3 and 4) of phase 1 if not meet the evaluation voting)]
5. Procurement	Tasks (1, 2, 3, 4)			Tasks [1, (3 and 4) of phase 1 if not meet the evaluation voting]
6. Pre-Construction	Task (1)			
7. Contractor	Task (1)			
8. Permit	Task (1)			
9. Project Estimating	Task (1)			
10. Project Scheduling	Task (1)			
11. Project Cost Control	Task (1)			

***Step 3'**. Develop a proposed quality control roadmap FEP process [**Demonstration**]*

The demonstration of logical FEP Swimlane roadmap for phase 1 was shown in Figure 4.4, which is identical with Figure 4.3, in which the project engineering and project management roles are distributed to their associated stakeholders. The demonstration of logical FEP Swimlane roadmap of phases (2, 3, 4) were shown in Figures (4.5, 4.6, 4.7), respectively.

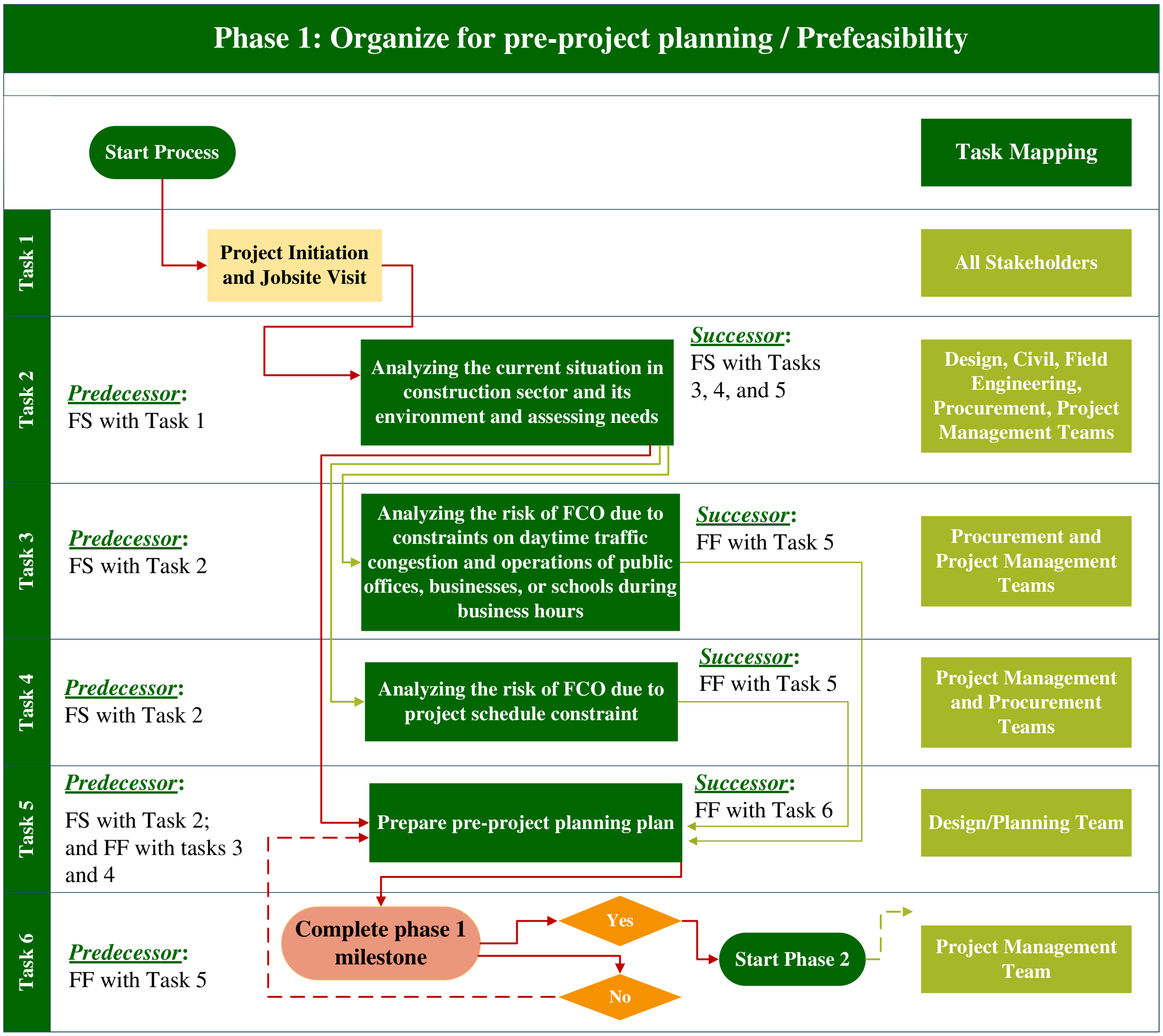


Figure 4.4 Demonstration of proposed logical FEP Swimlane roadmap between the stakeholders and their tasks for phase 1

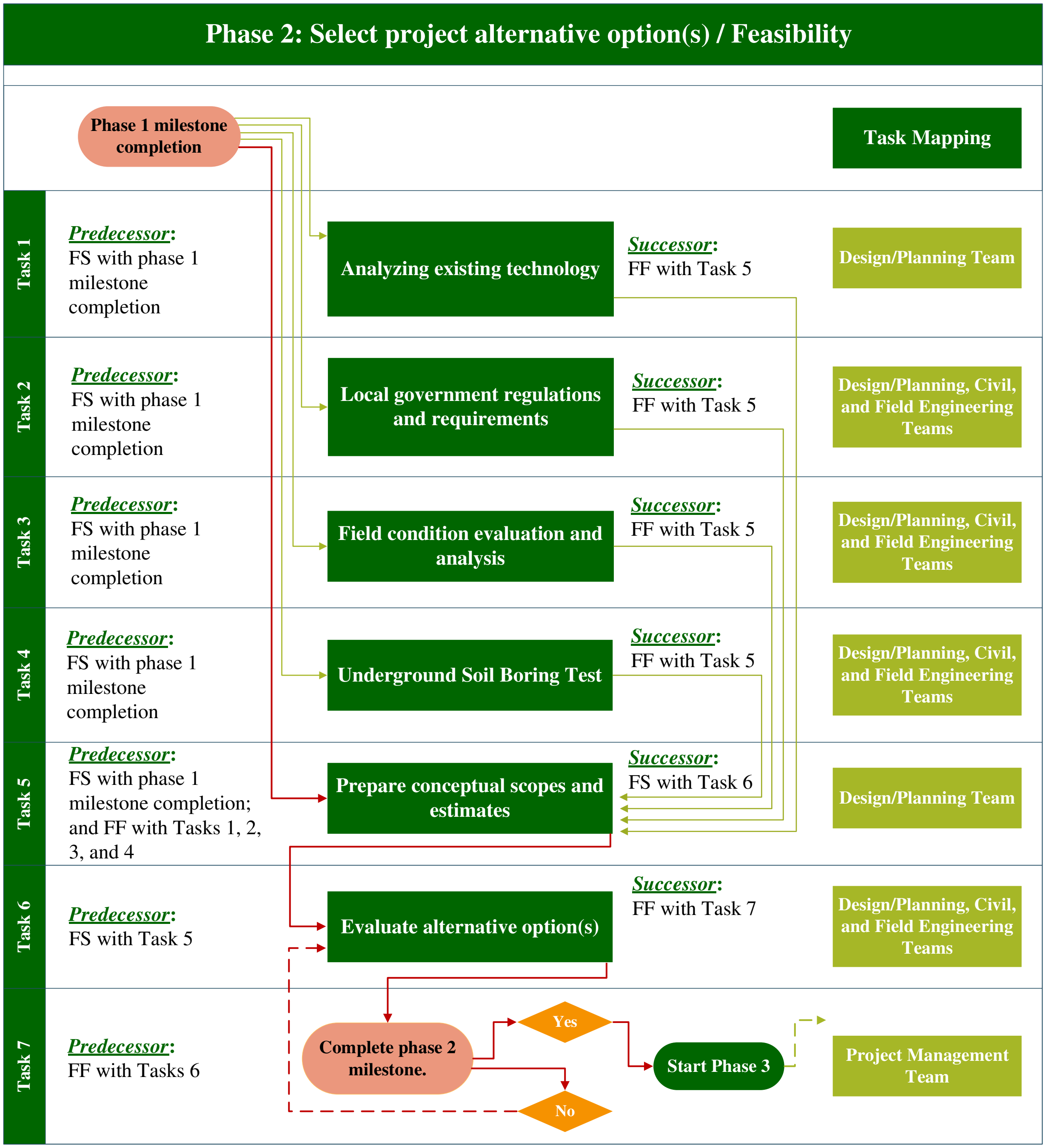


Figure 4.5 Demonstration of proposed logical FEP Swimlane roadmap between the stakeholders and their tasks for phase 2

