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Review of Statcom EPC Project Schedule and Optimization of the Overall Timeline

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ABSTRACT:

The thesis explores the optimization of Statcom project schedule within the context of Engineering, Procurement, and Construction projects, with a strong emphasis on identifying the bottle necks, the application of the Critical Path Method and fast-tracking techniques for efficient project management. EPC projects are known for their complexity due to the integration and interface of multiple disciplines, tight timelines, high cost implications, and the critical need for accurate scheduling. To make sure that projects are completed within contractual time, without compromising quality or exceeding the budget, is a major challenge for project managers, especially in large-scale infrastructure projects. The research aims to investigate the current Statcom project schedule, identify the bottlenecks, how CPM can be effectively utilized to identify critical tasks that directly impact project timelines, as well as strategies for mitigating potential delays. The thesis also examines the fast-tracking technique, where multiple tasks are performed simultaneously instead of sequentially, to reduce overall project duration. This is particularly crucial for industries such as energy infrastructure, where delays can significantly impact project costs and EPC companies' reputation. As a key part of this study, a Statcom project has been selected as a case study to provide real-world insight into the scheduling challenges faced in these complex projects and how optimization methods can be applied to enhance project outcomes. The research adopts a multi-method approach, incorporating theoretical frameworks, case study analysis, and qualitative interviews with managers and industry experts. The case study of the Statcom project serves as a practical reference to identify the bottle necks and use of CPM and fast-tracking techniques in improving project scheduling and performance. In-depth interviews managers reveal challenges in six major engineering phases which are system design, electromechanical design, hardware design, software design, procurement and installation phase. Ultimately, this thesis makes a significant contribution to the understanding of schedule optimization, offering practical insights for the ongoing Statcom project. By reducing project timelines, improving critical path identification, and managing bottlenecks through improved scheduling methods, the study provides a valuable roadmap for enhancing project efficiency in Electrical industry. The findings are intended to guide industry practitioners, helping them implement the best practices for managing complex projects under stringent timelines and resource constraints. Thus, the research offers actionable strategies for future projects, ensuring the study's lasting relevance in project management.

KEYWORDS: EPC Projects, Statcom, Fast Tracking, Critical Path Analysis, Project Schedule Optimization

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List of Abbreviations

CP	Constraint Programming
CPM	Critical Path Method
CCPM	Critical Chain Project Management
ECSO	Energy Service Companies
EPC	Engineering, Procurement and Construction
EF	Early Finnish
ES	Early Start
FACTS	Flexible AC Transmission Systems
LF	Late Finnish
LS	Late Start
SME	Small and Medium Enterprises
STATCOM	Static Synchronous Compensator in power systems.
SVC	Static Var Compensator
VSC	Voltage Source Converter
WOA	Whale Optimization Algorithm

1 Introduction

EPC (Engineering, Procurement, and Construction) projects are large-scale, multidisciplinary undertakings that encompass the design, procurement, construction, and commissioning of complex systems or infrastructures (Zamri Zakaria et al., 2024). Spanning several years, these projects demand intricate coordination across various phases to ensure seamless execution. Effective management hinges on robust planning, clear communication, and adaptive strategies to mitigate risks and deliver on time. Central to this process is project scheduling, a critical tool for aligning tasks, resources, and timelines. A well-structured schedule fosters efficient coordination, minimizes delays, and provides a clear roadmap for achieving project milestones (Suresh & Sivakumar, 2019). An overview of the study is provided in this section, outlining its background, purpose, research objectives, and key research questions. It also discusses the study's limitations, highlighting the scope and constraints that may impact the findings. By establishing these foundational elements, this section ensures a clear understanding of the study's direction and focus.

1.1 Background, Purpose & Problem Statement

EPC projects are large-scale, complex undertakings that require precise scheduling to adhere to their typical timelines of 36 to 60 months, which depend on the project scope and budget. Despite this, delays of 4 to 8 months are common, primarily due to inefficiencies and inadequate schedule management (Zamri Zakaria et al., 2024). Existing schedules often fall short of addressing the inherent complexities and inefficiencies of these projects. The absence of a comprehensive analysis of the schedule, including its interdependencies, durations, and resource allocation, has contributed to recurring delays. These ongoing challenges result in increased costs, strained stakeholder relationships, and reduced project quality. Therefore, a thorough evaluation of project

schedules is essential to identify inefficiencies, optimize timelines, and ultimately enhance overall project efficiency and outcomes (Suresh & Sivakumar, 2019).

Efficient project scheduling is important for the successful execution of EPC projects. The purpose of this thesis is to critically assess scheduling inefficiencies in EPC projects and identify opportunities to reduce project timelines by 2 to 3 months. By analyzing the initial project schedule, the research aims to evaluate critical and near-critical paths, as well as bottlenecks across various disciplines, including system design, electro-mechanical, hardware, and software. The goal is to propose actionable strategies and methodologies to optimize schedule efficiency, streamline project execution, and expedite completion, ultimately enhancing overall project success.

Efficient project scheduling is critical for the successful execution of EPC projects. However, these projects often face significant delays due to complex task relationships, mismanagement in resource allocation, activity blockages at different project phases and non-availability of advanced project management tools and techniques which can aid in addressing complexities and mitigating delays (Moon, 2020). These persistent issues highlight the need for an in-depth analysis of project schedules and the adoption of advanced techniques to enhance project execution timelines.

1.2 Research Questions and Objectives

The primary objective of the thesis is to investigate strategies for optimizing project schedules and identifying schedule efficiencies in EPC projects. For this, the study will review existing literature on the advanced scheduling tools and analyze the project scheduling techniques such as Critical Path Method (CPM), crashing, and fast-tracking to assess their applicability and effectiveness. Moreover, the study will identify scheduling bottlenecks by conducting interviews with project stakeholders and will develop

actionable recommendations for optimizing project timelines and improving overall scheduling efficiency in EPC projects. This research target is to reduce the gap between theoretical scheduling methodologies and their practical application in managing complex EPC projects.

Research Questions:

The research aims to answer the following research questions:

1. What are the main scheduling bottlenecks contributing to delays in EPC projects, specifically in the context of the STATCOM project?
2. How is the Critical Path Method (CPM) applied in the case project's schedule, and how do activity relationships influence the project total float and critical path?
3. What actionable strategies can be proposed to optimize the project time schedule and enhance overall scheduling efficiency in the STATCOM project?

1.3 Delimitations

The study focuses on analyzing STATCOM EPC project schedules, emphasizing activity sequences, interdependencies, critical paths, and near-critical paths across disciplines such as system design, electro-mechanical, hardware, and software. Thus, it does not delve into broader aspects of project management, such as risk assessment, budgeting or resource allocation beyond the scope of scheduling. Additionally, the research derives insights primarily from interviews with stakeholders directly involved in project planning and execution to identify scheduling inefficiencies and bottlenecks. Thus, it excludes budget or cost-related impacts of scheduling optimizations and delays caused by external factors, such as subcontractors or customers. Moreover, the study is limited to a single case study within the energy and grid solutions industry, which may constrain the applicability of the findings to broader contexts. By narrowing the scope, the study provides targeted recommendations to address the internal scheduling challenges unique to EPC projects.

1.4 Justification

The research aims to critically examine scheduling inefficiencies in EPC projects and propose actionable strategies to optimize timelines and enhance overall project efficiency. Leveraging a strong foundation in project management methodologies gained through academic and professional experience, the study seeks to address key challenges and uncover opportunities for improving scheduling practices. Techniques such as Critical Path Method (CPM), crashing, and fast-tracking will be applied to real-world scenarios to develop practical and effective solutions. This research aligns with and builds upon established expertise, contributing valuable insights into optimizing schedules and enhancing project outcomes.

Efficient use of Critical Path Method (CPM), effective scheduling, and fast-tracking are crucial in the energy and grid solutions industry to optimize project timelines, reduce delays, and ensure timely deployment of critical infrastructure. Given the complexity and scale of projects in this sector, these project management techniques help enhance efficiency, control costs, and mitigate risks associated with construction and commissioning, ultimately supporting the stability and reliability of power systems.

2 Literature Review

The Engineering, Procurement, and Construction (EPC) industry, faces significant challenges related to project scheduling and delays. The complexity of these projects, coupled with various external and internal factors, often results in time overruns that can have substantial financial and operational implications (Hansen, 2012). This literature review aims to synthesize existing research on project delays, advanced scheduling tools, and techniques like the Critical Path Method (CPM), crashing, and fast-tracking. Furthermore, it will explore the identification of scheduling bottlenecks through stakeholder interviews, ultimately seeking to reduce the gap among theoretical methodologies and practical applications in EPC project management.

The literature review explores key aspects of project scheduling and delays, examining their causes, impacts, and mitigation strategies. It delves into common factors contributing to project delays, such as resource constraints, scope changes, and unforeseen risks, along with their consequences on cost, timeline, and stakeholder satisfaction. The review also covers fundamental scheduling concepts and advanced techniques, including the Critical Path Method (CPM), which identifies essential tasks affecting project completion. Additionally, it discusses fast-tracking and crashing as methods to accelerate schedules by overlapping activities or allocating extra resources. Schedule optimization strategies are also explored to enhance efficiency while balancing constraints like budget and resource availability. In the literature review, previous studies, journals, articles, and articles were carefully analyzed to identify research gaps and relevant insights. Efforts were made to ensure that the selected literature aligned with the thesis objectives, supporting the research with a solid foundation and a thorough understanding of the subject.

2.1 EPC Projects

Engineering, Procurement, and Construction (EPC) projects are comprehensive contracts where a contractor manages all phases of a project, which includes design, procurement, and construction, delivering a complete facility to the client. This turnkey approach streamlines project execution and is commonly used in large-scale infrastructure projects such as power plants and refineries. A systematic assessment of risks in EPC projects by Zakaria in 2024 highlights that effective implementation, performance evaluation, and risk management are crucial for project overall success. The study identifies key areas such as stakeholder behavior, decision-making processes, and the role of Energy Service Companies (ESCOs) in managing risk (Zamri Zakaria et al., 2024). Furthermore, a study analyzing EPC critical activities in large-scale residential construction projects in Iran found that engineering design and project planning are significant factors contributing to project performance. The research utilized the TOPSIS method, a multi-attribute group decision-making technique, to rank these activities (Kabirifar & Mojtahedi, 2019).

Effective scheduling helps manage complex tasks, assign resources, and anticipate potential delays. Tools like the Critical Path Method (CPM) are widely used to identify the critical path and optimize project timelines. However, uncertainties and risks, such as supply chain disruptions or unforeseen technical challenges, can significantly impact the schedule. Therefore, integrating advanced scheduling techniques and proactive risk management is crucial to minimize delays and ensure the successful completion of EPC projects (Suresh & Sivakumar, 2019). These studies underscore the complexity and multifaceted nature of EPC projects, highlighting the need for effective management strategies, risk assessment, and performance evaluation to ensure successful project outcomes. Given the complexity of EPC projects with multiple stakeholders, strict regulations, and diverse resources, effective coordination across all phases is essential. The use of advanced project management tools, continuous monitoring, and adaptive strategies can enhance efficiency and reduce risks. Proactive risk management,

especially around delays and cost escalations, is key to keeping projects on track. Ultimately, successful EPC project delivery requires not only technical expertise but also a structured, holistic approach to planning and execution (Ketsopoulou et al., 2021).

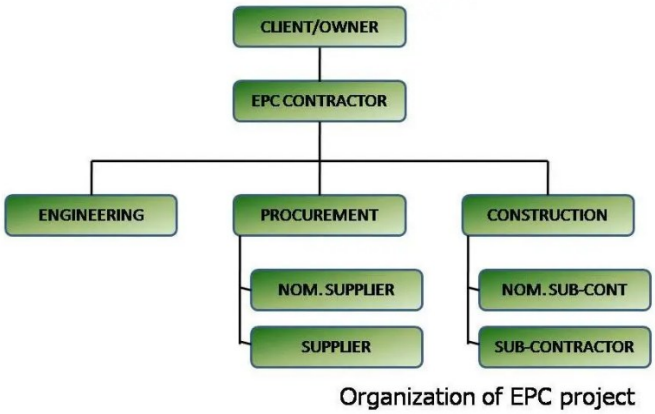


Figure 1. Typical EPC Project Organization (Hansen, 2012)

In an EPC project, the contractor assumes full responsibility from the outset, covering engineering services, material procurement, and construction. Typical examples of EPC projects include oil development plants, process plants, industrial factories, and infrastructure developments. As construction delivery systems have evolved, the EPC contract model has gained global popularity. A key advantage is that it transfers much of the client's risk to the main contractor, offering the client greater certainty regarding timeframes and costs, while the contractor takes complete responsibility for both design and execution. This growing preference for EPC contracts led organizations like FIDIC to develop a standardized contract framework, such as the FIDIC Conditions of Contract for EPC/Turnkey Projects (commonly known as the Silver Book), to better align with modern market conditions (Hansen, 2012).

2.2 Statcom Projects

This section delves into STATCOM (Static Synchronous Compensator), a crucial technology used in modern power systems to enhance stability and power quality. By providing dynamic voltage support, STATCOMs help to regulate the voltage and improve the system's response to fluctuations in load, thus preventing power disruptions (Rao et al., 2000). The study explores the application of CPM and fast-tracking methods in STATCOM projects, aiming to reduce project timelines without compromising quality or system reliability. Through the integration of advanced techniques such as Critical Path Method (CPM), this research evaluates how project timelines can be optimized while maintaining the necessary technical standards.

2.2.1 STATCOM Technology Overview

Static synchronous compensators (STATCOMs), part of the Flexible AC Transmission Systems (FACTS) family, are used for dynamic shunt compensation to regulate reactive power and enhance voltage stability in power systems. They outperform traditional static VAR compensators (SVCs) and are widely adopted in transmission and distribution networks under stressed conditions (Sharma et al., 2024). STATCOMs operate by injecting or absorbing reactive power via voltage source converters (VSCs) connected to DC energy storage devices, such as capacitors (Samreen Fiza, 2022). Their fast and dynamic response makes them especially effective in applications involving renewable energy and industrial loads, offering superior voltage control and grid reliability compared to conventional capacitor banks (Shaker, 2014). Various control strategies—ranging from PI/PID and adaptive PI to advanced techniques like Lyapunov-based adaptive and LQR-based linear optimal control—have been proposed to maintain optimal performance under dynamic conditions (Rao et al., 2000).

- The STATCOM supplies reactive power to the grid in capacitive mode when its output voltage is greater than the system voltage.
- In inductive mode, the STATCOM draws reactive power from the grid when its output voltage falls below the system voltage.
- If the STATCOM output voltage matches the system voltage, there is no transfer of reactive power. (Samreen Fiza, 2022).

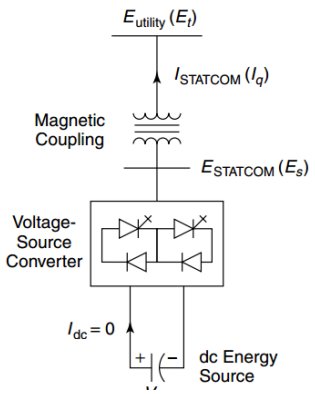


Figure 2. Principal Diagram of STATCOM (Shaker, 2014)

2.2.2 Market Report

The Static Synchronous Compensator (STATCOM) market is growing steadily, driven by several key factors. A major contributor is the rising combination of renewable energy sources like wind & solar, which introduce voltage fluctuations that STATCOMs help stabilize. Grid modernization efforts to support decentralized generation and improve system efficiency also boost demand. Additionally, advancements in power electronics and digital controls have made STATCOMs more efficient and cost-effective. Government regulations emphasizing grid stability and power quality further encourage utilities to invest in this technology (markwideresearch, 2025). According to the SkyQuest Technology report on STATCOM the STATCOM market was valued at USD 0.7 billion in 2023 and is projected to grow from USD 0.74 billion in 2024 to USD 1.18 billion by 2032,

with a CAGR of 6.0% during the forecast period (2025-2032). The market is segmented based on rated power, including low-power STATCOMs (less than 20 Mvar) and medium-power STATCOMs (20-100 Mvar), catering to different reactive power compensation needs. The key end-users of STATCOMs include utilities for grid stability, steel manufacturing for power quality, and renewable energy projects for voltage regulation. The mining sector uses STATCOMs to manage heavy electrical loads, while hydrogen power plants benefit from improved power stability.