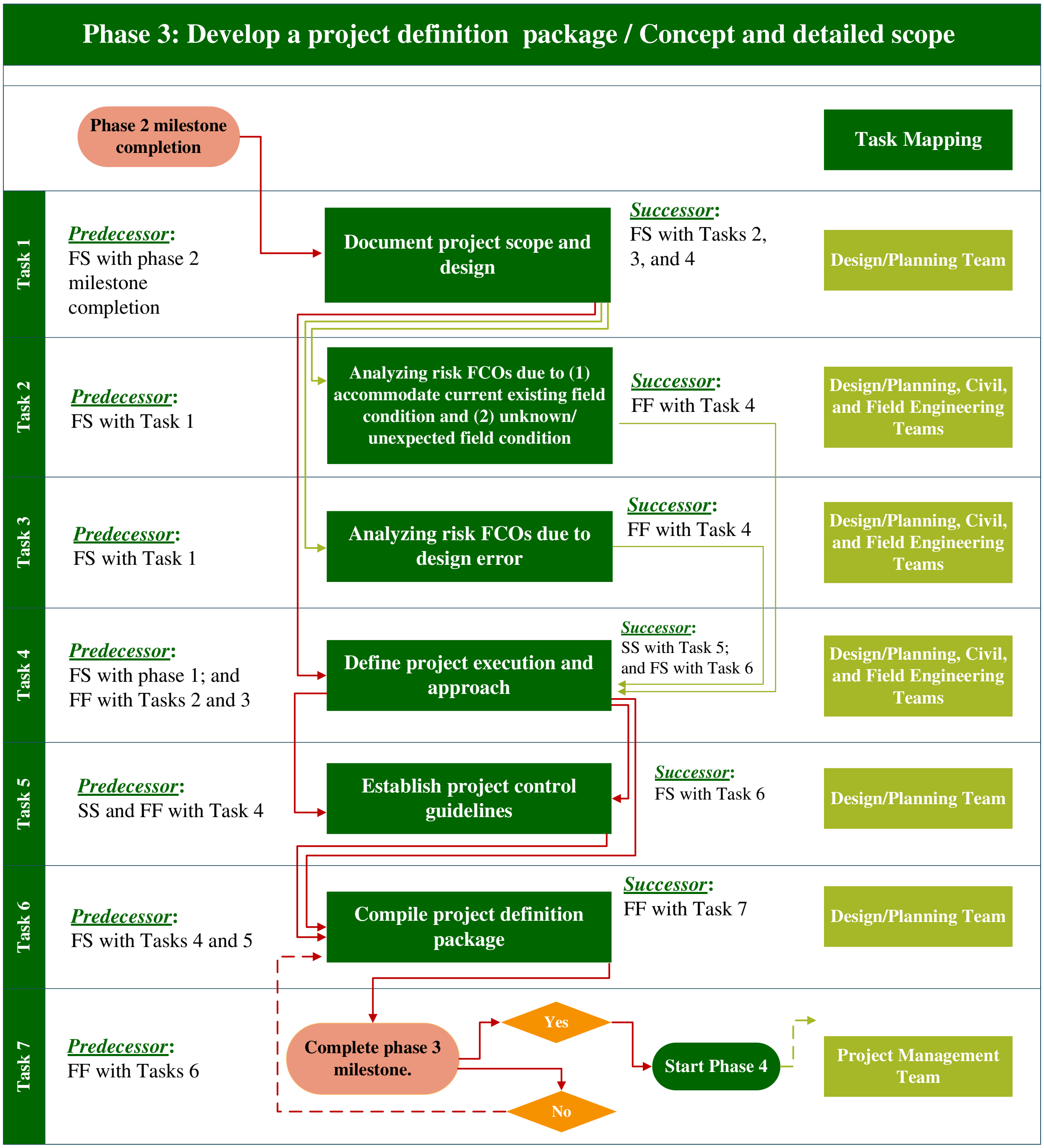


Figure 4.6 Demonstration of proposed logical FEP Swimlane roadmap between the stakeholders and their tasks for phase 3

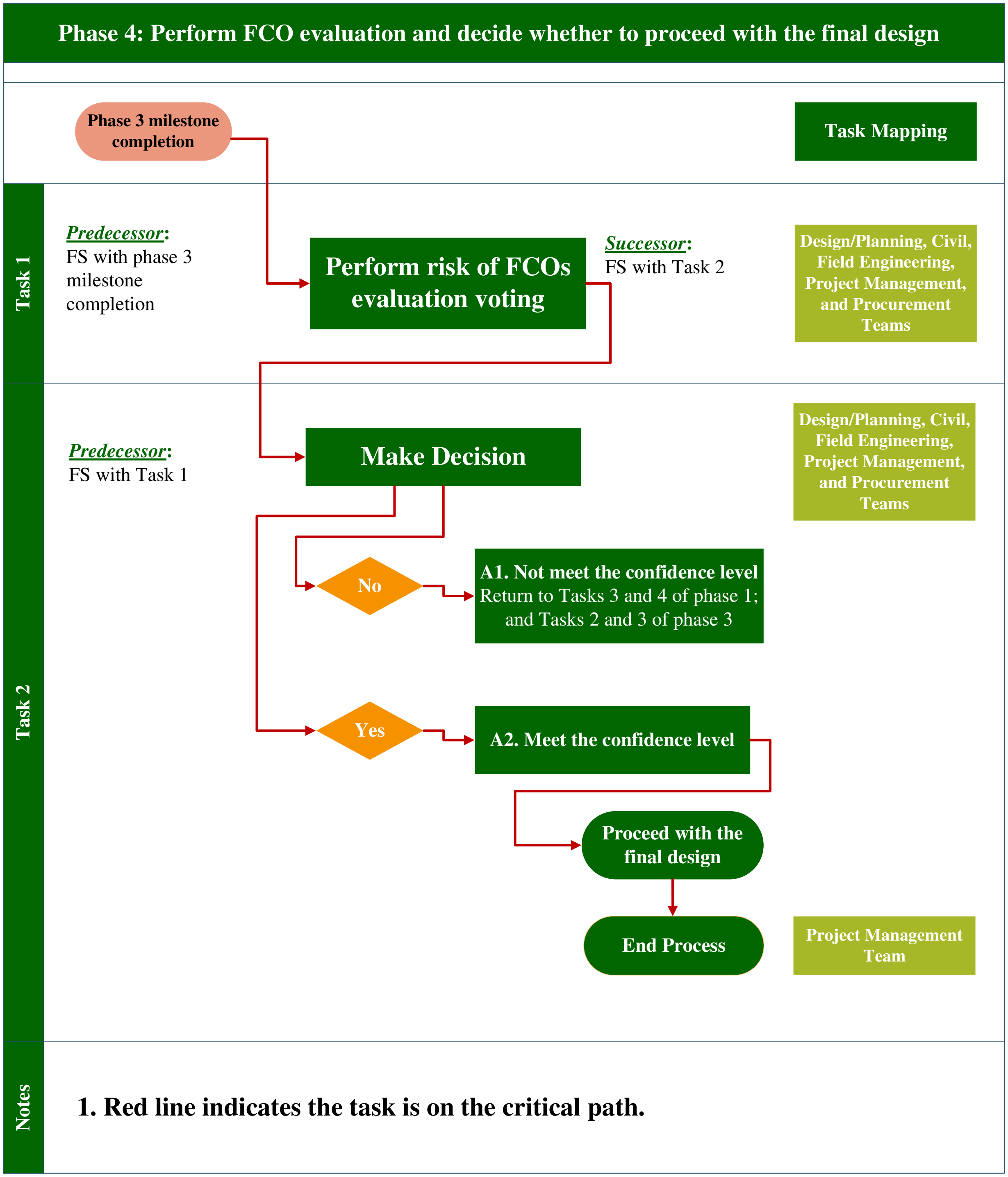


Figure 4.7 Demonstration of proposed logical FEP Swimlane roadmap between the stakeholders and their tasks for phase 4

Note that this study made the following judgements: (1) Phase 1: Task 5 has a longer duration than Tasks 3 and 4 since it is a main and critical task of this phase, (2) Phase 2: Task 5 has a longer duration than Tasks 1, 2, 3, and 4 since it is one of the main and critical tasks of this phase; 3. Phase 3: Task 4 has a longer duration than Tasks 2 and 3 since it is one of the main and critical tasks of this phase. Using the logical sequences, the critical path of the entire proposed quality control roadmap for FEP process is summarized in Table 4.9 as follows:

Table 4.9 The critical path of 4 phases

Phase 1	***Start Process*** *to* ***Task 1*** *to* ***Task 2*** *to* ***Task 5*** *to* ***Task 6*** *and to* ***Start Phase 2.***
Phase 2	***Phase 1 milestone completion*** *to* ***Task 5*** *to* ***Task 6*** *to* ***Task 7*** *and to* ***Start Phase 3****.*
Phase 3	***Phase 2 milestone completion*** *to* ***Task 1*** *to* ***Tasks*** *(4 and 5) to* ***Task 6*** *to* ***Task 7*** *and to* ***Start Phase 3.***
Phase 4	***Phase 3 milestone completion*** *to* ***Task 1*** *to* ***Task 2*** *to* ***Proceed with final design*** *and to* ***End Process***

If both Tasks 5 in phases (1 and 2) and Task 4 in phase 3 have the same or less durations than their identified comparison Tasks as judged earlier, then all the Tasks in the proposed quality control roadmap of FEP process are on the critical path.

*4.5.5 Application of Primavera Scheduling Software (P6) in the logical roadmap model for FEP **[Demonstration]***

The two typical scheduling software that can address the logical relationship between the tasks are Primavera (P6) and Microsoft Project. The software chosen is Primavera (P6), to address the logical relationship between the tasks in this study. The proposed roadmap model has four phases, and durations are assigned. To demonstrate, the durations chosen for this study are six months in total, with phases 1-4 having durations of 20, 30, 60, and 10 workdays, respectively (Table 4.10).

Table 4.10 Tasks, Predecessors and Relationships, and Durations

Phase	Task No.	Task Type	Predecessors and Relationships	Task Duration (workdays)
1 20 workdays	Start Process	Start milestone	--	0
	Task 1	Regular task	Start Process with SS	1
	Task 2	Regular task	Task 1 with FS	9
	Task 3	Regular task	Task 2 with FS	5
	Task 4	Regular task	Task 2 with FS	5
	Task 5	Regular task	Task 2 with FS, and Tasks (3 and 4) with FF	10
	Task 6	Finish milestone	Task 5 (FF)	0
2 30 workdays	Task 1	Regular task	Task 6 of Phase 1 with FS	5
	Task 2	Regular task	Task 6 of Phase 1 with FS	5
	Task 3	Regular task	Task 6 of Phase 1 with FS	5
	Task 4	Regular task	Task 6 of Phase 1 with FS	5
	Task 5	Regular task	Task 6 of Phase 1 with FS, and Tasks (1, 2, 3, and 4) with FF	15
	Task 6	Regular task	Task 5 of Phase 2 with FS	15
	Task 7	Finish milestone	Task 6 of Phase 2 with FF	0
3 60 workdays	Task 1	Regular task	Task 7 of Phase 2 with FS	20
	Task 2	Regular task	Task 1 of Phase 3 with FS	15
	Task 3	Regular task	Task 1 of Phase 3 with FS	15
	Task 4	Regular task	Task 1 of Phase 3 with FS, and Tasks (2 and 3) with FF	20
	Task 5	Regular task	Task 4 of Phase 3 with SS and FF	20
	Task 6	Regular task	Tasks (4 and 5) with FS	20
	Task 7	Finish milestone	Task 6 of Phase 3 with FF	0
4 10 workdays	Task 1	Regular task	Task 7 of Phase 3 with FS	10
	Task 2	Finish milestone	Task 1 of Phase 4 with FS	0
	Task 2. A1	Start milestone	Task 2 of Phase 4 with FS	0
	Task 2. A2	Finish milestone	Task 2 of Phase 4 with FS	0
	End Process	Finish milestone	Task 2. A2 with FF	0

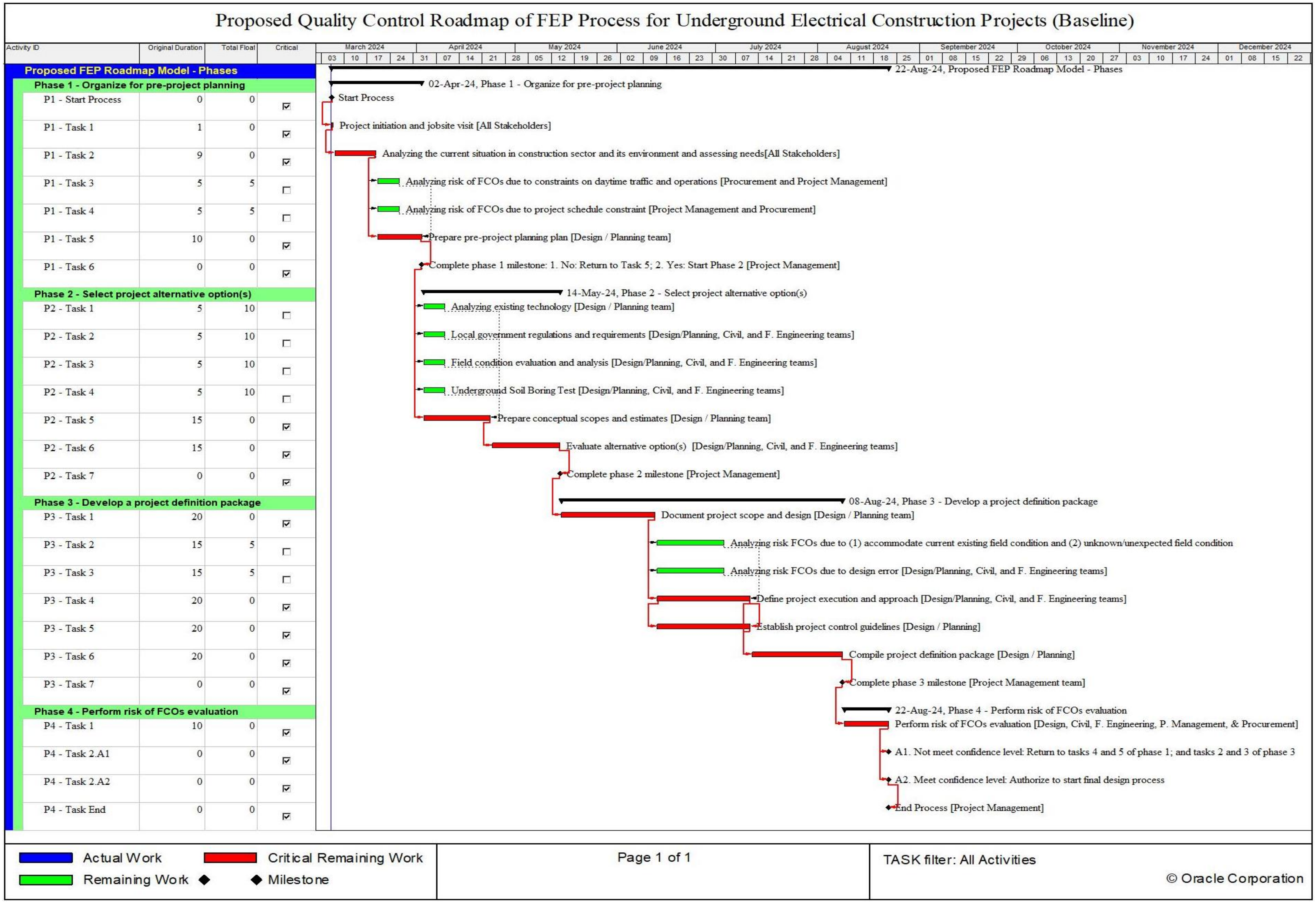
Figure 4.8 shows the logical sequence between the tasks in each phase of the proposed quality control FEP roadmap model. The critical path of Primavera (P6) program is identical to the critical path that this study analyzed in the previous section for the model. Using the software and the relationships show that FEP can be coordinated to minimize the risk of FCOs. The five

identified risk of FCOs should be evaluated and recognized by the assigned stakeholders through phases (1, 2, and 3) before performing the risk of FCOs evaluation voting in phase 4.

Additionally, the software can help to identify any delays or unfinished tasks from assigned stakeholders through the critical path evaluation that enable the project team to take corrective actions early in the process to minimize the negative impact to the process model.