Other industries also utilize STATCOMs for enhanced electrical performance and reliability. Geographically, the market is analyzed across various regions, highlighting regional growth opportunities and market dynamics. These insights reflect the increasing demand for STATCOMs to enhance grid reliability and industrial power management. According to the report, the largest market is Asia-Pacific which is driven by fast industrialization and significant investments in renewable energy projects, particularly in countries like China, Japan, India, and South Korea. Key players in the STATCOM industry include ABB, Siemens AG and General Electric GE (skyquest, 2025).

Figure 15 depicts the typical STATCOM facility, highlighting key components. The control room houses the system's monitoring and control equipment. VSC valves (Voltage Source Converter) regulate reactive power. Phase reactors help control current flow and filter harmonics. The transformer connects the STATCOM to the grid, adjusting voltage levels. The setup ensures voltage stability and improves power quality in electrical networks (GE Grid Solutions, n.d.).

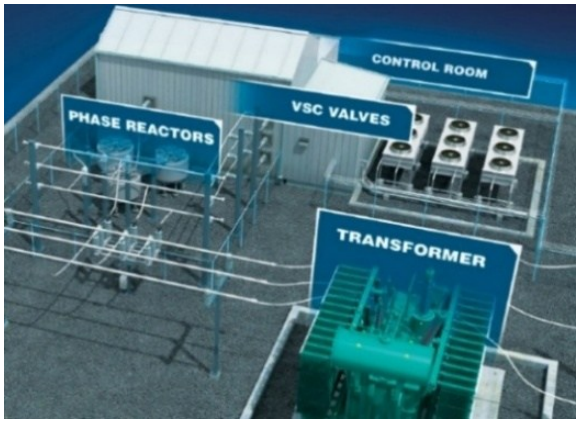


Figure 3. Static Synchronous Compensator (GE Grid Solutions, n.d.)

2.2.3 Applications and Benefits

STATCOMs are employed in a range of applications, including voltage regulation, stability improvement, and integration with renewable energy systems like wind farms. They help mitigate voltage fluctuations, enhance steady-state and dynamic stability, and prevent overvoltages during islanding conditions. Additionally, STATCOMs are used in distributed generation systems to address voltage stability issues, offering economical solutions through virtual configurations that utilize existing infrastructure (Sharma et al., 2024). Vetoshkin & Müller in 2021 stated some key advantages of STATCOM in the power grids. Although Vetoshkin's study effectively analyzed dynamic stability using STATCOM with synchronverter control, but his study overlooked long-term stability, economic and environmental impacts, integration with energy storage, regulatory considerations, and sensitivity analysis.

1. **Reactive Power Control**: STATCOMs are highly effective in controlling reactive power, maintaining voltage stability, and ensuring minimal reactive power flow between the grid and loads. By dynamically adjusting reactive power injections, they help mitigate voltage sags and swells, ensuring a more reliable and resilient power network.

2. **Voltage Control**: They provide fast and efficient voltage control, which is essential for maintaining system stability under stressed conditions. Unlike traditional solutions, STATCOMs can respond within milliseconds, making them highly suitable for dynamic grid conditions and fluctuating load demands.

3. **Enhanced Power Quality**: STATCOMs help in mitigating voltage fluctuations and improving power quality by compensating for reactive power imbalances and protecting the system from flicker-producing loads. This ensures compliance with power quality standards, reducing issues such as harmonics, transients, and electrical noise.

4. **Optimal Power Flow**: They facilitate optimal power flow by controlling both active and reactive power, which is crucial for managing demand and supply effectively, especially under contingency conditions. This improves transmission line utilization, reduces power losses, and enhances overall system reliability.

5. **Reduced Switching Losses**: Advanced STATCOM designs, such as those using hybrid cascaded converters, offer reduced switching losses and improved fault ride-through capabilities, enhancing overall system efficiency. These innovations help extend the lifespan of power electronic components, lowering maintenance costs and improving long-term operational performance.

6. **Integration with Renewable Energy**: STATCOMs, particularly those enhanced with energy storage, support grid balancing and the combination of renewable energy sources like solar and wind by providing fast frequency response and energy reserves. This helps stabilize variable generation, ensuring seamless integration into the grid while reducing curtailment and maximizing renewable energy utilization. Moreover, STATCOM's require less space compared to traditional reactive power compensation devices (Vetoshkin & Müller, 2021).

2.2.4 Challenges

Despite their advantages, STATCOMs face challenges such as optimal placement in complex distribution systems and the need for further improvements in control strategies. Research continues to explore new models, control technologies, and applications to enhance their effectiveness and efficiency. The development of virtual STATCOM configurations and advanced control algorithms represents promising areas for future research and application (Vetoshkin & Müller, 2021). Some challenges faced by the STATCOM industry, which hinder its growth and widespread adoption are:

1. **High Initial Investment Costs**: Implementing STATCOM systems requires substantial capital, which can be a significant barrier, especially for smaller utilities or organizations in developing regions (markwideresearch, 2025).
2. **Complex Integration and Maintenance**: Integrating STATCOMs into existing power grids involves complex processes, and their maintenance demands specialized expertise, potentially increasing operational costs (statsndata, 2025).
3. **Regulatory and Policy Uncertainties**: Varying regulations and policy frameworks across regions can create uncertainties, affecting the planning and implementation of STATCOM projects (maximizemarketresearch, 2025).
4. **Technological Advancements and Compatibility**: Rapid technological changes may render existing STATCOM systems obsolete, and ensuring compatibility with new technologies can be challenging (markwideresearch, 2025).
5. **Environmental and Social Concerns**: Deploying STATCOMs may raise environmental and social issues, such as land use and community acceptance, which can delay projects (statsndata, 2025).

Attending these challenges is vital for the STATCOM industry to realize its full potential in enhancing power system stability and efficiency.

2.3 Project Scheduling

Project scheduling is crucial in Engineering, Procurement, and Construction (EPC) projects due to their complexity and the need for precise coordination among various phases. Effective scheduling ensures that engineering designs are completed on time, materials and equipment are procured when needed, and project activities are executed without delays. This synchronization minimizes idle time, reduces costs, and enhances overall project efficiency (Peng et al., 2020). Research by Janaka in the context of the oil and gas industry emphasized the importance of early determination in EPC projects, highlighting that assessing the project's result in terms of cost, schedule, quality, and safety during the initial stages is crucial. This early assessment plays a significant role in influencing project success and mitigating potential overruns. Furthermore, the author identified critical activities within the EPC process, such as scope finalization, detailed execution scheduling, and cost estimation, which are essential for confirming that projects remain on track and within budget. Beyond traditional engineering-centric views, the paper advocated for a broader focus on strategic deliverables, arguing that addressing strategic issues concurrently enables project managers to achieve more predictable outcomes. The author stressed the significance of effective project planning and scheduling in EPC projects, particularly in the oil and gas sector, to avoid overruns and enhance project outcomes (Ruwanpura et al., 2006).

Janaka’s study offered valuable insights into project scheduling but had notable limitations. Its focus on the Canadian market restricted the applicability of findings to regions with different regulatory and supply chain conditions. While it emphasized pre-project planning, it overlooked execution-phase challenges like site conditions, contractor coordination, and real-time decision-making—critical factors for project success. A more holistic approach, covering both planning and execution, would provide a clearer understanding of project risks.

2.4 Schedule Optimization

Schedule optimization is a critical process in various fields, aiming to reduce overall costs, improve efficiency, and improve performance. It involves the application of mathematical models and algorithms to find the best possible schedule under given constraints and objectives. In process industries, optimization-based scheduling is crucial for efficient operations, though its practical application is often limited due to its complexity. Theoretical advancements have been made, but real-life implementation remains a challenge. In hot strip manufacturing, multi-objective optimization can reduce energy consumption by optimizing heating and rolling processes (Peng et al., 2020).

Iterative Improvement Techniques

Iterative improvement techniques such as iterative deepening, random search, tabu search, and genetic algorithms are commonly used for schedule optimization due to their ability to handle complex scheduling problems. These methods focus on local search strategies to enhance a given schedule, often balancing multiple, sometimes conflicting, criteria (Wang & Gao, 2024).

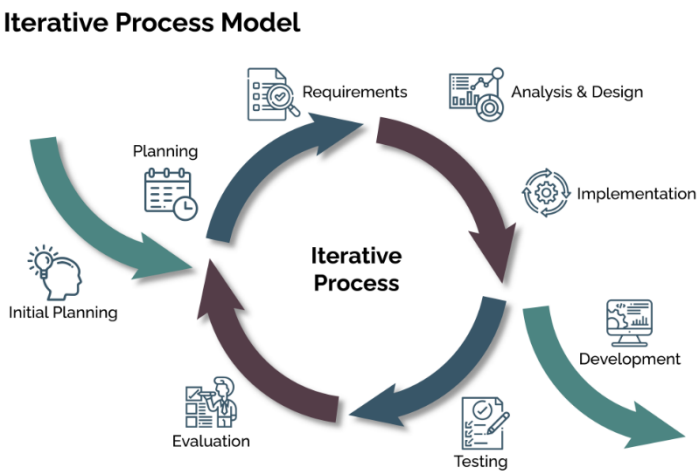


Figure 4. Iterative Process Model (Runtime, 2024).

Multi-Objective Optimization

Multi-objective optimization models are essential for addressing various aspects of scheduling, such as time, cost, quality, and safety. These models use techniques like genetic algorithms to optimize multiple objectives simultaneously, leading to improved project efficiency and economic benefits. For instance, integrating linear scheduling methods with critical chain project management can effectively manage uncertainties and optimize project duration and costs (Wang & Gao, 2024).

Data-Driven and Algorithmic Approaches

Data-driven methods, such as those using neural networks, can significantly reduce computation time in scheduling tasks by learning from existing data and improving model efficiency. Similarly, metaheuristic algorithms like the whale optimization algorithm (WOA) and its improved versions are applied in cloud computing to enhance task scheduling, resource utilization, and operational costs (Fu et al., 2019).

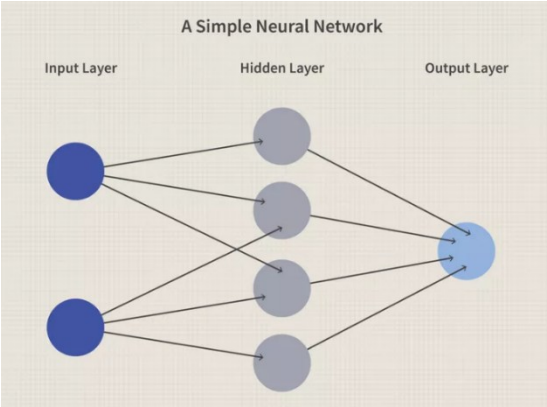


Figure 5. Neural network diagram by Sabrina Jiang (Sourced from James Chen, 2024)

Despite advancements, the practical implementation of optimization-based scheduling in industries is hindered by its complexity and the preference for simulation-based or manual methods. Future research could focus on developing more user-friendly and efficient optimization tools to bridge this gap. Additionally, incorporating risk

management mechanisms in project schedule optimization models could further enhance their applicability and effectiveness (Wang & Gao, 2024). Similarly, Ibbs, and Allen (2007) indicated that the successful implementation of scheduling techniques requires not only a thorough understanding of project dynamics but also the ability to adapt to changing circumstances. This highlights the need for a comprehensive approach that integrates advanced scheduling tools with real-time project data and stakeholder input.

2.5 Project Delays

Identifying scheduling bottlenecks is essential for optimizing project timelines, as they can stem from resource constraints, inefficient processes, and communication breakdowns (Cibi, 2024). Qualitative methods, such as stakeholder interviews, offer valuable insights into these challenges. As Lowe and Odeyinka highlighted the importance of stakeholder perspectives in uncovering scheduling bottlenecks, using interviews and surveys to gather qualitative data that complemented quantitative analyses. This holistic approach provides a deeper understanding of project dynamics and enables targeted interventions (John Lowe & Henry Odeyinka, 2002). Understanding the causes of delays is vital for effective mitigation strategies. Sembiring and Putra identified poor scheduling and resource constraints as key contributors to delays, advocating for the use of Critical Chain Project Management (CCPM) to optimize schedules and reduce multitasking, improving overall project efficiency. (Sembiring & Putra, 2020). However, Putra's study focused only on a single case study involving PT. A which restricted the generalizability of the findings to other projects or organizations. Similarly, Al-Momani emphasized the external factors impacting the project timelines, such as weather conditions, regulatory changes, and labor disputes but his study was also limited to the construction industry. These limitations underscore the need for broader research to address diverse contexts and industries (Al-Momani, 2000).

2.5.1 Project Delay Causes

Project delays in Engineering Procurement and Construction (EPC) projects can significantly affect the overall success and efficiency of operations. Understanding the causes and impacts of these delays is essential for effective project management.

1. **Project-related**: Delays due to challenges with land acquisition, where the project is stalled because of difficulties in securing or obtaining the necessary land to start or continue work.
2. **Management-related**: Problems with recruiting skilled technical staff or labor shortages can lead to delays. Without the right workforce in place or sufficient labor, the project cannot progress at the expected pace.
3. **Client-related**: Slow decision-making by the client can create bottlenecks, while suspension of work, whether temporary or long-term, halts progress. Additionally, clients may cause delays by taking too long to revise or approve important project documents, and any issues related to payment can slow down operations or reduce available resources.
4. **Consultant-related**: Consultants may take time to make crucial decisions, leading to delays. Complexities in the project, especially technical ones, can also slow progress as more time is needed to resolve issues.
5. **Contractor-related**: Subcontractor problems, such as their availability or performance, can disrupt project timelines. Delays may also arise from poor site mobilization and inadequate planning by the contractor, which leads to inefficient use of time and resources.
6. **Other factors**: External factors like a lack of water availability, extreme weather conditions (such as heat), or environmental restrictions can further contribute to project delays by limiting the resources or working conditions necessary to move forward. (Talukder et al., 2023)

Talukder and Elizabeth's research did not explore methodologies or tools for effective project scheduling and execution, creating a gap for further research on how specific scheduling techniques and project management tools can mitigate delays. Understanding these tools is crucial for preventing delays and improving project outcomes, underscoring the need for future research in this area. The Fishbone diagram (also known as a Cause-and-Effect or Ishikawa diagram) in Figure 4 by Talukder, visually presents various causes leading to project delays in construction or project management.