The proposed logical sequence between the tasks in each phase of the proposed quality control FEP roadmap model is the baseline of overall process. The status of overall process can be updated biweekly by the project team to monitor and report on the progress of the process. The total float availability of critical or non-critical task indicates the maximum amount of workdays that its task can be delay without impact to the overall quality control roadmap of FEP process. The critical task has zero float, if there is a delay it will directly impact to the overall FEP process. The non-critical task has a float greater than zero, if the delay exceeds its total float availability, the non-critical task will become a critical task and it consequently causes the delay to the entire quality control roadmap of FEP process.

The logical relationship is a practical illustration for team collaboration. The assigned stakeholders can effectively visualize the process, work together proactively on their own, and share tasks with the project team to meet the goals.



Proposed Quality Control Roadmap of FEP Process for Underground Electrical Construction Projects (Baseline)

Activity ID	Original Duration	Total Float	Critical
Proposed FEP Roadmap Model - Phases			
Phase 1 - Organize for pre-project planning			
P1 - Start Process	0	0	☑
P1 - Task 1	1	0	☑
P1 - Task 2	9	0	☑
P1 - Task 3	5	5	☐
P1 - Task 4	5	5	☐
P1 - Task 5	10	0	☑
P1 - Task 6	0	0	☑
Phase 2 - Select project alternative option(s)			
P2 - Task 1	5	10	☐
P2 - Task 2	5	10	☐
P2 - Task 3	5	10	☐
P2 - Task 4	5	10	☐
P2 - Task 5	15	0	☑
P2 - Task 6	15	0	☑
P2 - Task 7	0	0	☑
Phase 3 - Develop a project definition package			
P3 - Task 1	20	0	☑
P3 - Task 2	15	5	☐
P3 - Task 3	15	5	☐
P3 - Task 4	20	0	☑
P3 - Task 5	20	0	☑
P3 - Task 6	20	0	☑
P3 - Task 7	0	0	☑
Phase 4 - Perform risk of FCOs evaluation			
P4 - Task 1	10	0	☑
P4 - Task 2.A1	0	0	☑
P4 - Task 2.A2	0	0	☑
P4 - Task End	0	0	☑

22-Aug-24, Proposed FEP Roadmap Model - Phases

02-Apr-24, Phase 1 - Organize for pre-project planning

Start Process

Project initiation and jobsite visit [All Stakeholders]

Analyzing the current situation in construction sector and its environment and assessing needs[All Stakeholders]

Analyzing risk of FCOs due to constraints on daytime traffic and operations [Procurement and Project Management]

Analyzing risk of FCOs due to project schedule constraint [Project Management and Procurement]

Prepare pre-project planning plan [Design / Planning team]

Complete phase 1 milestone: 1. No: Return to Task 5; 2. Yes: Start Phase 2 [Project Management]

14-May-24, Phase 2 - Select project alternative option(s)

Analyzing existing technology [Design / Planning team]

Local government regulations and requirements [Design/Planning, Civil, and F. Engineering teams]

Field condition evaluation and analysis [Design/Planning, Civil, and F. Engineering teams]

Underground Soil Boring Test [Design/Planning, Civil, and F. Engineering teams]

Prepare conceptual scopes and estimates [Design / Planning team]

Evaluate alternative option(s) [Design/Planning, Civil, and F. Engineering teams]

Complete phase 2 milestone [Project Management]

08-Aug-24, Phase 3 - Develop a project definition package

Document project scope and design [Design / Planning team]

Analyzing risk FCOs due to (1) accommodate current existing field condition and (2) unknown/unexpected field condition

Analyzing risk FCOs due to design error [Design/Planning, Civil, and F. Engineering teams]

Define project execution and approach [Design/Planning, Civil, and F. Engineering teams]

Establish project control guidelines [Design / Planning]

Compile project definition package [Design / Planning]

Complete phase 3 milestone [Project Management team]

22-Aug-24, Phase 4 - Perform risk of FCOs evaluation

Perform risk of FCOs evaluation [Design, Civil, F. Engineering, P. Management, & Procurement]

A1. Not meet confidence level: Return to tasks 4 and 5 of phase 1; and tasks 2 and 3 of phase 3

A2. Meet confidence level: Authorize to start final design process

End Process [Project Management]

🟦 Actual Work
🟥 Critical Remaining Work
🟩 Remaining Work ◆
◆ Milestone

Page 1 of 1

TASK filter: All Activities

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Figure 4.8 Demonstration of proposed quality control roadmap for FEP process in Primavera

4.6 Discussion of the proposed quality control FEP roadmap and a project case study

The novelty of this study is the development of a comprehensive quality control approach for FEP based on Systems Engineering. While there have been efforts to improve the design process, this study is the first one known to the researcher to address quality control of FEP using the roadmap process. The approach involves three steps: (1) defining the FCOs, (2) evaluating their root causes, (3) and finding solutions. For step 1, the top five causes of FCOs were identified in a previous phase of the research and described in section 2.3 of the paper. The previous study indicated that most FCOs can be recognized in an FEP process, and it laid the foundation for the next phase, to promote collaboration among stakeholders, and identify issues and solutions early on in the project lifecycle. Step 2 continued the work of step 1 and distributed the weights of stakeholder votes based on responsibilities for each category of FCOs using the Analytical Hierarchy Process (AHP) methodologies. This was described in section 2.4. For step 3, this study proposed a comprehensive solution through the FEP roadmap model to integrate work from steps 1 and 2 into a map of logical relationships and tasks involving the stakeholders and their responsibilities for the risk of FCOs.

The proposed quality control roadmap model can show a transparent and streamlined process for decision-making in each phase of the FEP process. It includes effective collaboration between stakeholders aligned with the FEP timelines and milestones. The roadmap model shows an integrated planning and design process to reduce repeated work and risk of FCOs through a logical path prior to the final design (Halseth, 2008, Anjard, 1998, Hussain et al., 2017, Hijazi et al., 2018., California Department of Transportation, 2020, Wang et al., 2021, and Imran et al., 2022).

The proposed roadmap was tested by retroactively analyzing one project with high impacts of FCOs. The project involved expanding and upgrading existing old and low-voltage distribution circuits to higher load capacities to enhance reliability and safety to meet capacity demands. The project scope included rerouting duct bank conduits and installing underground cables, electrical devices, and underground civil structures. The project had six months of construction and testing.

The project had a forty-eight percent change in the cost, and the FCOs were due to Business Operating Hours, Project Schedule Constraints, Accommodate Current Existing Field Conditions, Unknown/Unexpected Field Conditions, and Correction of Work Due to Design Error. These high impacts of FCOs indicated that the project team had not done thorough preparation work prior to proceeding with the final design and awarding the construction contracts. If the project team performed the risk of FCOs evaluation as described in phase 4 of section 2.5, the score would be in a low confidence level range, which indicates that the project team would have a high risk level of FCOs in this project.

With the proposed quality logical FEP roadmap in this study, the Project Management and Procurement stakeholders should recognize the FCOs were due to Business Operating Hours and Project Schedule Constraint in phase 1. The FCOs were due to Accommodate Current Existing Field Condition, Unknown/Unexpected Field Condition, and Correction of Work Due to Design Error should be recognized by the design/planning, civil, and field engineering stakeholders in phase 3. This result indicated that the project team had done thorough preparation work prior to proceeding with the final design and awarding the construction contracts. If the project team performed the risk of FCOs evaluation as described in phase 4 of section 2.5, the score would be in a high confidence level range, which indicates that the project team would have a low risk level of FCOs in this project.

4.7 Conclusion and Future Directions

The significant of the work is found in its use of systems engineering methods and tools to develop the logical quality control FEP roadmap process that can enable the electric utility companies to assess the risk of FCOs before proceeding the final design. Due to technical complexity of the power industry construction projects, the utility companies face the number and severity of FCOs, especially the conversion from overhead to underground systems due to security and climate change factors, where the construction of the subgrade work is more challenging compare to the overhead work.

The proposed quality control FEP roadmap process for the underground electrical construction projects consist of four phases which the process tasks are mapped to stakeholder responsibilities to ensure the risks of FCOs are considered early in FEP. Some tasks involve shared responsibilities to enhance multidisciplinary collaboration in the project team. Especially, the tasks are connected through a logical sequencing in each phase to ensure the quality control in the roadmap process. The critical path in each phase and entire process were identified and analyzed that enable stakeholders can effectively visualize their own assigned tasks along with others to ensure the milestones are captured timely across process. The critical path was also illustrated by Primavera (P6) program.

The novelty of this study is the integration of project stakeholder’s responsibilities into a comprehensive quality control FEP roadmap process based on Systems Engineering, in which the project stakeholders participate to the entire quality process with the goal is to minimize the number and severity of FCOs. Additionally, the proposed logical FEP roadmap is intended to provide the electric utility companies a quality control process that the project team utilizes and decides when quality goal is reached such that the final design can begin.

For the project case study with high impacts of FCOs, the proposed logical quality control FEP roadmap in this study indicates that the Project Management and Procurement stakeholders should recognize the FCOs were due to Business Operating Hours and Project Schedule Constraint in phase 1. The FCOs were due to Accommodate Current Existing Field Condition, Unknown/Unexpected Field Condition, and Correction of Work Due to Design Error should be recognized by the design/planning, civil, and field engineering stakeholders in phase 3. If the project team performed the risk of FCOs evaluation as described in phase 4 of section 2.5, the score would be in a high confidence level range, which indicates that the project team would have a low risk level of FCOs in this project.

Overall, this study provides power industry practitioners with a quality control FEP roadmap process using the logical relationship sequences and the cross-functional Swimlane diagrams. Future research can focus on integration of the Primavera (P6) program and the System Modeling Language (SysML) into a roadmap process model, where Primavera (P6) and SysML are known for logical relationships and interfaces among stakeholders, respectively.

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CHAPTER 5

Conclusions, recommendations, and research needs

This chapter summarizes the findings and contributions of the research, and it presents the recommendations for professional practice, as well as a discussion of needs for future research.

5.1 Conclusions

If project teams recognize risks of FCOs during FEP rather than during construction, they will improve project quality, as well as save money and time. The critical path of the front-end planning (FEP) process for the quality control roadmap proposed here will enable them to recognize FCO risks by applying systems engineering methods to enhance the effectiveness of teamwork during FEP among stakeholders. The quality control process is based on three related studies, (1) defining FCO issues by identifying and analyzing their risks and root causes, (2) evaluating stakeholder responsibilities for the root causes of FCOs by distributing the weights of their votes for each category of FCOs to obtain an integrated metric of FEP team confidence, and (3) finding the solutions to address risks of FCOs through the quality control roadmap FEP model.

The first study showed that for the case study utility underground projects have higher risk of FCOs in both magnitude and frequency than overhead projects due to their invisible nature and requirements for more field investigations during planning and design. This finding is important because it provides signals to professional practitioners and academic researchers that such projects require additional work, as compared to overhead electrical projects. The study provided important findings about types of root causes of FCOs to help practitioners identify risks during FEP and it provides them with a comprehensive understanding about factors causing cost overruns, especially when electric utilities convert from overhead to underground systems due to security and climate change factors. The analysis also indicated that most root causes of FCOs can be managed during the front-end planning process, and it laid the foundation for the next phase, which aimed to promote collaborative working relationships among stakeholders to identify issues and solutions during FEP.

The second study set the stage for members of the FEP team to vote their confidence levels about risk control of FCOs before proceeding to final design. Analytical Hierarchy Process (AHP) methodologies were used to distribute responsibilities so that votes could be weighed during FEP according to responsibilities of stakeholders for reducing risks of FCOs. The roles and responsibilities of stakeholders are specified to enable the voting process to assess their confidence about when quality is high enough to minimize FCOs. This is an important step to support development of a quality control roadmap where risk of FCOs and essential tasks are mapped to stakeholder responsibilities through logical relationships in the roadmap model, in which the logical relationships between the tasks will be assigned through the roadmap process to ensure all the tasks being performed and completed on time to assure the quality to avoid the risk of FCOs and delay to the FEP process.

The third study was to develop a comprehensive quality control approach for FEP by using the results from studies 1 and 2. The proposed roadmap model consists of four phases. Project team stakeholders can perform assigned tasks and assess the risk of FCOs during the first three phases, and during the fourth phase the project team will vote on risk evaluation to decide if confidence in reducing change order risk is high enough to proceed with final design.

The proposed quality control roadmap model provides a transparent and streamlined process for decision-making in each phase of the FEP process. It includes effective collaboration between stakeholders aligned with the FEP timelines and milestones. The model shows an integrated planning and design process that will reduce repeated work and risk of FCOs through a logical path prior to the final design. A logical path includes both tasks are on and/or not on the critical path in the proposed quality control roadmap model process. The project team can monitor and evaluate the progress by updating the process schedule biweekly to see if there are any tasks being delay to take corrective actions early in the process to minimize the negative impact to the process model.

While there have been efforts to improve the design process, this study is the first one known to the researcher to use systems engineering methods to address the risk of FCOs through a proposed quality control roadmap of the FEP process. The roadmap model is innovative in that it provides an integrated planning and design process to reduce repeated work and the risk of FCOs through the logical path among tasks and stakeholders prior to final design. Additionally, the proposed quality control roadmap model can show a transparent and streamlined process for decision-making in each phase of the FEP process. It promotes and enables effective collaboration between stakeholders aligned with the FEP timelines and milestones. The findings and referenced solutions to the risk of FCOs from this study indicates that the FCO is the “symptom” and not a “norm”, and its impacts are can be reduced significantly by a well prepared initial planning and design process.

5.2. Contributions

The contributions of the three studies are considered to be:

- Development and demonstration of a method to use construction databases to identify causes and severities of FCOs.
- Demonstration of how to use the AHP methodology to distribute stakeholder responsibilities and attributes of change orders.

- Development of new methods to organize collaboration and coordinated work among project team members involved with planning and design.
- Demonstration of use of systems engineering tools to include project scheduling and system models to show logical relationships among tasks and stakeholders during FEP.
- Assembly of advanced methods into a methodology to test quality control by reducing risk of FCOs.
- Promoting the uses of systems engineering to enhance the effectiveness of interdisciplinary teamwork among stakeholders through a critical path of the front-end planning process.
- Providing new findings for the research literature of the electric power industry about change orders and their effects on underground electrical construction.
- Promoting the uses of the critical path method in the FEP roadmap to ensure the quality control that enable the project team to take corrective actions early in the process to minimize the negative impact to the process model.

Besides the above contributions to reduce the risk of FCOs, the studies point to another important concern to the construction industry about safety of this highly technical standard field. Especially, the fatigue of overtime work due to the FCOs which may impact the physical and psychological well-being of the construction workers, and they may lose safety awareness and have higher risk of accidents in the construction field. Thus, reducing the risk of FCOs will help the utility companies to save the costs due to the overtime and is an effective way for the construction project team to minimize the risk of construction accidents.

5.3 Future Research

The most immediate research need is for testing of the FEP method for projects in the electric power industry. A utility can receive training in the use of the method and conduct a test run on an underground project. Such a test would enable the utility to examine their construction database to ascertain if they are able to identify the frequency and severity of change orders of different types. Then, the utility can organize its stakeholders to examine the method and determine its feasibility or needed modifications. Research questions would include whether the AHP method is appropriate to distribute responsibilities and severities of FCOs and whether development of the critical path for the roadmap works well with the software they use. This study could help determine if the results of this work are transferable.

Future research can study projects with zero impact of FCOs to see how the project team performed on those projects during the FEP process. The findings can add the value to improve on the quality control roadmap. In addition, future studies can focus on how some FCOs affect accident rate in the construction utility workers. In particular, when construction workers perform FCO's tasks during overtime that may affect to their physical and psychological well-being, which may lead to the accidents on the jobsite.

This dataset of this study was based on the projects completed in 2016-2020. The study indicated the importance of the collaborative working relationship between the stakeholders during the FEP process. The lasting effects of the Covid-19 pandemic, which led industry practitioners to implement a remote or hybrid working model for FEP, may impact the effectiveness of communication and collaborative working relationships among stakeholders in the future. Future research should examine the severity of the frequency and magnitude of FCOs for projects where

FEP occurred during the pandemic to ascertain effects on FCOs. The results may indicate additional needed features in the quality control roadmap methods.

In terms of planning, other studies could include integrating the four logical relationships of (Start to Start, Finish to Start, Finish to Finish, and Finish to Start) from the scheduling program such as Primavera (P6) or Microsoft Project program into the System Modeling Language (SysML) to enhance the logical relationships and interfaces among stakeholders in the process, in which the project team enables to assesses the risks and take the corrective actions early to ensure the quality control through the logical sequences along with the interactions between tasks and stakeholders in the network process.