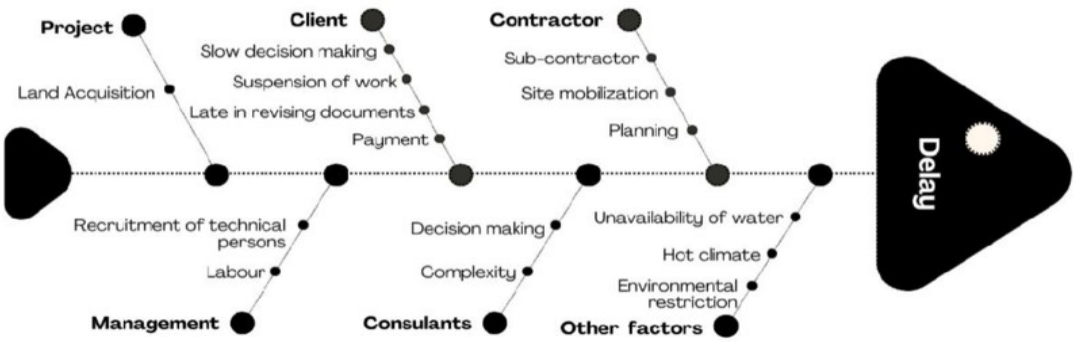


Figure 6. Fishbone diagram for Project delay causes & impact (Talukder et al., 2023)

2.5.2 Project Delay Impacts

Moon Elizabeth in 2020 discussed the impacts of project delays, highlighting their effects on cost, efficiency, and stakeholder satisfaction.

- **Financial Penalties**: Delays often result in significant penalties as specified in project contracts, which can affect the financial viability of the project. These penalties can accumulate quickly, leading to substantial financial losses for contractors.
- **Customer Satisfaction**: Timely completion is a critical customer value in EPC projects; delays can lead to dissatisfaction and damage relationships with clients. Maintaining customer trust is essential for future business opportunities.

- **Increased Costs**: Extended project timelines can lead to increased costs due to additional labor, equipment rental, and other overheads. These unexpected expenses can strain project budgets and affect profitability.
- **Reputation Damage**: Frequent delays can harm the reputation of the contracting company, making it harder to secure future projects. A strong reputation is vital in the competitive EPC market, and delays can tarnish this image.
- **Complexity in Management**: The involvement of multiple stakeholders can complicate project management, making it difficult to identify responsible parties when issues arise. Effective stakeholder management is crucial to reduce the risks linked with delays (Moon, 2020).

This diagram in Figure 7, outlines a decision-making process for assessing project delays in construction or contractor projects, categorizing them to determine their impact and compensation eligibility. The process begins by identifying a delay and evaluating whether it is critical—one that affects the overall project timeline using methods like the Critical Path Method (CPM). If not critical, the next step is to determine if it is excusable, meaning it is beyond the contractor's control (e.g., natural disasters, owner-directed changes). Non-excusable delays, such as subcontractor issues or poor work, are the contractor's responsibility and not eligible for compensation. If an excusable delay entitles the contractor to extra time or money, it is compensable, typically due to owner-driven changes or errors. Some excusable delays, like natural disasters, remain non-compensable. For compensable delays, the impact is assessed using foresight, hindsight, and contemporaneous methods. Concurrent delays—overlapping delays from multiple causes—are also considered to evaluate project impacts. This categorization ensures fair compensation while distinguishing between delays within and beyond the contractor's control (industrialaudit, 2015).

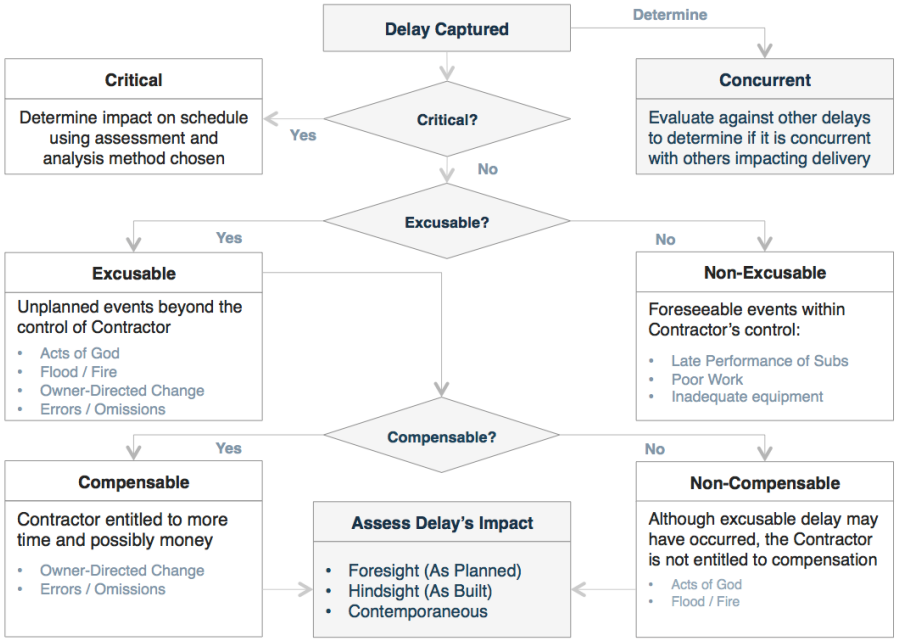


Figure 7. Delay categorization (industrialaudit, 2015)

Similarly, the flowchart by Kumar & Raj in Figure 6 illustrates a process for managing project delays through a structured flow. The process starts with updating the project schedule based on time monitoring. Progress reporting is conducted regularly to provide visibility of the project's status. Along with this, variance analysis is performed to evaluate the planned performance with the actual performance, helping to detect any discrepancies. Performance measurement is also part of this step, ensuring the project is meeting its performance standards. Next, a decision is made on whether a project delay has occurred. If no delay is identified, the steps are repeated in the next reporting period. However, if a delay is confirmed, the process moves forward with an evaluation of the delay's impact on the project. Based on this, the project baseline is revised to reflect the adjusted timeline. The next step involves conducting a delay analysis to understand the cause and implications of the delay, followed by a schedule-specific risk analysis to assess potential risks related to the schedule. Mitigation measures are then developed and implemented to reduce the impact of the delay. Once these measures are in place, the process repeats for the next reporting period to ensure continuous control over the project's progress and schedule, creating a cycle of monitoring and adjustment until the project is completed (Kumar & Raj, 2015).

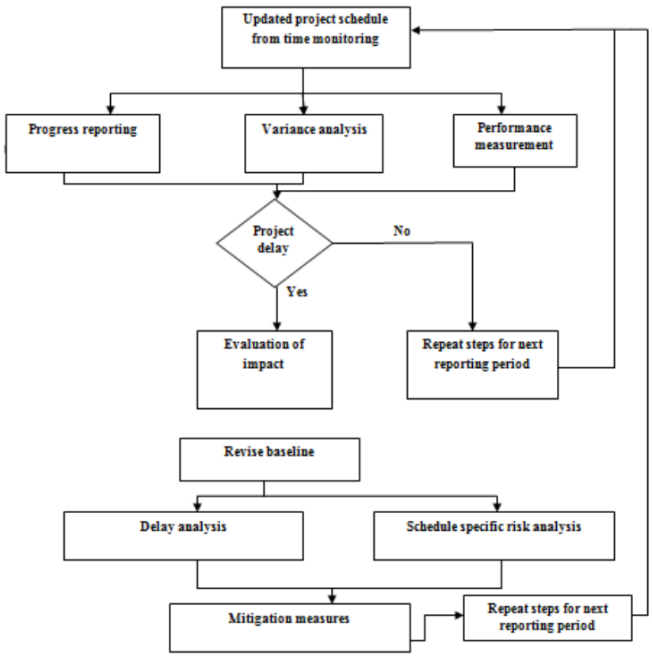


Figure 8. Flow chart for Delay control (Kumar & Raj, 2015).

2.6 Advanced Scheduling Tools

In response to the challenges posed by project delays, various advanced scheduling tools have been developed to enhance project management practices. Among these, tools like Critical Path Method (CPM) and fast-tracking are widely utilized to optimize project schedules and reduce delays. CPM identifies the longest sequence of critical tasks, helping managers focus on activities that directly impact project timelines, while fast-tracking accelerates progress by overlapping tasks that would typically be performed sequentially (Ruwanpura et al., 2006). These techniques, when combined with advanced analytics, provide a robust framework for tackling scheduling challenges in complex projects.

2.6.1 Critical Path Method

Critical Path Method (CPM) has emerged as a foundational technique for project scheduling. It assists project managers in recognizing the longest succession of linked tasks that dictates the total project duration, thereby promoting effective scheduling and time control. However, while CPM is widely utilized, it has limitations, particularly in dynamic environments where project scopes frequently change (Morris & Pinto, 2010). CPM is a network-based approach that identifies the longest path of dependent tasks in a project, known as the critical path. This critical path defines the minimum achievable project duration, since any delay in its constituent tasks will directly affect the project's completion timeline. It requires computation of the earliest and latest possible start and finish times for each activity, thereby enabling project managers to prioritize tasks and allocate resources efficiently. The method is widely applicable across many fields, such as marketing, education, and software development (Yokoyama & Goto, 2016).

The following CPM example outlines the key tasks for launching a website. Tasks are shown in rectangular nodes, with some running simultaneously, like defining the target market, designing, and drafting content. However, only critical tasks, marked with colored arrows, impact the deadline. CPM helps prioritize tasks, create accurate schedules, improve communication, and map project plans (Zakaria, 2025).

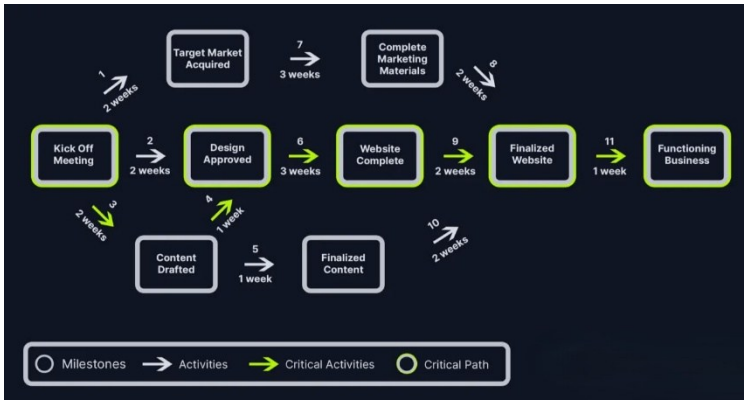


Figure 9. CPM Example (Zakaria, 2025).

2.6.1.1 CPM Applications

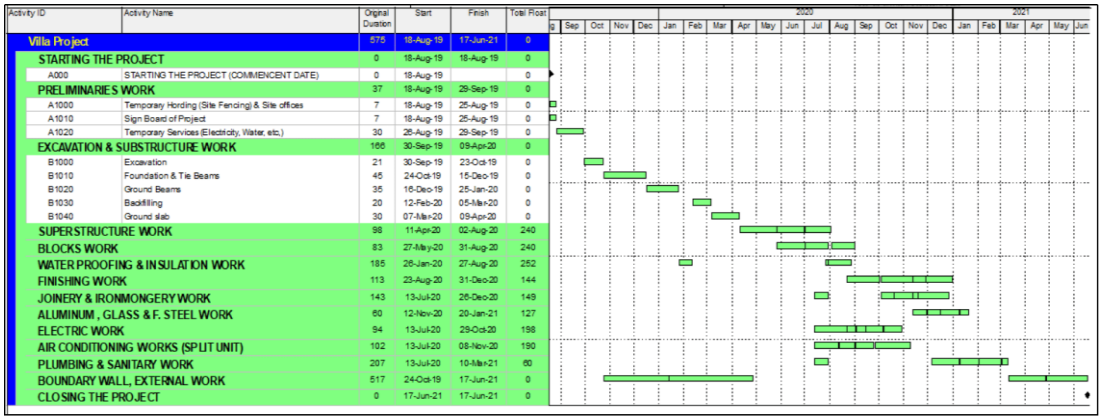
Cynthia and Ezra studied GMS Digital Marketing to analyze and improve the management of time in advertising planning. The authors listed some key applications of CPM based on the context of the study:

1. **Identifying Critical Activities**: By using CPM, project managers can determine which activities are critical for the project's success. This involves analyzing the sequence of tasks and identifying those that cannot be prolonged without impacting on the overall project schedule.
2. **Forward and Backward Scheduling**: The CPM process involves two main procedures: a forward pass to determine the earliest start (ES) and earliest finish (EF) times, and a backward pass to establish the latest start (LS) and latest finish (LF) times. This dual approach helps in creating a comprehensive schedule that optimizes time management.
3. **Cost Management**: CPM is not only about time management; it also aids in cost-cutting. With critical path understanding, project managers can negotiate costs and schedules effectively, ensuring that projects are completed on time while minimizing expenses.
4. **Resource Allocation**: The method helps in identifying the need for additional resources, such as labor, to meet project target dates. By examining the critical path, managers can assign resources more efficiently to ensure timely completion of tasks.
5. **Improving Efficiency**: The application of CPM leads to improved efficiency in project execution. By concentrating on critical activities and optimizing the schedule, organizations can reduce delays and enhance overall productivity in their advertising efforts (Ezra et al., 2024).

In summary, CPM in project management improves time management, identifies critical activities, and enhances cost, resource, and overall efficiency (Ezra et al., 2024). However, Ezra's findings, based on the advertising market, may not apply to other industries with different dynamics. The research focuses on pre-planning and lacks empirical data from varied contexts. Evaluating these findings in industries like the STATCOM sector, where real-time decision-making is crucial, could provide broader insights.

2.6.1.2 CPM Software

Software like Primavera P6 and MS Project (including its web and desktop version) have been designed to facilitate the process of Critical Path Method (CPM) scheduling and to calculate the total float for activities without manual calculations. Primavera P6 is widely used and recognized project and portfolio management tool for planning, scheduling, and executing projects, with a primary emphasis on the CPM scheduling method. The CPM technique centers around tasks and their logical relationships. The green bar charts on the right side are visually representing the planned dates and durations for each activity (Stolevski, 2022).



Activity ID	Activity Name	Original Duration	Start	Finish	Total Float
Villa Project		575	18-Aug-19	17-Jun-21	0
STARTING THE PROJECT		0	18-Aug-19	18-Aug-19	0
A000	STARTING THE PROJECT (COMMENCENT DATE)	0	18-Aug-19		0
PRELIMINARIES WORK		37	18-Aug-19	29-Sep-19	0
A1000	Temporary Hording (Site Fencing) & Site offices	7	18-Aug-19	25-Aug-19	0
A1010	Sign Board of Project	7	18-Aug-19	25-Aug-19	0
A1020	Temporary Services (Electricity, Water, etc.)	30	26-Aug-19	29-Sep-19	0
EXCAVATION & SUBSTRUCTURE WORK		166	30-Sep-19	09-Apr-20	0
B1000	Excavation	21	30-Sep-19	23-Oct-19	0
B1010	Foundation & Tie Beams	45	24-Oct-19	15-Dec-19	0
B1020	Ground Beams	35	16-Dec-19	25-Jan-20	0
B1030	Backfilling	20	12-Feb-20	05-Mar-20	0
B1040	Ground slab	30	07-Mar-20	09-Apr-20	0
SUPERSTRUCTURE WORK		98	11-Apr-20	02-Aug-20	240
BLOCKS WORK		83	27-May-20	31-Aug-20	240
WATER PROOFING & INSULATION WORK		185	26-Jan-20	27-Aug-20	252
FINISHING WORK		113	23-Aug-20	31-Dec-20	144
JOINERY & IRONMONGERY WORK		143	13-Jul-20	26-Dec-20	149
ALUMINUM , GLASS & F. STEEL WORK		60	12-Nov-20	20-Jan-21	127
ELECTRIC WORK		94	13-Jul-20	29-Oct-20	198
AIR CONDITIONING WORKS (SPLIT UNIT)		102	13-Jul-20	08-Nov-20	190
PLUMBING & SANITARY WORK		207	13-Jul-20	10-Mar-21	60
BOUNDARY WALL, EXTERNAL WORK		517	24-Oct-19	17-Jun-21	0
CLOSING THE PROJECT		0	17-Jun-21	17-Jun-21	0

Figure 10. Primavera P6 Gantt chart (Stolevski, 2022)

Furthermore, Stolevski explained the difference between linear scheduling and critical path scheduling. The image clearly illustrates that Linear Scheduling (left) represents work progress over time and distance, commonly used for repetitive or continuous activities like road or pipeline construction. It shows how different tasks overlap and progress along a spatial dimension. Whereas CPM Scheduling (right) uses a Gantt chart format to display task dependencies and durations. It determines the critical path, which is the longest chain of interdependent tasks that dictates the minimum duration required to complete the project. Both methods help manage project timelines but are suited for different types of work—linear scheduling for location-based projects and CPM for complex, interdependent tasks.