Future research can also examine feasibility of the quality control roadmap for the FEP process in other industry sectors such as wastewater treatment plants, heavy civil works such as highways and airport, and refinery construction programs. This type of roadmap can integrate project activities linked to stakeholder responsibilities.

Appendix A - Application of the Analytic Hierarchy Process method

This appendix explains application of detailed judgements and computations used to apply the Analytical Hierarchy Process (AHP) method in chapter 3.

A.1 Overview of the AHP method

Before choosing the AHP method, this study assessed the Choosing by Advantages (CBA) method, which is a new generation multi-criteria decision-making method developed by Jim Suhr in 1999. Additionally, the 5-Point Likert's scale technique developed in 1932 by Rensis Likert, was also assessed to calculate the Relative Importance Index (RII) of stakeholder's responsibility and the rank of field change orders that each stakeholder be responsible for in the FEP process. However, these two methods are not applicable to the goals of this study because these methods not provide the tools to validate the effectiveness of the distribution in this study's goals. Moreover, this study involved with two levels of the distribution, the first level is the distribution of the weight of five stakeholder responsibility for overall FEP, and the second level is the distribution of the weight of each stakeholder's responsibility for each FCO category. Another important factor in this study is the distribution has to be effectively consisted with the combined severity of frequency and magnitude ranking. The AHP method provides the tool to calculate the consistency ratio to ensure the distribution is acceptable. Due to this complexity of the distribution in this study, the AHP method was chosen and this study followed the validation steps to ensure the all distributions meet with the AHP requirements to ensure the quality of the proposed FEP quality control model.

The AHP method applies a theory of measurement through pairwise comparisons and relies on the judgements of experts to derive priority scales as aids to decision-making. It has been used in many studies since its development by Saaty and Vargas (1980). The calculation for the pairwise comparisons is used to estimate the distribution of responsibility of FEP stakeholders, and the check for the consistency this distribution can be performed in both software programs and by spreadsheet analysis. While it is primarily a decision-making tool, it can also be used to rank factors according to their influence in other situations. For instance, other studies have used it for selection of best water supply sources, evaluating construction supply chain relationships, integrating supplier selection frameworks in a supply chain, and assessment of change order impact factors on construction project performance (Ihimekpen et al., 2017; Kim et al., 2017; Wang et al., 2017; Alshdiefat et al., 2018; and Gunduz et al. 2019).

A.2 How AHP was used in the paper

The AHP method was used in the paper as a part of a proposed front-end planning (FEP) quality control process that allows construction project teams to assess the confidence levels of risk perception for field change orders. The process is used involves collaborative working relationships across disciplines during the FEP process up to final design. The pairwise comparisons from the AHP method were used to distribute FEP responsibility among stakeholders (See Figure A-1, Step 3 / Section 3.2.3) and the weight of each stakeholder's responsibility for each FCO category (Step 4b / Section 3.2.4).

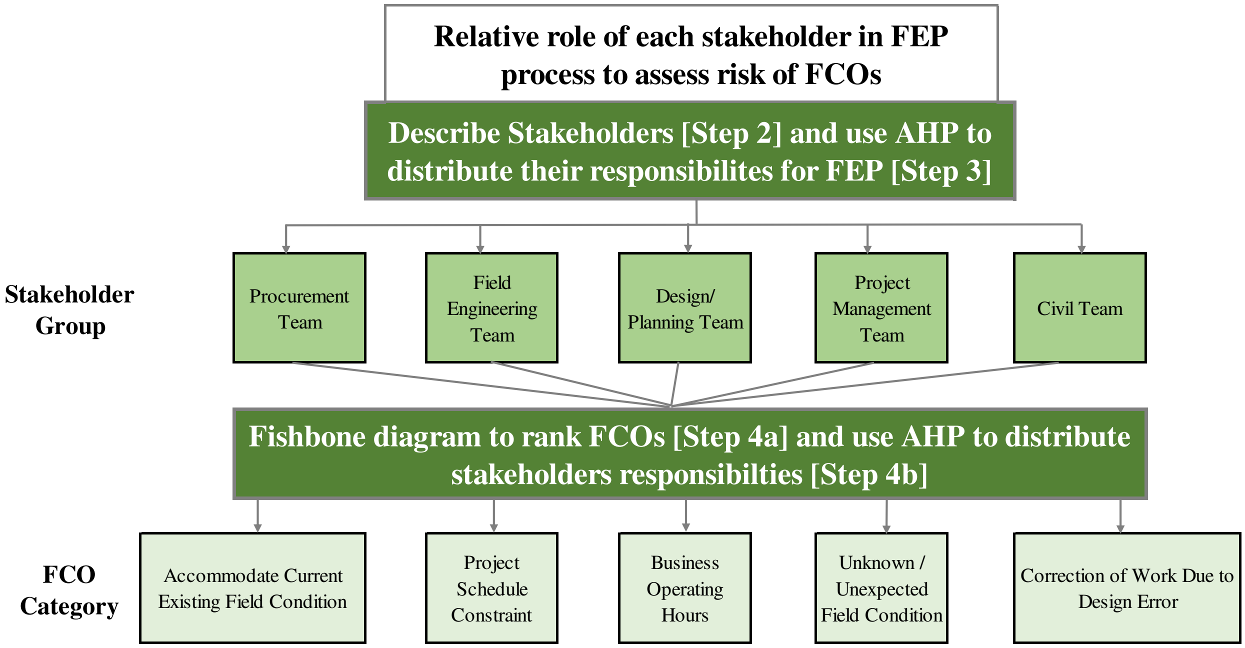


Figure A-1 Framework for overall AHP

A.3 The AHP intensity scale

Judgments in determine pairwise comparisons are based on application of the AHP Intensity Scale (Table A-1) that enables stakeholders or experts to rank factors according to relevant criteria. It uses the 1 to 9 scale in the ascending order where 1 is the lowest importance and 9 is the highest importance, which provide scales 1 to 9. The relative greater and lesser intensity of the AHP scale is summarized in Table A-1.

Table A-1 AHP Intensity Scale

AHP Intensity Scale			
Intensity Description	**Counting for higher or lesser Intensity**	**Relative Greater Intensity**	**Relative Lesser Intensity (Reciprocal)**
Equal Importance	**Equal to itself**	**1.00**	
Equal to Moderate Importance	2 times higher or lesser	2.00	0.50
Moderate Importance	3 times higher or lesser	3.00	0.33
Moderate to Strong Importance	4 times higher or lesser	4.00	0.25
Strong Importance	5 times higher or lesser	5.00	0.20
Strong to Very Strong Importance	6 times higher or lesser	6.00	0.17
Very Strong Importance	7 times higher or lesser	7.00	0.14
Very Strong Importance to Extreme Importance	8 times higher or lesser	8.00	0.13
Extreme Importance	9 times higher or lesser	9.00	0.11

Note: The relative greater important is based on the relative greater intensity scale column. The relative lesser important is based on the relative lesser relative intensity scale column (Reciprocal).

A.4 Use of the AHP Intensity Scale for FEP responsibility among stakeholders

For step 3, section 3.2.2, Table A-2 shows a sample pairwise comparison of the responsibilities of five stakeholders, which is identical with Table 3.3 in the main paper. The reasoning that follows is based on the expert opinion and AHP Intensity Scale in Table A-1:

Table A-2 Sample of pairwise comparison of the stakeholder responsibility for overall FEP

Stakeholders [Column 1]	Procurement Team [Column 2]	Project Management Team [Column 3]
Procurement Team	1.00	0.50
Project Management Team	2.00	1.00
Field Engineering Team	6.00	5.00
Civil Team	8.00	7.00
Design/Planning Team	9.00	8.00

Column 2 shows judgments about the relative importance of the five stakeholders.

a. Procurement team: the least importance among the five stakeholders in FEP, score of 1.
b. Project management team: equal to moderate importance as it coordinates with all stakeholders during the FEP, score of 2.
c. Field engineering team: strong to very strong importance for site investigation, score of 6.
d. Civil team: very strong importance to extreme importance as it studies site conditions and subgrade to ensure constructability, score of 8.
e. Design/planning team: the main team in FEP with extreme importance, score of 9.

To use this initial scaling to determine the distribution scores of the other stakeholders, a reference column is needed for the table. The Procurement team was selected as the reference column because it had the lowest score and facilitates using the AHP Intensity Scale to judge according to relative greater intensity.