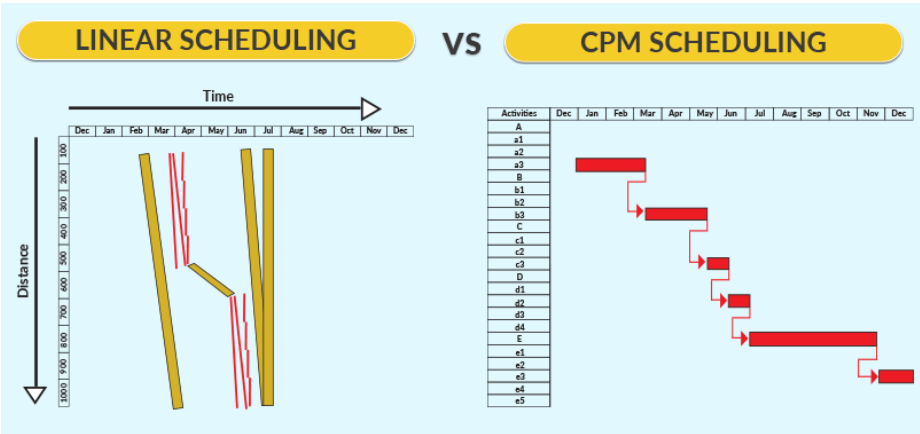


Figure 11. Linear Vs. CPM Scheduling (Stolevski, 2022)

2.6.2 Fast Tracking

In addition to CPM, other scheduling techniques such as crashing and fast-tracking have gained prominence in the literature (Hendrickson & Au, 1989). Fast-tracking is a strategic approach often used in project management to expedite the completion of tasks by overlapping phases or activities, ultimately leading to quicker delivery and increased efficiency. This method can be particularly beneficial in dynamic environments where time constraints are critical, allowing teams to adapt and respond swiftly to changing

project requirements (Abuwarda & Hegazy, 2019). Fast-tracking requires an integrated approach where all stakeholders are involved from the beginning. This ensures consistency and uniformity throughout the project execution stages, which is particularly beneficial in projects where the schedule is a key driver (Subramanian et al., 2019).

Fast-tracking increases the likelihood of risks but offers benefits, such as improved resource utilization and the ability to recover lost time or meet tighter deadlines. It can be particularly useful when project circumstances change or when specific priorities need to be met ahead of the original schedule. However, it also increases risk by requiring parallel work, which is harder to manage and control. It demands extra planning to ensure that the triple constraint—quality, scope, and budget—is maintained, as the added complexity can lead to unforeseen issues (Landau, 2024).

According to Landau, projects can be fast-tracked in the following way:

1 Define Goals and Capabilities: Clarify project goals and team capabilities to ensure fast-tracking is feasible.

2 Identify Task Dependencies: Identify tasks that shall be completed before successor activities and those that can run in parallel.

3 Review Project Schedule: Find tasks that can be done simultaneously without affecting the overall project.

4 Evaluate Alternatives: Determine what parts of the schedule can be adjusted.

5 Decide on Fast-Tracking: Select tasks that can be fast-tracked based on the evaluation.

6 Seek Consensus: Involve the team and stakeholders for approval before proceeding.

7 Monitor Progress: Continuously track progress and address issues as they arise.

2.6.2.1 Fast-Tracking Strategies

Abuwarda and Hegazy emphasized the importance of integrating multiple fast-tracking strategies to manage complex projects but noted the difficulty of considering all acceleration options due to constraints like resource limits and milestones. Hegazy and Abuwarda identified four primary strategies for fast-tracking:

1. **Linear Activity Crashing**: This concerns reducing the duration of critical tasks, often at an increased cost. Techniques include working overtime or adding more workers.
2. **Discrete Activity-Mode Substitution**: This strategy allows project managers to choose between different execution modes for activities, weighing cost against speed. For example, outsourcing work can be faster but more expensive.
3. **Path Substitution**: This involves replacing a series of activities with alternative paths that may be faster, such as using prefabricated materials instead of traditional methods.
4. **Activity Overlapping**: This strategy allows for the partial parallel execution of activities, which can save time but may increase the risk of resource conflicts and rework (Abuwarda & Hegazy, 2019).

Although Abuwarda and Hegazy highlighted that recent studies focus on advanced optimization techniques, such as Constraint Programming (CP), for more flexible and efficient scheduling. However, while the multi-dimensional optimization model by Hegazy and Abuwarda appears theoretically sound, its practical application may be challenging for project managers unfamiliar with CP.

2.6.2.2 Fast Tracking Vs. Project Crashing

The objective of schedule compression is to shorten project timelines, typically by employing fast tracking or project crashing methods. Fast-tracking involves executing project activities simultaneously, while project crashing adds additional resources. Both techniques help recover lost time. Neither technique is inherently better or worse; they serve different purposes and shall be chosen as per the project's needs. If opting for fast-tracking, ensure activities on the critical path are completed in parallel. If the critical path cannot be shortened, reducing the project's duration will not be possible (Landau, 2024).

Crashing is a project timeline compression technique where additional resources (e.g., manpower, equipment, or financial investment) are allocated to critical path activities to reduce project duration (Hendrickson & Au, 1989). It focuses on adding resources rather than changing task sequences. Crashing is effective when the added resources lead to a tangible reduction in completion time. However, it often results in increased costs and potential inefficiencies due to workforce overload or diminishing returns (Yokoyama & Goto, 2016). Conversely, fast-tracking entails overlapping tasks that would typically be performed sequentially. While this approach can lead to significant time savings, it also introduces risks associated with increased complexity and potential rework (Hendrickson & Au, 1989).

Table 1. Fast-Tracking Vs. Crashing (by author)

Aspect	**Fast Tracking**	**Crashing**
Method	Overlapping tasks	Adding resources
Cost Impact	Minimal to moderate	High
Risk Level	High (errors, rework)	Moderate (cost overrun)
Best used	Activities can logically overlap	Additional resources can reduce duration.

Figure 12 illustrates the differences between a normal project schedule, a fast-tracked schedule, and a crashed schedule, highlighting the impact of each approach on project duration and resource allocation.

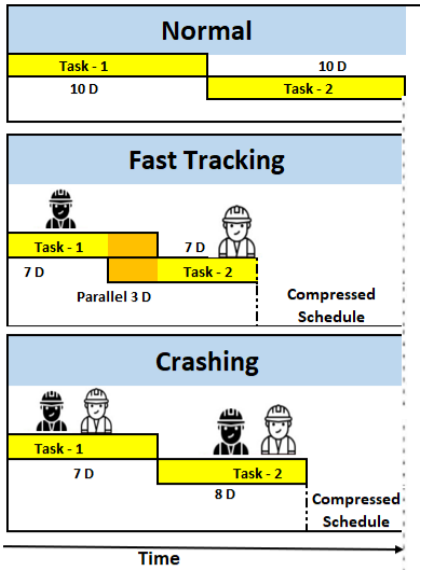


Figure 12. Fast-Tracking Vs. Project Scheduling (Anubhav Sharma, 2024)

2.6.2.3 Fast-Tracking Limitations and Challenges

Fast-tracking offers the potential for accelerated delivery, but it also brings increased complexity and heightened risks that must be carefully managed. Despite its potential advantages, fast-tracking has its own challenges and limitations that must be weighed when deciding whether to implement this strategy. Moazzami in 2011 and Egeblakin and Omotayo in 2021 studied the fast-tracking limitation and challenges in the construction industry. Egeblakin and Omotayo's study was based on the construction project in Qatar.

1. **Increased Complexity and Risks:** Fast-tracking increases risks due to overlapping design and construction phases, leading to rework, cost overruns, and quality issues. This overlap can cause errors, scope creep, and misalignment of goals. A systems-based approach, like causal loop diagrams, helps identify and mitigate risks by revealing cascading issues.
2. **Impact on Project Change:** While fast-tracking shortens project duration, it doesn't necessarily increase changes but makes managing them harder. Real-

time decisions leave little time to assess full implications, leading to reactive changes. Effective change management is crucial to stay on track.

3. **Pseudo-Physical Barriers**: Reducing a schedule by more than 25% often results in poor outcomes. Compressing tasks increases resource shortages and delays. Some project elements, like regulatory approvals, can't be fast-tracked without compromising safety or compliance. Managers must carefully assess realistic timelines.
4. **Safety and Methodology Challenges:** Fast-tracking can rush safety procedures, increasing accident risks. Safety protocols may need adaptation, requiring extra resources or expertise. Consistent safety monitoring throughout the project is necessary to address risks from compressed timelines.
5. **Limited Resource Flexibility**: Fast-tracking demands more resources, increasing the risk of delays, cost overruns, and burnout. Coordinating resources effectively is key to avoiding conflicts and shortages.
6. **Quality Assurance and Control Strain:** The speed of fast-tracking strains quality assurance, potentially causing defects and non-compliance. A rigorous quality management approach is vital, though challenging under tight deadlines.
7. **Stakeholder Misalignment:** The rapid pace of fast-tracking can cause stakeholder misalignment if changes aren't communicated clearly. Proactive communication strategies are essential to manage differing priorities and ensure alignment.

While these studies examine the challenges and risks of fast-tracking in construction projects, their narrow focus is limited to the construction industry. As a result, their applicability to other contexts or industries is restricted.

2.7 Case Studies

In this section of the literature review, two case studies from the construction industry and one case study from the oil and gas sector have been reviewed, exploring regional

and contractual aspects and offering insights into the specific difficulties faced within this context.

2.7.1 Case Study 1: Contract-based EPC Project

The study titled "A Case Study of Implementing Project Management Processes in EPC Contracts" by Shafiq, Thaheem, Albattah and Sami-Ur-Rehman investigated the project management processes of an EPC contractor involved in a large power transmission revamp project in Saudi Arabia. The project faced significant delays and rework, leading to a strained relationship with the client. To address these issues, the study employed a mixed-method data collection approach within a single case study framework. This involved a comprehensive review of existing project management documentation, one-to-one interviews, and focus group sessions with key project personnel to gather insights into the current practices and identify gaps in the project management processes.

The findings revealed a variety of factors that hindered effective project performance across all aspects of the EPC project. Key issues included unclear project scopes, inadequate technical specifications, and collaborative difficulties during the initial planning phase. The study identified that timely and accurate information is crucial for defining project requirements before proposal submission. Additionally, the research highlighted the importance of addressing gaps in project management phases like initial planning, engineering management, and quality control to enhance overall project performance. Recommendations were provided for each project management area, aimed at improving processes and mitigating delays, which could serve as a valuable resource for future research and practice in EPC project management.

In conclusion, the study contributed significantly to the understanding of project management processes in EPC contracts by identifying critical gaps and providing

actionable recommendations. However, a notable limitation of the study was its reliance on a single case study, which, while offering in-depth insights, may restrict the generalizability of the findings to other EPC projects or contexts. The study's focus on one specific project means that the results may not fully represent the broader challenges faced by EPC contractors in different settings or industries. Overall, the research serves as a foundation for future studies aimed at improving project management practices in the EPC sector (Sami Ur Rehman et al., 2022).

2.7.2 Case Study 2: Construction Industry

The study by Bragadin and Kähkönen focused on the assessment of schedule health in construction projects, emphasizing the importance of a quality construction schedule for project success. It identified a methodical approach to evaluate schedule quality, which has been a relatively under-researched area in construction management. The research culminated in the development of a Schedule Health Assessment method that incorporates various criteria to measure schedule quality effectively. The study used a constructive research approach to develop effective construction schedules, refining requirements through sample applications. It introduced a schedule management approach, benefiting SMEs, and evaluated 48 Schedule Health Assessment criteria, categorized into contractual compliance, schedule development, and components, with 8 obligatory and 40 complementary criteria.

The study concluded that the proposed Schedule Health Assessment method is a valuable tool for project schedulers, particularly in SMEs, to produce and maintain high-quality schedules. The method was tested through a case study, yielding a satisfactory schedule quality score of nearly 70%, demonstrating its practicality and alignment with project practices (Bragadin & Kähkönen, 2016). The diagram below by Bragadin and Kähkönen illustrates the structure of the Schedule Health Assessment method, which evaluates construction project schedule quality. It outlines 75 schedule requirements categorized into five groups: general requirements, construction process, schedule

mechanics, cost and resources, and control process. The figure visually depicts how these components interact, emphasizing a holistic approach where deficiencies in one area affect others. Additionally, it represents the assessment process, showing how planners can use defined metrics to identify deficiencies and improve schedule maintenance. Overall, the diagram serves as a key visual tool for understanding the methodology and its systematic approach.

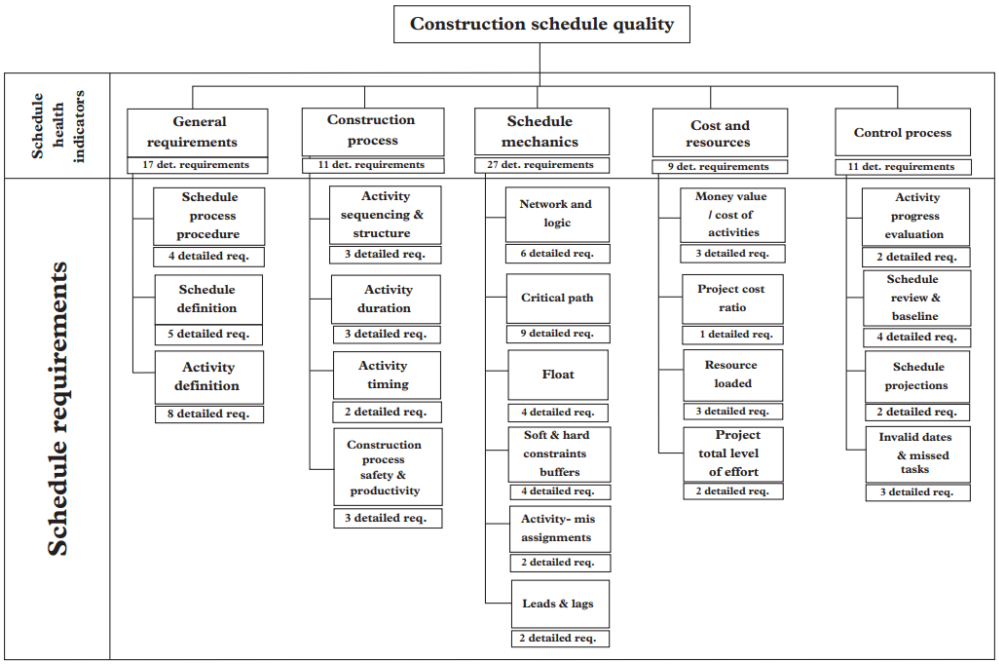


Figure 2 Schedule Health Indicators and schedule requirements

Figure 13. SHI and SR by Bragadin & Kähkönen

However, Bragadin and Kähkönen's study focused the contract-based management, which restricted its ability to fully capture the complexities of diverse construction projects, particularly those that do not strictly adhere to contractual obligations. Additionally practical challenges of implementing the 75 schedule quality requirements, especially in SMEs with limited resources, limit the broader applicability of the findings.