The scores for the remaining stakeholders compared to the Procurement Team are now determined using the AHP Intensity Scale to guide the distribution. Table 3.5 in the main paper shows the scores of other columns. As one example, the relative score for the Project Management Team compared to the Procurement Team is judged to be 2 due to the difference in their importance judgments. Table A-2 can now be expanded by adding columns for the other teams. In it, the Procurement Team is given a score of 1 because it has equal responsibility with itself. The other scores are scaled in a similar way as in Column 2. Note that the values above the diagonal are the reciprocals of the values below the diagonal. For instance, the Project Management Team has a score of 2 in column 2 which is 2 times higher than the Procurement Team according to the AHP Intensity Scale. Thus, the pairwise comparison score for Procurement compared to Project Management will be the reciprocal of 2, which is 0.50 as shown in Column 3 (Table A-2 in the appendix or Table 3.3 in main paper). The result of entire distribution of the stakeholder responsibility for overall FEP is shown in Table 3.5 of section 4.3.

A.5 Distribute the weight of the stakeholder's responsibility for each FCO

This procedure is from **step 4b / section 3.2.4.** Table 3.4 in the text indicates the scores for the Procurement Team for each FCO cause. The judgments for the scores in column 2 were based on the relative classifications shown in the Fishbone Diagram from step 4a. It provides the same type of initial information that was used earlier to scale stakeholder responsibilities for overall FEP in Step 3, see Tables 3.3 and 3.4. The further scores in Table 3.4 were determined through scaling using the AHP Intensity Scale in the same way. The result of entire distribution of the weight of the Procurement team's responsibility for each FCO category is shown in Table 3.7 of section 4.3. Four other tables for other team's responsibilities are shown in Tables A-3, A-4, A-5, and A-6.

Table A-3 Distribution of Design/Planning Team responsibility for each FCO category

Design/Planning Team	Business Operating Hours	Project Schedule Constraint	Correction of Work Due to Design Error	Unknown / Unexpected Field Condition	Accommodate Current Existing Field Condition	Weight Vector (W.V.)	Normalized Weight Vector (N.W.V.)	Rank
Business Operating Hours	1.000	0.500	0.333	0.200	0.111	0.326	0.041	5
Project Schedule Constraint	2.000	1.000	0.500	0.250	0.125	0.500	0.062	4
Correction of Work Due to Design Error	3.000	2.000	1.000	0.333	0.143	0.778	0.097	3
Unknown / Unexpected Field Condition	5.000	4.000	3.000	1.00	0.200	1.644	0.205	2
Accommodate Current Existing Field Condition	9.000	8.000	7.000	5.000	1.00	4.789	0.596	1
Column Total	**20.000**	**15.500**	**11.833**	**6.783**	**1.579**	**8.038**	**1.000**	
(Column Total) x Relative (N.W.V.)	0.812	0.964	1.146	1.387	0.941	5.250		
Lambda max (λmax) = Sum [(Column Total) x Relative (N.W.V.)]	5.250	CR = 0.056 < 0.1, which indicates the distribution is acceptable. The RI of 5 comparisons is 1.12 by Satty (1980).						
Consistency Index (CI) = [(λmax -n) / (n-1)]	0.063							
Consistency Ratio (CR) = (CI/RI)	0.056							

Table A-4 Distribution of Civil Team responsibility for each FCO category

Civil Team	Correction of Work Due to Design Error	Business Operating Hours	Project Schedule Constraint	Unknown / Unexpected Field Condition	Accommodate Current Existing Field Condition	Weight Vector (W.V.)	Normalized Weight Vector (N.W.V.)	Rank
Correction of Work Due to Design Error	1.000	0.333	0.250	0.167	0.111	0.274	0.035	5
Business Operating Hours	3.000	1.000	0.500	0.250	0.143	0.557	0.072	4
Project Schedule Constraint	4.000	2.000	1.000	0.333	0.167	0.850	0.109	3
Unknown / Unexpected Field Condition	6.000	4.000	3.000	1.000	0.250	1.783	0.229	2
Accommodate Current Existing Field Condition	9.000	7.000	6.000	4.000	1.000	4.324	0.555	1
Column Total	**23.000**	**14.333**	**10.750**	**5.750**	**1.671**	**7.788**	**1.000**	
(Column Total) x Relative (N.W.V.)	0.809	1.025	1.174	1.316	0.928	5.251		
Lambda max (λmax) = Sum [(Column Total) x Relative (N.W.V.)]	5.251	CR = 0.056 < 0.1, which indicates the distribution is acceptable. The RI of 5 comparisons is 1.12 by Satty (1980).						
Consistency Index (CI) = [(λmax -n) / (n-1)]	0.063							
Consistency Ratio (CR) = (CI/RI)	0.056							

Table A-5 Distribution of Field Engineering Team responsibility for each FCO category

Field Engineering	**Correction of Work Due to Design Error**	**Business Operating Hours**	**Project Schedule Constraint**	**Unknown / Unexpected Field Condition**	**Accommodate Current Existing Field Condition**	**Weight Vector (W.V.)**	**Normalized Weight Vector (N.W.V.)**	**Rank**
Correction of Work Due to Design Error	1.000	0.500	0.200	0.167	0.111	0.284	0.036	5
Business Operating Hours	2.000	1.000	0.250	0.200	0.125	0.416	0.053	4
Project Schedule Constraint	5.000	4.000	1.000	0.500	0.200	1.149	0.146	3
Unknown / Unexpected Field Condition	6.000	5.000	2.000	1.000	0.250	1.719	0.219	2
Accommodate Current Existing Field Condition	9.000	8.000	5.000	4.000	1.000	4.282	0.546	1
Column Total	**23.000**	**18.500**	**8.450**	**5.867**	**1.686**	**7.850**	**1.000**	
(Column Total) x Relative (N.W.V.)	0.832	0.981	1.236	1.284	0.920	5.254		
Lambda max (λmax) = Sum [(Column Total) x Relative (N.W.V.)]	5.254							
Consistency Index (CI) = [(λmax -n) / (n-1)]	0.064							
Consistency Ratio (CR) = (CI/RI)	0.057	CR = 0.057 < 0.1, which indicates the distribution is acceptable. The RI of 5 comparisons is 1.12 by Satty (1980).						

Table A-6 Distribution of Project Management Team responsibility for each FCO category

Project Management	**Unknown / Unexpected Field Condition**	**Correction of Work Due to Design Error**	**Accommodate Current Existing Field Condition**	**Business Operating Hours**	**Project Schedule Constraint**	**Weight Vector (W.V.)**	**Normalized Weight Vector (N.W.V.)**	**Rank**
Unknown / Unexpected Field Condition	1.000	0.333	0.250	0.143	0.111	0.266	0.034	5
Correction of Work Due to Design Error	3.000	1.000	0.500	0.200	0.143	0.533	0.068	4
Accommodate Current Existing Field Condition	4.000	2.000	1.000	0.250	0.167	0.803	0.102	3
Business Operating Hours	7.000	5.000	4.000	1.000	0.333	2.157	0.275	2
Project Schedule Constraint	9.000	7.000	6.000	3.000	1.000	4.082	0.521	1
Column Total	**24.000**	**15.333**	**11.750**	**4.593**	**1.754**	**7.840**	**1.000**	
(Column Total) x Relative (N.W.V.)	0.813	1.042	1.203	1.263	0.913	5.235		
Lambda max (λmax) = Sum [(Column Total) x Relative (N.W.V.)]	5.235							
Consistency Index (CI) = [(λmax -n) / (n-1)]	0.059							
Consistency Ratio (CR) = (CI/RI)	0.052	CR = 0.052 < 0.1, which indicates the distribution is acceptable. The RI of 5 comparisons is 1.12 by Satty (1980).						

A.6 Calculation of weight vectors

The method of calculation for the weight vectors (known as eigenvectors) and its normalized value, lambda max (λmax), consistency index (CI), and consistency ratio (CR) were developed by previous investigators (Kunz, J., 2010; Moore & Weatherford, 2001; Mahmud et al., 2016; Ihimekpen et al., 2017; Kim et al., 2017, Wang et al., 2017, Alshdiefat et al., 2018, and Gunduz et al. 2019). The AHP calculation used here by spreadsheet program is a common practice. and evident from literature, except for the calculation of the weight vector. The method that this study used in the development of the proposed quality control management process is to determines the weight vector by multiplying the values of all elements and calculating the nth root of the product in each row, while the other method calculates the average of all elements in each row. This study assessed the calculation of both methods and the results indicates that the percent difference of the normalized weight vectors is relatively small in magnitude and the rank of distribution is consistent between the two methods. The calculation for the weight vectors of this study is shown in Step 2 (Table A-7).