2.7.2 Case Study 3: Oil and Gas Sector

The study by Yi, Lee and Ahn focused on the impact of design delays on the schedule performance of Engineering, Procurement, and Construction (EPC) projects in the oil and gas sector. It highlighted the significant losses incurred by Korean contractors due to inadequate engineering performance. A Monte Carlo simulation was employed using Primavera Risk Analysis to analyze three sample onshore oil and gas projects, revealing that the engineering phase is crucial for project success.

The simulation results showed that engineering delays could impact project schedules up to ten times more than procurement and construction delays. Piping design activities had the greatest influence on overall schedule performance. To minimize delays, the study proposed a six-step design schedule management process, including milestone and productivity management. The result indicated an outline of a comprehensive design schedule management approach that includes monitoring key milestones using variance analysis, tracking critical drawing release dates for construction readiness, managing design productivity with weekly progress curves, ensuring smooth coordination through interface checklists, overseeing vendor print submissions linked to payment milestones, and managing work fronts to maintain continuous progress across project areas. The findings confirmed that well-structured and focused engineering phases significantly improve project success rates.

The study concludes that efficient management of the design phase is essential for the timely completion of EPC projects. By implementing the proposed design schedule management process, contractors can better allocate resources and manage engineering tasks, ultimately improving project outcomes (Yi et al., 2019). However, the study did not account for unforeseen external risks, which could affect the baseline schedule and overall project performance. Moreover, it assumed that no delays were experienced in

the case study projects, which may not reflect real-world scenarios where unforeseen events often occur.

2.8 Research Gap

Existing literature on project scheduling methodologies, like the Critical Path Method and fast-tracking, underscores their theoretical effectiveness in optimizing project timelines. However, their practical application in complex STATCOM projects remains underexplored. While CPM provides a structured approach to scheduling, its efficiency can be compromised by uncertainties in execution, resource constraints, and dependency conflicts when tasks are overlapped using fast-tracking.

Despite advancements in scheduling tools and project management software, there is limited empirical research on how CPM-based scheduling and fast-tracking strategies can be optimized to increase the project schedule efficiency while maintaining quality and cost-effectiveness in STATCOM projects. However, literature lacks insight into how such technologies can be practically implemented to identify bottlenecks, enhance scheduling efficiency in real-world EPC projects, particularly in the power systems sector. Therefore, this research will search to bridge this gap by examining the effectiveness of CPM-based scheduling and fast-tracking in STATCOM projects, identifying key challenges, and proposing practical solutions to improve scheduling efficiency while mitigating risks associated with parallel execution.

2.9 Theoretical Framework

EPC projects are inherently complex due to their large scale, diverse stakeholders, and interdependent processes, making them more susceptible to delays. These delays can arise from various factors, including unforeseen technical challenges, supply chain issues, and resource mismanagement, affecting project timelines and overall success.

Scheduling tools play a crucial role in managing these complexities, helping project managers allocate resources efficiently and predict potential delays. The Critical Path Method (CPM) is commonly used to identify critical tasks that directly impact the project timeline, while fast-tracking, a technique used to overlap project phases, can accelerate project completion. However, despite their usefulness, both CPM and fast-tracking need to be studied further to understand their impact on reducing project timelines and minimizing delays in EPC projects. The conceptual framework of this research aims to bridge the gap by examining how these scheduling tools can be used to improve project scheduling efficiency and complete the projects within contractual timeline in the EPC sector. Research conducted on practical projects will provide valuable insights into how these tools can be applied in the latest STACOM projects, offering practical solutions to reduce project timelines and address current scheduling challenges.

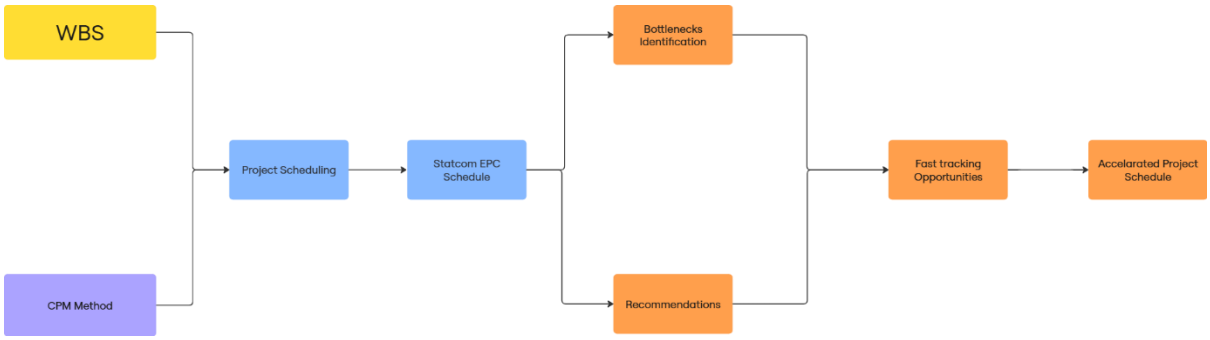


Figure 14. Theoretical Framework (by author)

3 Empirical Study: STATCOM project

An analytical review of the current project schedule is conducted to assess the planning and execution framework for a STATCOM EPC project. The project encompasses several interdependent phases, including engineering, procurement and manufacturing, followed by the installation and commissioning phase.

3.1 Project phases

The project schedule is organized into the following key disciplines/phases, each of which will be analyzed to identify bottlenecks, float values to review the effectiveness of activities relationships and use of the CPM method, and opportunities for optimization.

1. System Design: System design is the foundational phase that outlines the structure and behavior of the overall project. It involves defining system architecture, components, interfaces, and data flows. According to Lemon, system design translates user requirements into a blueprint for implementation. This phase is crucial as it ensures alignment between technical specifications and business objectives (Mark Lemon, 2011). In the context of the STATCOM, the system design phase includes essential tasks such as main equipment studies, harmonic analysis, modeling and verification processes. The timely completion and delivery of system design documents directly affect procurement schedules, manufacturing timelines, and site implementation progress.

Below are the activities listed in the case project’s schedule, with particular emphasis on those exhibiting a high total float. Total float represents the maximum allowable delay for an activity without impacting the project's overall completion date. High total float values may indicate scheduling inefficiencies, weak dependencies, or misaligned activity relationships, which can mask underlying risks in project execution. Identifying such activities is essential for refining the critical path and improving overall schedule

reliability. As explained by Keane and Caletka, "total float is often used as a buffer, but excessive float can suggest poor planning or unclear activity sequencing," making it a valuable indicator in schedule optimization efforts (Keane & Caletka, 2008).

Table 2. System design schedule activities (by author)

Sr. #	Activity Name	Original Duration	Free Float	Total Float
1	Main equipment study	95	0	424
2	Harmonic Performance and Rating study	87	0	454
3	Insulation coordination study	91	0	422
4	STATCOM Interharmonic Model	128	0	988
5	RAM study	65	0	1093
6	Losses study	60	0	750
7	Magnetic fields study	67	0	1118
8	DRPC High Frequency Interference Study	107	0	1122
9	Audible noise study	70	0	1183
10	Electrical Fields Study	67	0	1118
11	SSTI Network Model	181	0	894
12	Desktop simulation plant model	5	0	425
13	Other studies	62	0	787

2. Electromechanical Design: Electromechanical design integrates mechanical and electrical engineering disciplines to create functional systems. This phase involves the design of enclosures, wiring, motor integration, and sensor placement. Khandpur notes that the synergy between mechanical form and electrical function is critical for system reliability and performance (Khandpur, 2006). The following table presents the electromechanical activities along with their total float values, which may lead to scheduling inefficiencies or hidden risks if not properly addressed.

Table 3. Electromechanical activities (by author)

Activity ID	Activity Name	Original Duration	Free Float	Total Float
1	VSC Valves Spc & Drawings	5	0	0
2	Cooling System Spec	5	0	0
3	MV Component Spec	60	0	123
4	Magnetic fields study	20	0	1137
5	DRPC High Frequency Interference Study	60	0	1187
6	Audible noise study	20	0	1183
7	Electrical Fields Study	20	0	1159

3. Hardware Design: The Hardware (HW) design discipline involves the creation of detailed drawings for the STATCOM cubicles. This phase is critical as it ensures that the technical specifications and design layouts for the cubicles are accurately developed. The successful completion of HW design is essential for ensuring that all subsequent manufacturing, installation, and commissioning activities can proceed without delays. The following table shows hardware design activities with high and negative float.

Table 4. Hardware design activities (by author)

Sr. No	Activity Name	Original Duration	Free Float	Total Float
1	P&C spec - Common HW specification	52	0	-31
2	P&C spec - Control HW specification	50	0	307
3	P&C spec - DFR specification	52	0	369
4	Control cubicles - Drawings	22	0	307
5	Protection Setting Calculation	10	0	325
6	Communication cubicle	10	0	686
7	Marshalling and interface cubicles	15	0	632
8	LV cables - Drawings and lists	50	0	861
9	Signal list - HW Basic	10	122	429
10	Signal list - HW Detailed	50	0	900

4. Software Design: Software design includes architectural design, module decomposition, data structures, and algorithm development. Terry and William argue that robust software design enhances system modularity and maintainability, which is essential in embedded and integrated systems (Terry Ruas, 2020). This encompasses the development and configuration of control and monitoring systems and testing a real digital simulator system. It includes key activities such as the specification of control software, design and desktop testing, as well as dynamic performance studies. The activities are highly interdependent, with each step building upon the completion of the previous one to ensure the functionality and reliability of the software. Effective management of these activities, including proper sequencing and timely execution, is crucial to maintaining the project's schedule and mitigating potential risks associated with delays. The diagram below illustrates the key software design and testing activities.

Table 5. Software design activities (by author)

Sr. No.	Activity Name	Original Duration	Free Float	Total Float
1	Control SW specification	90	0	418
2	Control software design and desktop testing	131	0	367
3	PSCAD Large Network Model Verification Study	120	0	354
4	STATCOM Digsilent EMT Model and verification report	83	0	688
5	Dynamic performance study	173	0	396
7	Internal SW Testing	182	0	307
6	Customer SW test	5	0	367

5. Procurement: Procurement involves sourcing components, selecting vendors, and managing supply chain logistics. Kabirifar emphasizes the strategic role of procurement in ensuring timely and cost-effective material availability. In EPC projects, procurement is often a bottleneck due to long lead times and coordination issues (Kabirifar & Mojtahedi, 2019). In the context of the Statcom project, proper planning, timely PO placements, and management of procurement activities will help mitigate potential delays in procurement and guarantee that the project proceeds smoothly, on schedule,

and within budget. The following table lists the key equipment items that need to be procured as part of the project.

Table 6. Procured equipment list (by author)

Activity ID	Activity Name	Original Duration	Free Float	Total Float
1	VSC valves	503	0	629
2	Control cubicles	379	0	866
3	Marshalling and interface cubicles	319	0	866
4	Optical fibres	106	0	861
5	Cooling system	456	0	881
6	Reactors	435	0	885
7	Surge arresters	395	0	912
8	Surge capacitors	400	0	915
9	Instrument transformers	427	0	893
10	Wall bushing	365	0	932
11	Pre-charge circuit	402	0	917
12	Disconnectors	391	0	924
13	Insulators (for VSC Valve)	384	0	918

6. Installation and Configuration: The final phase includes physical installation, wiring, system integration, and configuration. This step transforms the design into a functioning product. According to Sampaio, this phase is critical for testing, commissioning, and handover activities, and any flaws here can derail the project timeline (Santos & Sampaio, 2023). This phase will be scrutinized for critical path and scheduling risk due to site readiness and availability of required material at site. The table below summarizes the key activities analyzed in this section, alongside their original durations and current float values.

Table 7. Installation and commissioning activities (by author)

Sr. No.	Activity Name	Original Duration	Free Float	Total Float
1	Equipment tests	50	0	307
2	Subsystem tests	90	0	430
3	Commissioning tests	54	0	307

3.1 Schedule Timeframe

Effective scheduling is pivotal in project management, as it delineates the sequence and duration of tasks, ensuring that project objectives are met within the stipulated timeframe. According to Gilbert, meticulous scheduling not only facilitates timely project completion but also enhances resource allocation and risk management (Gilbert, 2024). The overall project schedule for this project spans 60 months, beginning in January 2025 and ending in December 2030. This extended timeline reflects the complexity, technical integration, and coordination efforts required for delivering high-voltage grid-support infrastructure.

The diagram below presents the current schedule of the ongoing Statcom project.

- Earliest Start: Jan-2025
- Latest Finish: Dec-2030
- Total Schedule Duration: 60 months

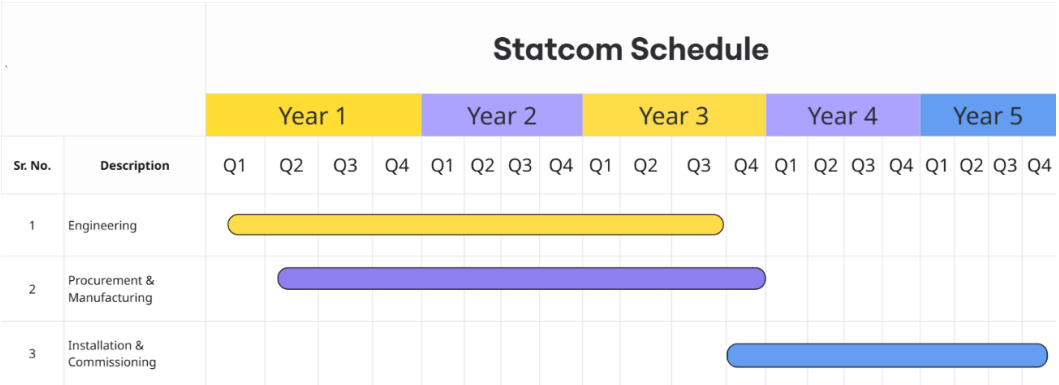


Figure 15. Project timeline of the ongoing Statcom project (by author)

3.2 Key Configuration Settings

The STATCOM project schedule is structured using a defined set of configuration parameters that directly influence the outcomes of critical path analysis, float calculations, and the overall visibility of scheduling risks. These foundational settings establish how the schedule is calculated and interpreted during planning and execution.

The float in the project schedule is calculated using the Finish Float approach, which assesses how much an activity can be postponed without delaying the project's finish. This approach ensures focus remains on activities that could directly impact overall project completion. According to Yang, understanding and managing float is crucial for effective project scheduling and timely completion. Activities are classified as critical when their Total Float is less than or equal to zero, indicating they have no scheduling flexibility. This highlights the importance of maintaining progress on these tasks to avoid project delays. The Critical Path Method (CPM) identifies such activities as critical, as they directly influence the project's duration (Jyh-Bin Yang, 2017).

The schedule applies the Retained Logic calculation method with early start-based lag calculation, which maintains the logical sequencing of activities even when delays occur. This approach supports more accurate forecasting and delay impact assessments by preserving planned dependencies. As noted by Nagata and Mutschler, Retained Logic ensures that the original activity relationships are honored, providing a realistic schedule progression (Mark Nagata & Neil Mutschler, 2019).

Notably, open-ended activities—those lacking either a logical predecessor or successor—are not automatically treated as critical. While this maintains a cleaner critical path view, it may also obscure potential risks if such activities are not closely monitored. The presence of open-ended activities can lead to inaccuracies in the critical

path analysis, potentially hiding scheduling risks (Jyh-Bin Yang, 2017). Additionally, resource leveling has not been performed, meaning that the schedule does not account for resource constraints when calculating activity timelines. This could introduce practical challenges during execution if overlapping resource demands are not resolved.

Summary of Configuration Settings:

1. Float Calculation: Finish Float
2. Critical Activity Definition: Total Float ≤ 0
3. Calculation Logic: Retained Logic with early start-based lag
4. Open-Ended Activities: Not made critical (Indicates some schedule risks might not be visible through the critical path method)
5. Resource Leveling: Not performed

These settings form the technical backbone of the schedule and are essential for interpreting downstream results such as float distribution, risk exposure, and critical path continuity.

3.3 Schedule Statistics

The STATCOM project schedule comprises a total of 1,004 individual activities, reflecting the extensive scope and complexity of the EPC work involved. The granularity of the schedule underscores the complexity and interdependence of the technical disciplines involved. These activities are interconnected through 1,751 logical relationships, highlighting a highly interlinked task structure that requires precise coordination. Such a dense network of dependencies increases the sensitivity of the overall schedule to delays or disruptions in any single path, particularly those on or near the critical path.

Furthermore, 45 activities are governed by imposed constraints, such as start-no-earlier-than (SNET) or mandatory finish conditions, which can restrict scheduling flexibility and may artificially shift or mask critical path visibility. Constraints, while often necessary due to contractual, logistical, or technical reasons, need to be managed carefully to avoid unintended scheduling bottlenecks. Taken together, these figures point to a highly detailed and tightly coupled project schedule that necessitates continuous tracking, float analysis, and timely interventions. Effective schedule governance is critical in such environments to mitigate cascading delays and ensure adherence to key milestones.

Table 8. Project schedule metrics (by author)

Metric	Value	Description
Total Activities	1004	Number of individual tasks in the project schedule
Relationships (Dependencies)	1751	Dependencies connecting the activities
Constrained Activities	45	Activities with imposed start and finish constraints
Average relationships per activity	1.74	Indicates the average number of dependencies per activity (total logical relationships / total number of activities)
Constraint types	Start/Finish Constraints	Type of constraints applied to the activities

3.4 Constraint and Logic Quality Check

A comprehensive schedule quality assessment of the STATCOM project can reveal several structural inconsistencies and logic-related risks that could affect the accuracy, reliability, and robustness of the critical path analysis and overall project tracking (Gilbert, 2024). One key issue in the project is the presence of 33 activities without defined predecessors and 111 activities without successors. These open-ended tasks can compromise the logical flow of the project network, potentially obscuring the true critical path and

reducing the effectiveness of float analysis. According to PMI's Practice Standard for Scheduling, schedules with missing dependencies are more susceptible to inaccurate forecasting and poor progress control (Project Management Institute, 2007). In addition, there was 1 case of invalid milestone logic, where a milestone is either improperly constrained or mislinked, reducing its effectiveness as a project control point.

Another significant issue is the existence of 177 mismatched calendar relationships, where linked activities use different calendars (e.g., differing work weeks or holidays), resulting in misaligned durations and inconsistent float calculations. Such discrepancies can lead to scheduling anomalies and hinder the accurate representation of timeframes. Together, these issues highlight the importance of rigorous logic checks and schedule validation prior to execution. Ensuring that all activities are properly linked, logically sequenced, and operating under consistent calendars enhances the integrity of schedule forecasts and supports more effective decision-making. The following table presents a summary of schedule Logic and constraint quality issues in the project.

Table 9. Schedule Logic and Constraint Quality Issues (by author)

Metric	Value	Description
Activities without Predecessors	33	Open starts that may obscure the critical path
Activities without Successors	111	Open ends that hinder float and delay tracking
Invalid Milestone Logic	1	Mislinked or improperly constrained milestone
Mismatched Calendar Relationships	177	Links across activities with inconsistent calendar settings

3.5 Calendar configuration

The project schedule for the project case utilizes a local standard working calendar, which is structured around a five-day workweek, spanning Monday through Friday, with a total of 37.5 working hours per week. This baseline calendar is applied uniformly across

the schedule to maintain consistency in resource allocation, task duration estimation, and baseline comparison. While the use of a single standard calendar supports internal planning coherence, it also introduces limitations when applied across geographically diverse project locations. In particular, the installation and commissioning activities, which are expected to occur in different countries, may be subject to site-specific working practices, including public holidays, local labor regulations, and regional workweek variations.

Failure to account for these differences can result in inaccurate float calculations, misleading activity durations, and ultimately, schedule slippage. As emphasized by Niazi and Painting, aligning project calendars with actual site conditions is essential for ensuring schedule realism and effective project control (Niazi & Painting, 2017). Therefore, customized calendars should be assigned to activities based on their geographic and operational context to improve schedule reliability and forecasting accuracy.

3.6 Critical Path and Risk Pointers

The critical path of the STATCOM project schedule consists of a tightly linked sequence of activities that are essential for achieving on-time project completion. Defined by zero total float and free float, these tasks possess no scheduling flexibility, making them highly sensitive to delays and requiring strict monitoring and timely execution. Critical activities span multiple project phases, including software development, detailed engineering, factory acceptance testing (FAT), equipment installation, subsystem testing, and final commissioning, underscoring the cross-functional interdependencies within the EPC scope. The number and diversity of these activities reflect the complexity and integrated nature of the project, where any delay may lead to direct slippage in the overall completion date.

The number and diversity of critical path activities reflect the complexity and integrated nature of the project. Any delay in these tasks may lead to direct slippage in the project's planned finish date. As noted by Herroelen and Leus, critical path-based risk analysis is essential in complex projects to ensure visibility into schedule vulnerabilities and to develop effective contingency strategies (Herroelen & Leus, 2005). To strengthen project schedule management, a focused review of the critical path is recommended throughout the project lifecycle, particularly at key milestones and during phase transitions. Below are the case Statcom project critical activities extracted from the Primavera P6 schedule.

Table 10. Critical Path Activities and Float Analysis (by author)

Activity ID	Activity Name	Original Duration	Free Float	Total Float
1	Software development	106	0	0
2	STATCOM EMT Model and Verification Report	167	0	0
3	Verification study & network model RTDS	165	0	0
4	RTDS - Customer FAT	10	0	0
5	Control cubicles transportation	16	0	0
6	Installation STATCOM Cubicles	10	0	0
7	Installation P&C Cubicles	10	0	0
8	Remaining works Cubicle installation	10	0	0
9	Cable Pulling	30	0	0
10	Optical fibers terminations/connection	30	0	0
11	LV Cable glands and termination	30	0	0
12	Remaining works Cabling	20	0	0
13	MV Switchgear, Auxiliary Transformers, AC/DC Auxiliary systems - Commissioning	20	0	0
14	VSC/Cubicles - Equipment tests	40	0	0
15	Protection & Control - Commissioning	30	0	0
16	AIS equipment - Commissioning	10	0	0
17	Remaining works Equipment tests PET	10	0	0
18	VSC/Cubicles - Subsystem tests	67	0	0
19	Transformer - Packaging & delivery	20	0	0
20	Installation PTR	37	0	0
21	Remaining works outdoor equipment	20	0	0
22	Remaining works Subsystem tests	15	0	0
23	LV Cable glands and termination	30	0	0
24	Project management meeting to be initiated by Contractor before start of complex functionality test	1	0	0

25	Complex Function Test	65	0	0
26	Remaining works Cabling	20	0	0
27	MV Switchgear, Auxiliary Transformers, AC/DC Auxiliary systems - Commissioning	20	0	0
28	VSC/Cubicles - Equipment tests	40	0	0
29	Protection & Control - Commissioning	30	0	0
30	AIS equipment - Commissioning	10	0	0
31	Remaining works: Equipment tests	10	0	0
32	VSC/Cubicles - Subsystem tests	80	0	0
33	Remaining works: Subsystem tests	15	0	0
34	Project management meeting to be initiated by the Contractor before the start of the complex functionality test	1	0	0
35	Complex Function Test	65	0	0
36	Preparation of project documentation	100	0	0
37	Confirmation project documentation	20	0	0
38	Transformer - Manufacturing & FAT	225	0	0
39	Project Management	54	0	0
40	Engineering	54	0	0
41	P&C Spec - Control SW specifications	109	0	0

3.7 WBS of the Project

The Work Breakdown Structure (WBS) provides a hierarchical breakdown of the project scope into manageable sections, supporting effective planning, scheduling, and control (Mukul Burghate, 2018). The following diagram presents the current WBS for the case STATCOM project, consisting of engineering, procurement and installation and commissioning activities.

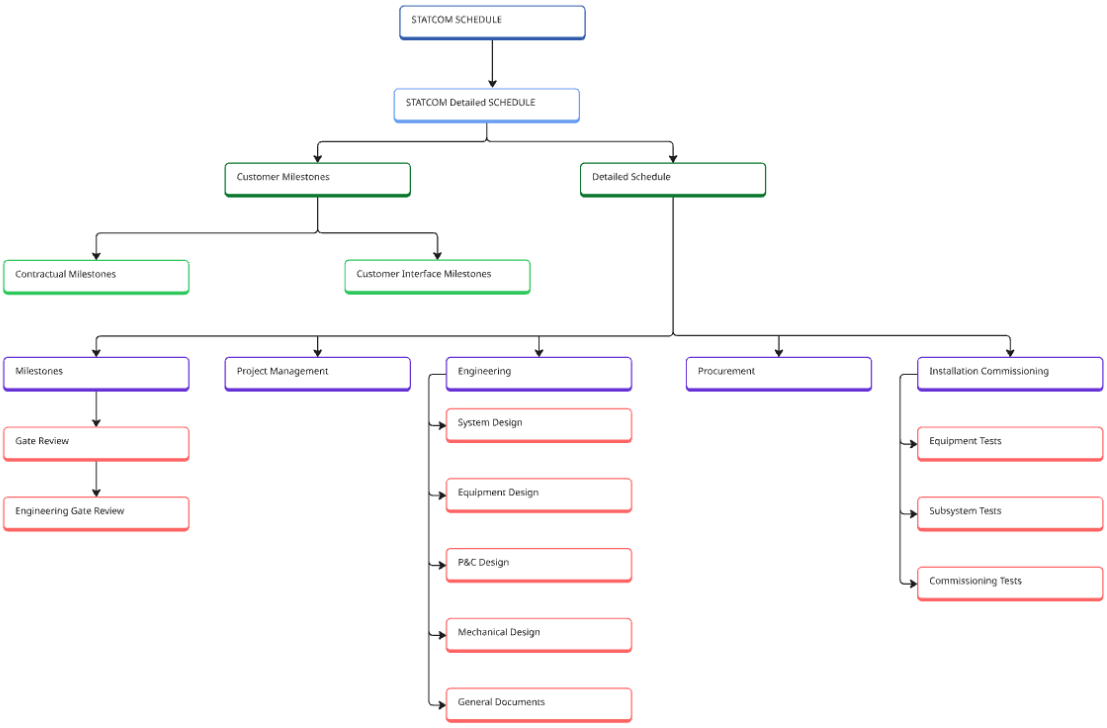


Figure 16. WBS of Statcom project (by author)

Thus, in summary, the STATCOM project is a valuable case study due to its complexity, long duration, and critical role in enhancing grid stability and supporting renewable integration. Its detailed EPC scope offers rich insights into project scheduling, coordination, and risk management in large-scale power infrastructure.

4 Methodology

Research method refers to the systematic plan for conducting research, incorporating the strategies, methods, and tools used to collect and analyze data in order to answer specific research questions (C. R. Kothari, 1990). This qualitative case study explored the application of Critical Path Method and fast tracking in a Statcom project within an EPC company. Interviews with project managers and decision-makers provided in-depth insights into real-world challenges, decision-making processes, and optimization strategies. Thematic analysis was used to find key themes which are related to project scheduling, resource allocation, and efficiency. To make sure the validity and reliability of the findings, the results were cross-checked with interview transcripts and other data sources to confirm consistency and accuracy in identifying emerging themes and insights.

4.1 Sampling

Sampling refers to the method of extracting a smaller group from a larger population to make generalizations about the overall population. It allows researchers to gather data efficiently without examining every member of the population, making studies more feasible in terms of time, cost, and resources (Ilker Etikan, 2016). For sampling, a case company with an ongoing Statcom project was selected to provide relevant insights into the application of CPM, project scheduling, and optimization. The company was chosen based on its involvement in a live Statcom project, ensuring the data collected was pertinent to the research. A total of 16 interviews were conducted with engineers, officers, and project managers or managers who are directly involved in the process of the project. The interviewees were selected on the basis of their active involvement in the STATCOM project.

4.2 Data Collection

Data collection refers to the organized process of obtaining information from multiple sources to address research questions, assess hypotheses, or analyze outcomes. It can be qualitative (e.g., interviews, group feedback, & observations) or quantitative (e.g., surveys, experiments, numerical records). The accuracy, reliability, and validity of research heavily depend on how well the data is collected and managed (Sajjad Kabir, 2016). The data collection methods employed in this study included a combination of literature review, case studies, interviews, and a case study approach focused on an ongoing project:

1. **Case Studies**: In addition to the theoretical review, several case studies from existing literature were examined. These case studies provided real-world examples of CPM applications, project management challenges, and optimization methods in various project-based industries. This helped in identifying best practices and potential areas for improvement in Statcom project management.

2. **Interviews**: Focused-group interviews were conducted with 16 project managers and industry experts in early April 2025. The interviews were conducted online using Microsoft Teams.

3. **Open-ended questionnaire:** Open-ended questionnaires allow interviewees to give answer to the questions in their own words, providing rich, detailed, and often unexpected insights that structured formats may miss (Sajjad Kabir, 2016). In this study, data was collected using an open-ended questionnaire consists of 11 questions which are designed to explore participants' experiences and perspectives in depth.

4. **Case Study of an Ongoing Project**: An ongoing STATCOM project was selected as a case study. This allowed the research to gather real-time data and observe how CPM techniques were being implemented in practice. By analyzing this existing case, the study was able to assess current project scheduling and optimization strategies, providing a practical context for the theoretical concepts discussed.

4.3 Data analysis

Data analysis in this study was conducted through manual thematic analysis. Interview responses were carefully reviewed and segmented into meaningful units, which were then coded to represent specific ideas or concepts. These codes were grouped into broader categories to identify key themes across the data. Microsoft Excel was used to organize and structure the codes, supporting the creation of tables that visualized recurring patterns, issues, and bottlenecks. This process enabled a systematic and transparent exploration of the participants' perspectives and helped uncover the underlying themes critical to understanding their experiences.

4.4 Data Validity and Reliability

Several strategies were employed to ensure the validity and reliability of the study. A structured interview process was followed to maintain consistency across interviews, ensuring that each participant answered the same set of questions in a consistent manner. To enhance validity, the preliminary findings were shared with participants to confirm the accuracy and alignment with their perspectives. In addition, the analysis was conducted in alignment with established literature and theoretical frameworks, ensuring that the themes identified were grounded in existing research. This process reinforced the credibility of the study's findings by comparing them with recognized concepts.

4.5 Limitations & Ethical Considerations

The key limitation of this study is the focus on a single, ongoing STATCOM project. While this allowed for a detailed, in-depth exploration of project scheduling practices, the findings would not be completely generalized to other organizations or projects in the STATCOM field. Additionally, since all participants were from the same company, there is

a potential for a limited range of perspectives, which could have introduced bias in the responses. The findings are therefore specific to the practices and experiences of the case company and may not reflect broader industry trends.

Ethical considerations were thoroughly addressed through the research process. All participants were fully informed about the study's purpose and ensured that confidential company details would not be part of the thesis before interviews. Prior to the interviews, the participants were also told that the sessions would not be recorded, as explicitly requested by interviewees. The questionnaire was shared with participants in advance, giving them ample time to prepare and reflect on the questions. To ensure confidentiality, all the data was anonymized, and no identifying information about the company or participants was disclosed in the report. Additionally, all ethical guidelines of the research institution were strictly followed, ensuring transparency, integrity, and respect for participants' privacy throughout the study.