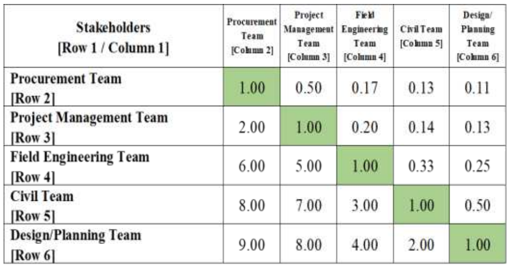
A brief explanation of how AHP is used to distribute stakeholder responsibilities for FEP as following steps. Note that the AHP is used to distribute the weight of each stakeholder's responsibility for each FCO category is the same with the following steps.

Table A-7 The AHP calculation

Step 1. Developing a pair wise comparison matrix for the stakeholders. The value of judgement and calculation is shown in the table.

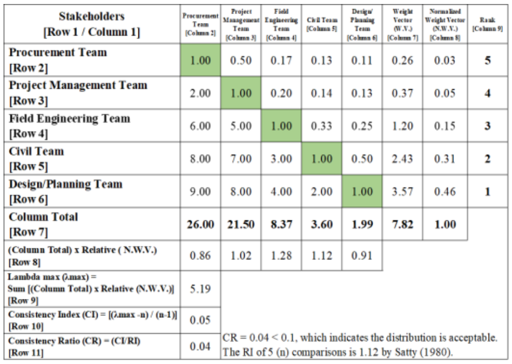
[(Aij), where i,j = (1, 2, 3, 4, 5)]

$$A = \begin{bmatrix} A_{1,1} & A_{1,2} & A_{1,3} & A_{1,4} & A_{1,5} \\ A_{2,1} & A_{2,2} & A_{2,3} & A_{2,4} & A_{2,5} \\ A_{3,1} & A_{3,2} & A_{3,3} & A_{3,4} & A_{3,5} \\ A_{4,1} & A_{4,2} & A_{4,3} & A_{4,4} & A_{4,5} \\ A_{5,1} & A_{5,2} & A_{5,3} & A_{5,4} & A_{5,5} \end{bmatrix}$$



Stakeholders [Row 1 / Column 1]	Procurement Team [Column 2]	Project Management Team [Column 3]	Field Engineering Team [Column 4]	Civil Team [Column 5]	Design/ Planning Team [Column 6]
Procurement Team [Row 2]	🟩 1.00	0.50	0.17	0.13	0.11
Project Management Team [Row 3]	2.00	🟩 1.00	0.20	0.14	0.13
Field Engineering Team [Row 4]	6.00	5.00	🟩 1.00	0.33	0.25
Civil Team [Row 5]	8.00	7.00	3.00	🟩 1.00	0.50
Design/Planning Team [Row 6]	9.00	8.00	4.00	2.00	🟩 1.00

Overall result FEP responsibility among stakeholders



Stakeholders [Row 1 / Column 1]	Procurement Team [Column 2]	Project Management Team [Column 3]	Field Engineering Team [Column 4]	Civil Team [Column 5]	Design/ Planning Team [Column 6]	Weight Vector (W.V.) [Column 7]	Normalized Weight Vector (N.W.V.) [Column 8]	Rank [Column 9]
Procurement Team [Row 2]	🟩 1.00	0.50	0.17	0.13	0.11	0.26	0.03	**5**
Project Management Team [Row 3]	2.00	🟩 1.00	0.20	0.14	0.13	0.37	0.05	**4**
Field Engineering Team [Row 4]	6.00	5.00	🟩 1.00	0.33	0.25	1.20	0.15	**3**
Civil Team [Row 5]	8.00	7.00	3.00	🟩 1.00	0.50	2.43	0.31	**2**
Design/Planning Team [Row 6]	9.00	8.00	4.00	2.00	🟩 1.00	3.57	0.46	**1**
Column Total [Row 7]	**26.00**	**21.50**	**8.37**	**3.60**	**1.99**	**7.82**	**1.00**	
(Column Total) x Relative (N.W.V.) [Row 8]	0.86	1.02	1.28	1.12	0.91			
Lambda max (λmax) = Sum [(Column Total) x Relative (N.W.V.)] [Row 9]	5.19							
Consistency Index (CI) = [(λmax -n) / (n-1)] [Row 10]	0.05							
Consistency Ratio (CR) = (CI/RI) [Row 11]	0.04	CR = 0.04 < 0.1, which indicates the distribution is acceptable. The RI of 5 (n) comparisons is 1.12 by Satty (1980).						

Step 2. Determine the weight vector (eigenvector) by multiplying the values of all stakeholders and calculating the nth root of the product in each row. In this study, n = 5 for five stakeholders.

$$\text{Weight Vector} = \sqrt[n]{\prod_{i=1}^{n} A_{ij}}$$

$$\text{Where } j = (1,2,3,4,5),\ \ n = 5$$

For an example, the weight vector of the Procurement team was calculated as following. The weight vectors of other teams are calculated in the same way. The results are shown in Column 7.

- $\text{Weight Vector No. 1 (W.V. No. 1)} = \sqrt[5]{(A_{1,1} \text{ x } A_{1,2} \text{ x } A_{1,3} \text{ x } A_{1,4} \text{ x } A_{1,5})}$

$$= \sqrt[5]{(1.00) \text{ x } (0.50) \text{ x } (0.17) \text{ x } (0.13) \text{ x } (0.11)} \quad = 0.26$$

Step 3. Normalized weight vector (N.W.V.) for each stakeholder was calculated by dividing the weight vector of each stakeholder to the total weight vectors of all stakeholders.

For an example, the normalized weight vector of the Procurement team was calculated as following. The normalized weight vectors of other teams are calculated in the same way. The results are shown in Column 8.

- Normalized Weight Vector No. 1 (N.W.V No. 1) =

$$\frac{\text{(W.V. No. 1)}}{\text{(W.V. No. 1)+(W.V. No. 2)+(W.V. No. 3)+(W.V. No. 4)+(W.V. No. 5)}}$$

$$= \frac{0.26}{(0.26)+(0.37)+(1.20)+(2.43)+(3.57)} = \frac{0.26}{7.82} = 0.03$$

Step 4. Calculate the lambda max (λmax) value. The λmax is calculated by totaling the sum of all the judgment values in each column and multiplying with the relative normalized weight vector in each row. The results are shown on Rows 8 and 9.

- λmax = ∑{[Sum of (Aij) in each column] x [Relative normalized weight vector in each row]}

- In this study, the λmax is calculated as follows:

- λmax = [(A1,1+A2,1+A3,1+A4,1+A5,1) x (N.W.V. No. 1)
  + (A1,2+A2,2+A3,2+A4,2+A5,2) x (N.W.V. No. 2)
  + (A1,3+A2,3+A3,3+A4,3+A5,3) x (N.W.V. No. 3)
  + (A1,4+A2,4+A3,4+A4,4+A5,4) x (N.W.V. No. 4)
  + (A1,5+A2,5+A3,5+A4,5+A5,5) x (N.W.V. No. 5)]

- λmax = [(1.00+2.00+4.00+8.00+9.00) x (0.03)
  + (0.50+1.00+3.00+7.00+8.00) x (0.05)
  + (0.25+0.33+1.00+5.00+6.00) x (0.10)
  + (0.13+0.14+0.20+1.00+2.00) x (0.33)
  + (0.11+0.13+0.17+0.5+1.00) x (0.48)]

= 0.83 + 1.00 + 1.30 + 1.15 + 0.91 = 5.19

Step 5. Calculate the Consistency Index. The result is shown on Row 10.

$$\text{Consistency Index (CI)} = \frac{\lambda\text{max - n}}{\text{n - 1}}$$

$$= \frac{(5.19 - 5)}{(5 - 1)} = 0.05$$

Step 6. Check for the Consistency Ratio (CR), the value of CR should be less than 10%; otherwise, the judgement value from steps 3 and 4b need to be adjusted. The RI value is from the Saaty's Index Table. The result is shown on Row 11.

$$\text{Consistency Ratio (CR)} = \frac{\text{CI}}{\text{RI}}$$

Where RI is Randon Index. The RI of five comparisons is 1.12 by Satty (1980).

$$\text{CR} = \frac{0.05}{1.12} = 0.04$$

Random index (RI)

N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.58

Source: Satty 1980

LIST OF ABBREVIATIONS

AHP : Analytic Hierarchy Process

CPM : Critical Path Method

FCO : Field Change Orders

FEP : Front-End Planning

OH : Overhead

UG : Underground