5 Results

The results section presents the key findings derived from the case study, which are essential for answering the research questions and demonstrating the link between data and interpretation (Merriam & Tisdell, 2016). This chapter presents the findings from interviews with key stakeholders involved in the system design, electromechanical design, hardware design, software design, and procurement phases. The aim was to identify bottlenecks in each phase and gather suggestions for improvement. The results highlight key challenges and proposed solutions, which will inform the critical review of the Work Breakdown Structure (WBS) and critical path schedule in the next chapter.

5.1 Bottlenecks

The following section presents the interview-based findings that identify key scheduling bottlenecks across each phase of the STATCOM project: system design, electromechanical design, hardware design, software design, procurement and installation and configuration activities.

5.1.1 System Design

During the interviews, specific efforts were made to identify key bottlenecks affecting the timely completion of system design activities in the STATCOM project. A major issue highlighted was the dependency of the Main Equipment Study on client-provided data. Although a predefined list of required information is shared with the customer at the start of the project, delays and incomplete submissions are common. This directly impacts the finalization of system design and slows overall project progress.

> “We can’t move forward with the Main Equipment Study until we receive complete input data from the customer. Even though we share a data checklist early on, there are always delays or missing parameters, and that stalls the entire design timeline.”
> —P1(Manager)

The Main Equipment Study, considered foundational to the basic design phase, plays a critical role in enabling downstream engineering and procurement activities. The project manager emphasized that client-side delays represent one of the most significant bottlenecks in the early design timeline. In addition to client-related delays, New Product Introduction (NPI) activities were also identified as a recurring challenge. According to the lead engineer and design engineer, the incorporation of new features or technologies often disrupts the system design process. These changes require additional validation, coordination across departments, and updates to technical documentation, all of which introduce uncertainty and delay.

As stated by the Lead Engineer:

> "Introducing new features through NPI activities often throws a wrench into our schedule. The system design has to be adjusted, validated, and coordinated again—it's not just a plug-and-play situation." —P2 (Lead Engineer)

The design Engineer further stated:

> "The design team ends up doing multiple iterations when NPI elements are added mid-phase. It slows us down because these additions require extra validation and alignment with other teams." —P3 (Design Engineer)

As system design serves as the foundation for procurement, manufacturing, and site implementation, any delays in this phase can have a cascading impact on the entire project schedule. Such delays risk pushing back contractual milestones and increasing exposure to Liquidated Damages (LDs). These findings reinforce the importance of early identification and mitigation of design-phase bottlenecks to maintain overall schedule integrity.

5.1.2 Electromechanical Design

One of the notable bottlenecks identified in the electromechanical design phase, which was identified during the data collection, is the dependencies on upstream inputs and coordination with external stakeholders. Interviewee 4 emphasized that progress in valve specifications and drawings is directly tied to the timely completion of earlier studies, stating that:

> "The completion of the Main Equipment Study is a major input for the valve specifications and drawings." —P4 (Team leader, EM design)

This dependency implies that any delays in the Main Equipment Study create a cascading effect, stalling subsequent design activities and threatening the overall project timeline. In addition to internal dependencies, coordination with external vendors also emerged as a critical factor. Interviewees 5 and 6 both underlined the importance of involving the cooling system vendor at the earliest possible stage, preferably from the tender phase. As noted by one of them, "the cooling system vendor should ideally be involved from the tender stage," enabling the parallel development of technical documentation and integration of design requirements. Without this early engagement, there is a heightened risk of misalignment. As one interviewee warned,

> "There is a risk that changes will be required in the drawings after vendor finalization, which not only causes schedule disruptions but also leads to increased costs due to rework." —P5

A clear pattern across these insights is the importance of early-phase planning and integration. Delays in finalizing upstream studies or deferring vendor involvement result in downstream inefficiencies. As summarized by an interviewee,

> "Proactive integration of technical inputs is essential for keeping the schedule on track and avoiding rework." —P6

These findings highlight how both internal and external coordination challenges contribute significantly to bottlenecks in the electromechanical design phase, underscoring the need for a more synchronized and anticipatory approach to design management.

5.1.3 Hardware Design

The interview revealed that in the hardware design phase, a key bottleneck is the timely acquisition and confirmation of customer-specific requirements for standard cubicle designs. The lead engineer from the hardware design department emphasized that "customer requirements for the standard cubicle design are a crucial input for completing the design process," and any delays in receiving or validating these requirements can significantly impact the schedule. These inputs are foundational for progressing with the detailed hardware design, and uncertainty or late-stage changes can disrupt planned timelines.

Another critical constraint in hardware design is the finalization of hardware specifications. As stated by the hardware engineer:

> "Delays at hardware stage can have a direct and cascading effect on the design and manufacturing of the cubicles." —P9

This delay can affect downstream activities such as procurement and installation. The dependency of manufacturing schedules on accurate and timely design outputs means that any upstream hold-ups can quickly snowball, creating wider disruptions in the overall project execution. These insights underscore the importance of front-loading customer engagement and streamlining the specification approval process to prevent bottlenecks in the HW design phase.

5.1.4 Software Design

Results indicate that control software development is one of the project activities with the highest level of uncertainty, posing a substantial risk to schedule adherence. Interviewee 10, a manager, emphasized that,

> "Software design plays a critical role in the broader project timeline, as any delays or issues during this phase can have a ripple effect on the overall schedule." —P10 (Manager, SW)

A key bottleneck highlighted by Group 4—consisting of Interviewees 10, 11 (Lead Engineer), and 12 (Tester)—was the unavailability of essential input from the customer during the initial stages of the project. They emphasized that receiving all necessary customer input early is crucial for defining control functions and minimizing changes later. Without timely access to this information, software teams are forced to make assumptions or delay development, both of which can lead to rework and schedule disruptions.

Another constraint in the software phase is the limited availability of testing facilities. With multiple projects running in parallel, the testing laboratory space and resources become a shared bottleneck. Interviewees observed that the demand for testing resources may exceed capacity, resulting in delays during validation and commissioning. This issue highlights the importance of effective resource planning and cross-project coordination to ensure timely access to testing environments.

Together, these findings point to two main areas of concern: the timely collection of customer inputs and the strategic allocation of shared resources. Addressing both is essential for minimizing delays and maintaining momentum in the software development phase.

5.1.5 Procurement

The procurement phase presents several critical bottlenecks that directly influence the broader project timeline. One of the main issues identified during the data collection was the prolonged period vendors require to submit their offers, which, when coupled with the internal administrative approval process, results in substantial delays. Interviewee 13 stated that:

> "The time vendors take to submit offers, combined with internal approval requirements, significantly extends the procurement timeline, which can pose a considerable risk to schedule adherence." —P13 (procurement manager)

Interviewee 13 further emphasized that the timely delivery of procured equipment is a recurring challenge during the evaluation stage. According to the manager,

> "Several vendors fail to meet the equipment delivery timelines, which leads to disruptions not only in procurement but also in subsequent stages such as installation and commissioning." —P13 (procurement manager)

Interviewee 14, a Lead Officer, reinforced the cascading nature of this issue, stating that delays in equipment delivery have a direct negative impact on installation and the overall project timeline. These insights reveal how procurement-related inefficiencies—ranging from delayed vendor responses to poor delivery performance—can create bottlenecks that ripple through the entire project. Addressing these challenges requires improving vendor management practices, streamlining administrative approvals, and enforcing stricter delivery accountability to maintain project momentum and prevent downstream delays.

5.1.6 Installation and Commissioning Activities

Results indicated that the installation and commissioning phases are particularly vulnerable to delays caused by external dependencies and logistical inefficiencies. A

major bottleneck identified in this phase is the dependency on the completion of civil works and building construction, which are typically executed by third-party contractors hired by the customer. As Interviewee 16, a Technical Project Manager, highlighted the impact that external contractors can have on the project schedule by stating,

> "Equipment installation cannot proceed until civil works and building readiness are completed." —P16 (Technical project manager)

Material-related issues also emerged as a recurring source of disruption. Interviewee 15, a Project Manager, pointed out that

> "Discrepancies in material deliveries—such as incorrectly sized bolts, missing software license dongles, or unavailable tools—have caused delays at the site. These issues often lead to unplanned stoppages, rescheduling of tasks, and increased coordination efforts, compounding the challenges faced during installation." —P15 (Project Manager)

Moreover, both managers emphasized the complex nature of stakeholder interactions during this phase. They noted that the installation and commissioning stages involve numerous interfaces that must be carefully managed to prevent delays, highlighting the importance of proactive communication and coordination. These findings suggest that meticulous planning, thorough material verification, and effective stakeholder interface management are essential to preventing bottlenecks and ensuring the smooth execution of installation and commissioning activities.

5.2 Critical Path Analysis and Activity Dependencies in the Case Project

The following section presents the analysis of the Critical Path Method (CPM) and activity dependencies in the case project, highlighting how task relationships impact scheduling

efficiency across the five key phases: System Design, Electromechanical Design, Hardware Design, Software Design, and Procurement and installation phase.

5.2.1 System Design

System design is a critical component of the engineering phase in EPC projects, as it establishes the technical baseline for all downstream activities, including procurement, construction, and commissioning (Eiampikul, 2017). Following the identification of activities with high total float, a detailed review was conducted to evaluate whether these activities were appropriately categorized under the System Design Work Breakdown Structure (WBS). This assessment involved both document analysis and qualitative input from interviews with key project personnel, including a project manager, lead engineer, and design engineer. The findings revealed that several activities currently listed under the System Design WBS were not directly related to system design. According to Interviewees 1, 2, and 3, the misclassification of non-design-related tasks into this phase has created ambiguity, diluted accountability, and hindered focused planning and execution. All the managers in group 1, stressed that:

> "Only activities directly related to system design should be included under the System Design WBS."

5.2.2 Electromechanical Design

This section analyzes the activities associated with the Electromechanical discipline by examining both free float and total float values. Insights from the interviews are used to assess the accuracy and quality of activity relationships, which help to spot potential scheduling inefficiencies and areas for improvement. During a group interview with key project stakeholders—Interviewee 4 (Team Leader), Interviewee 5 (Lead Engineer), and Interviewee 6 (Engineer)—it was observed that while the activities listed under the Electromechanical Work Breakdown Structure (WBS) were generally appropriate, the

way they were linked in the schedule was a concern. The interviewees pointed out that the high total float values associated with these activities indicate a lack of properly defined interdependencies, which misrepresents the actual project timeline and weakens the effectiveness of the schedule. They emphasized that valve and cooling system deliverables are critical components of the basic design phase and are essential to the timely progression of the overall project. According to the participants, these activities should be reflected on the critical path with zero total float, as delays in these areas would directly impact subsequent engineering and procurement processes.

5.2.3 Hardware Design

This section analyzed the activities associated with HW design discipline in which both free float and total float values were examined to assess the quality of activities relationships. During a group interview with key stakeholders—Interviewee 7 (Manager), Interviewee 8 (Lead Engineer), and Interviewee 9 (Hardware Engineer)—concerns were raised regarding the current scheduling of activities within the Hardware (HW) design discipline. The interviewees unanimously agreed that the total float values assigned to these activities are not accurate, pointing to a lack of properly defined sequencing and interdependencies.

This observation aligned with the presence of both significant total float and instances of negative float in the schedule, suggesting inconsistencies in how the relationships between tasks are structured. The participants specifically highlighted that the finalization of hardware specifications and cubicle drawings are critical milestones in the project. Delays in these areas were described as having a direct and cascading impact on downstream processes, including procurement and manufacturing, ultimately risking substantial delays to the overall project timeline.

5.2.4 Software Design

In a group interview with Interviewee 10 (Manager), Interviewee 11 (Lead Engineer), and Interviewee 12 (Software Tester), it was consistently emphasized that the control software design and testing phases represent some of the longest and most critical activities in the entire project. The interviewees unanimously noted that the total float currently assigned to these activities in the project schedule does not accurately reflect their true duration or criticality. They stressed that the scheduling logic needs to better represent the dependencies and sequence of tasks involved in the software workflow. According to the participants, the actual timeline for software development, testing, and delivery should be used as a basis when developing or refining the project schedule to ensure that it reflects reality and minimizes risk. These insights highlight the necessity of aligning the project schedule with practical execution timelines. To support the findings, a process diagram was developed to illustrate the major steps within the control software discipline—SW model preparation, SW testing, and testing with the customer. This visualization reflects the real-world sequence and duration of these phases, as reported by the interviewees, and underscores the need for accurate scheduling and resource planning aligned with these critical activities.

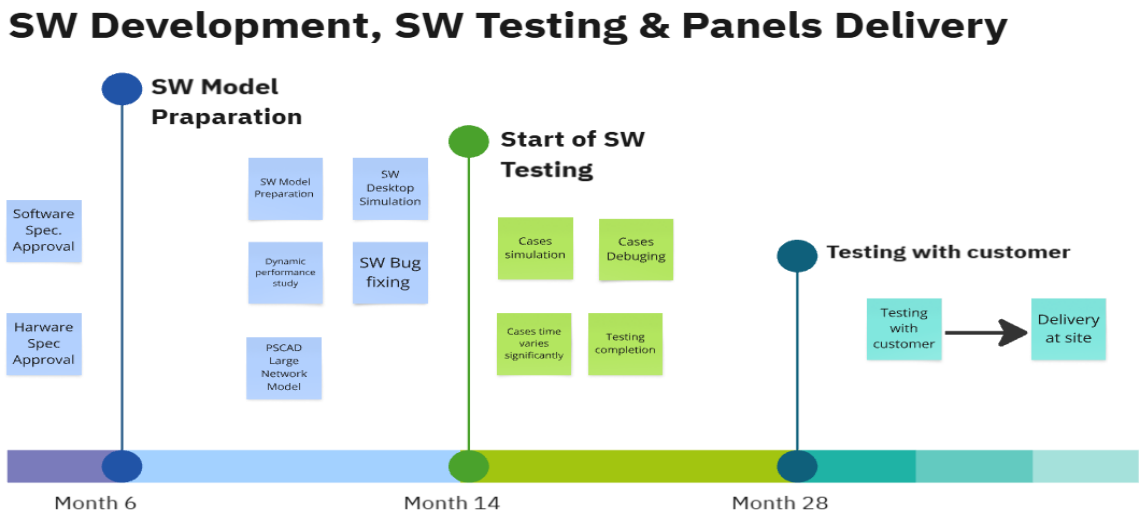


Figure 17. SW testing timeline (by author)

5.2.5 Procurement

During a group interview with Interviewee 13 (Manager) and Interviewee 14 (Lead Officer), several key insights were shared regarding the procurement-related activities in the project schedule. Both interviewees observed that the case schedule exhibits a general pattern of significant total float across all procurement activities, which fails to accurately reflect the real-world constraints and timelines. A critical example highlighted during the discussion was the control cubicle, which currently shows a total float of 866 days. Both interviewees agreed that this is a misrepresentation, given the control cubicle's long lead time and its crucial role in initiating control software testing. As a key component in the manufacturing and testing phases, its delivery timing directly affects multiple downstream activities. Therefore, its placement in the schedule must be revised to reflect its criticality and prevent potential delays.

5.2.6 Installation and Commissioning Activities

This section analyzes three critical activities—equipment tests, subsystem tests, and commissioning tests—each of which plays a pivotal role in the project's successful completion. Findings from a group interview with Interviewee 15 (Project Manager) and Interviewee 16 (Technical Project Manager) revealed significant concerns regarding the current project schedule. Specifically, they criticized the improper assignment of activity relationships during the schedule preparation, noting that:

> "The activity relationships were not properly assigned during the preparation of the case schedule, leading to misleading float values—specifically, the 307 days of total float assigned to commissioning activities." —P15, P16

According to both managers, this float allocation is "unjustified and creates a false sense of flexibility," masking critical scheduling risks. They emphasized that the current float values do not accurately represent the true sequencing and dependencies of activities, thereby undermining effective progress tracking and forecast reliability. Furthermore,

the interviewees identified a gap in the logical structuring of the installation and commissioning phase. They pointed out that the dependencies between these tasks and preceding project activities are not sufficiently modeled. As expressed in the interview:

> "There is considerable potential for improvement in the interrelationships between project activities." —P15, P16

This misalignment, they explained, makes it difficult to determine which activities truly govern the project timeline and may lead to missed deadlines if not addressed. To mitigate these issues, both project managers advocated for the development of a well-defined and realistic critical path. They stressed that:

> "A critical schedule is essential for effective project planning and control," —P15, P16

highlighting that the Critical Path Method (CPM) is the industry-standard approach for identifying and managing key activities. By leveraging CPM, the team can ensure that scheduling reflects true dependencies and supports accurate planning, monitoring, and decision-making throughout the execution phase.

6 Discussions

The following section discusses the identified bottlenecks and interdependent activities across various project phases. Based on the results and findings from the interviews, recommendations are provided for each phase to enhance project flow and mitigate potential delays. Additionally, this section includes a revised Work Breakdown Structure (WBS), proposed critical activities and their interrelationships, a schedule compression chart, and a revised timeline bar chart, all aligned with the updated theoretical framework.

6.1 Engineering Recommendations

The following section presents targeted recommendations, based on interview insights, to address scheduling bottlenecks and improve efficiency across the five key phases of the STATCOM project: system design, electromechanical design, hardware design, software design, procurement and installation and commissioning activities.

6.1.1 System Design

Based on the bottlenecks identified at this level and stakeholder interviews, key critical activities are validated and documented. Finally, potential mitigation strategies are proposed to address bottlenecks, manage constraints on the critical path, and improve overall scheduling performance.

1. Refine the System Design WBS: The first step toward improving schedule performance is the accurate classification of activities within the System Design Work Breakdown Structure (WBS). Activities unrelated to system design should be reallocated to their appropriate categories. This refinement will improve the structure and logic of

the schedule, allow more reliable linking of dependencies, and enhance monitoring accuracy. As stated by the Lead Engineer,

> "When non-design activities are mixed into the design WBS, it clouds everything, tracking becomes confusing and decisions get delayed." —P2

2. Strengthen Client Coordination Early: To mitigate delays in receiving customer input, Interviewee 2 recommended a face-to-face milestone meeting with the client, ideally held about eight weeks after project kickoff. This session should focus on finalizing the required input data and aligning on key system design deliverables.

> "We need a fixed date for an early customer meeting. That's when everyone should sit down and lock the data—we lose weeks chasing info otherwise." —P2 (Lead Engineer)

3. Implement Fast-Tracking for Long-Lead Items: To improve procurement timelines without compromising design quality, it is recommended to initiate RFQs (Requests for Quotation) for transformers and reactors in parallel with the execution of the Main Equipment Study and Harmonic Modeling. Transformers, being long-lead items, often delay the construction phase if not ordered promptly. However, care must be taken to ensure purchase orders are placed only after formal document approvals, maintaining alignment with the finalized system design and avoiding the risk of reordering or redesigning.

> "We should start the RFQ process in parallel—it doesn't mean placing the order, but at least we're ready when the design gets approved." —P3 (Design Engineer)

4. Critical Deliverables Alignment: The current schedule showed total float values for system design deliverables ranging from 422 to 1,093 days, indicating significant scheduling flexibility. This raises concerns about the accuracy of activity sequencing and whether the schedule reflects the project's actual execution logic and priorities. It is recommended that the three essential system design deliverables, which are the main

equipment study, harmonic performance and rating study and insulation coordination study, should have zero total float to enhance clarity, traceability, and overall control of project execution during the early engineering phase.

Table 11. Revised schedule of activities (by author)

Sr. #	Activity Name	Original Duration	Free Float	Total Float	Remarks
1	Main equipment study	95			
2	Harmonic Performance and Rating study	87			
3	Insulation coordination study	91			
4	STATCOM Inter-harmonic Model	128			
5	RAM study	65			
6	Losses study	60			

6.1.2 Electromechanical Design

The findings led to several key recommendations in the EM activities aimed at improving efficiency and reliability. First, it is essential to clearly define activity dependencies within the project schedule. The current planning framework shows a disproportionately large total float, which does not accurately reflect the actual sequence and interdependence of tasks. By refining these relationships, project managers can better identify the true critical path, enabling more effective monitoring and timely response to potential delays.

Second, early engagement of the cooling system vendor should be ensured, ideally during the tendering phase. Interview insights revealed that late involvement often results in last-minute design modifications, leading to schedule disruptions and cost implications. Early collaboration can allow for the parallel development of technical documentation and system integration plans, significantly reducing the likelihood of rework and facilitating smoother procurement and manufacturing timelines.

Finally, the study emphasizes the urgency of finalizing and releasing the project layout at an early stage. The layout serves as a foundational input for multiple critical analyses, including noise, magnetic, and electrical studies, that must be completed before progressing to subsequent phases. Delays in layout finalization can have a ripple effect across several disciplines, making early layout availability a key enabler of project momentum and cross-functional coordination.

6.1.3 Hardware Design

The findings revealed that early collaboration between hardware designers and the testing team is critical to ensuring a seamless transition between the design and validation phases. Given that these functions are typically carried out by different teams, establishing a clear line of communication from the outset can significantly enhance coordination. As highlighted during the interviews, proactive engagement enables early identification and resolution of HW-related issues, which, if left unaddressed, may surface later during testing and cause unanticipated delays.

This integrated approach not only streamlines the design-to-test workflow but also promotes shared understanding of design intent and test requirements. By aligning expectations and feedback loops early in the project, both teams are better equipped to anticipate challenges, minimize rework, and contribute to a more efficient and predictable development process. Ultimately, these practices foster a more synchronized project environment, reducing the risk of bottlenecks and ensuring that both design quality and testing timelines are upheld.

6.1.4 Software Design

The results underscored the importance of early and structured customer engagement in the control software development process. To ensure timely execution, customers

must be proactively guided regarding software development requirements and the critical role of timely input provision. Clear communication at the outset—particularly concerning the data needed to define control functions—can significantly reduce the risk of late-stage changes and rework, thereby safeguarding the project timeline. In addition, the findings pointed to resource planning as a key enabler of smooth execution. To avoid bottlenecks during the testing phase, it is essential that dedicated laboratory space for software testing is reserved in advance. This measure can help prevent scheduling conflicts, especially in environments where multiple projects compete for limited testing infrastructure.

A further strategy identified to accelerate project delivery involves the parallel production of replica cubicles. These cubicles, built independently of the main project units, serve as a testbed for control software validation. By decoupling software testing from the physical installation timeline, this approach enables development and testing to progress concurrently with on-site activities. According to project estimates, this overlapping of tasks has the potential to reduce the overall project duration by at least five months, offering a substantial efficiency gain without compromising quality or system readiness.

6.1.5 Procurement

The findings suggested that overcoming procurement-related bottlenecks requires a shift toward more strategic vendor engagement. Establishing long-term partnerships with key suppliers can enhance mutual accountability and encourage timely submission of offers. Such partnerships promote a collaborative working environment where expectations are clearly communicated, and vendors are more likely to align with project schedules and quality standards.

Furthermore, the results highlight the importance of implementing structured monitoring mechanisms, such as regular manufacturing progress reports. By requiring vendors to provide timely updates on production status, project teams can identify emerging delays at an early stage. This proactive visibility enables better risk management and ensures that corrective measures—such as expediting production or reallocating resources—can be implemented before delays affect downstream activities like delivery, installation, and commissioning.

6.1.6 Installation and Commissioning Activities

The study indicates that ensuring readiness before initiating installation activities is critical to minimizing disruptions and maintaining project momentum. To support this, a comprehensive preparedness checklist should be established to verify that all required resources, approvals, and preconditions are in place prior to commencement. Such a checklist would serve as a practical control mechanism, helping teams identify and resolve any gaps or outstanding tasks before mobilization on site. In addition, the research underscores the significance of implementing a robust interface management system to coordinate the numerous interactions between internal teams, subcontractors, and client representatives. Given the complexity of installation and commissioning, where responsibilities overlap across disciplines and organizations, structured interface management ensures transparent communication, aligned expectations, and prompt issue resolution. These mechanisms are crucial for seamless execution and reducing the risk of cascading delays during the final project stages.

6.2 Proposed Frameworks

This thesis examined scheduling inefficiencies in a STATCOM EPC project, aiming to reduce the overall project duration through Critical Path Method (CPM) analysis, fast-tracking strategies, and an in-depth evaluation of the Work Breakdown Structure (WBS).

The original 60-month schedule (January 2025–December 2030) revealed significant vulnerabilities, including 45 constrained activities, 33 without predecessors, 111 without successors, and 177 calendar mismatches. Qualitative interviews and schedule data analysis highlighted major bottlenecks in software development, system integration, and commissioning phases. In response, the study proposes a revised WBS, redefined critical path activities with improved logic links, and an optimized scheduling approach. Supporting visuals, including a schedule compression chart and timeline bar chart—illustrate a practical roadmap for improving project delivery and enhancing control.

6.2.1 Proposed WBS

The STATCOM project WBS organizes the scope into three main domains: Engineering, Procurement, and Installation & Commissioning. Engineering is further divided into system design, hardware, software, and electromechanical tasks, offering clear deliverable traceability and cross-disciplinary interdependency mapping. However, analysis revealed logic issues, many activities lacked defined predecessors or successors, and control software was not separately identified, risking oversight of critical tasks. This fragmentation hinders critical path visibility. To enhance control and progress monitoring, the WBS needed refinement to improve logical structure and schedule hierarchy.

The original project schedule did not distinctly categorize the Software (SW) discipline, embedding its activities within the broader Protection and Control (P&C) design. This approach overlooked the complexity and criticality of software design in the STATCOM project lifecycle, particularly in areas such as system integration, functional testing, and commissioning. As part of the WBS enhancement, Software has now been established as an independent discipline, highlighting its strategic importance.

Moreover, Level 2 WBS was removed due to its limited value in supporting effective planning or monitoring. To further improve structure and usability, Level 3 WBS elements were streamlined and integrated with milestone-based components from the detailed schedule. This restructuring produced a clearer, more cohesive hierarchy—enhancing deliverable traceability, simplifying progress tracking, and strengthening alignment with execution strategies. The revised and recommended WBS diagram presented below reflects the refined structure, incorporating clear discipline-based categorization and streamlined hierarchy to support effective planning, execution, and monitoring throughout the STATCOM project lifecycle.

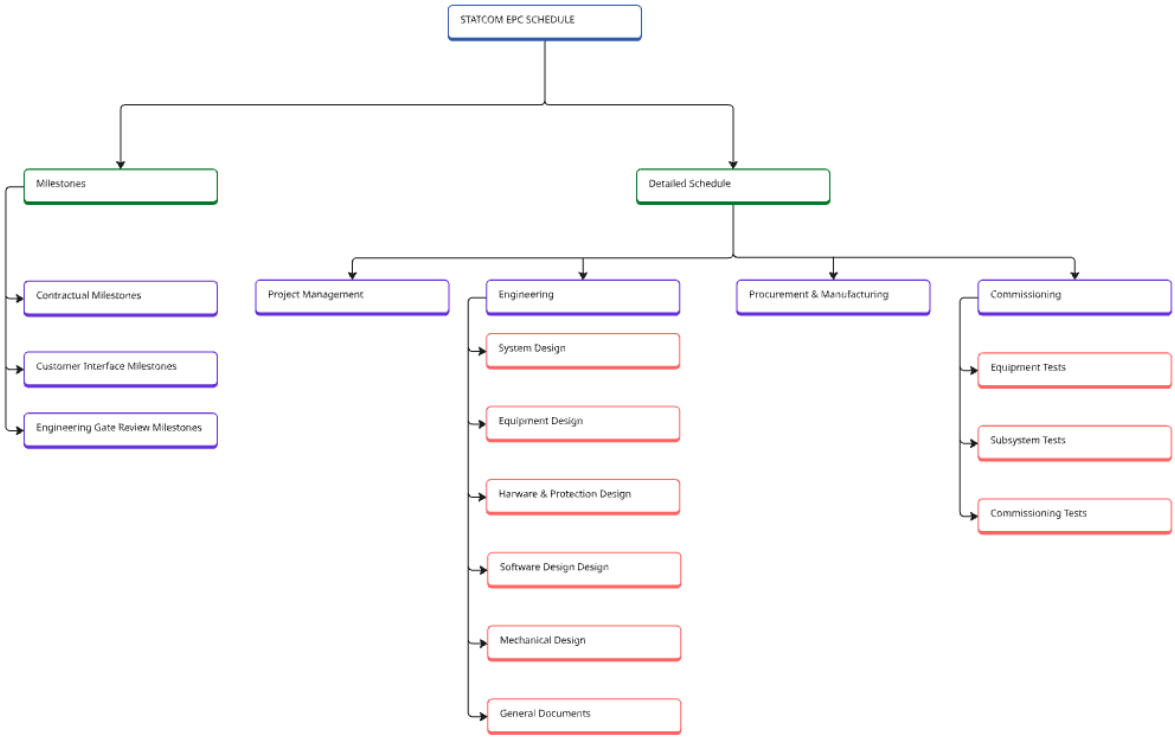


Figure 18. Proposed new WBS of Statcom project (by author)

6.2.2 Proposed Critical Path Activities and Activity Relationships

The CPM analysis showed that the schedule uses "retained logic" without resource leveling, limiting flexibility in handling out-of-sequence tasks. Key issues included open-ended logic, invalid milestone links, and a lack of proper activity relationships—many tasks had no predecessors or successors, disrupting the project flow and critical path accuracy. The use of generic calendars further distorted float calculations and milestone forecasts, while the absence of float analysis hindered the identification of scheduling flexibility. Additionally, some non-critical tasks were incorrectly marked as critical, misguiding management priorities.

To improve reliability, the schedule must address four key areas: logical sequencing, calendar accuracy, float analysis, and correct critical path identification—aligning the plan with CPM best practices for better control and predictability. Below are the major critical activities identified after reviewing the project timeline and interviews.

Table 12. Revised critical activities (by author)

Sr. No	Activities	Total Float	Remarks
1	Main equipment study	0	
2	Hardware documents	0	
3	Software Documents	0	
4	Procurement of Statcom panels materials	0	
5	Manufacturing of Statcom panels	0	
6	Testing of HW panels	0	
7	Software testing on panels	0	
8	Installation of panels at site	0	
9	Pre-commissioning works	0	
10	Commissioning works	0	

The newly proposed critical path activities—particularly those related to software development, RTDS verification, equipment installation, and commissioning—must be explicitly incorporated into the STATCOM schedule during the planning phase. These

activities should be defined with both total float and free float equal to zero, in accordance with the Critical Path Method, to ensure that their timely execution is strictly enforced.

6.2.3 Schedule Compression Impact Chart

The schedule impact chart was developed to understand the impact of the expedited schedule. Software development and testing emerged as significant contributors to schedule risk due to their duration and direct link with the installation and commissioning of the Statcom project schedule.

Table 13. Schedule compression impact table (by author)

Sr. No	Description	Original duration	Fast Tracked Duration	Method	Remarks
1	Engineering	36 Month	34.5 Months	Fast tracking of RFQs & vendor documents	
2	Procurement	39 Months	37.2 Months	Parallel involvement of vendors	
3	Installation & Commissioning	60 Months	55 Months	Parallel SW testing and panels installation at site	

6.2.4 New Timeline Bar Chart

A revised project timeline was constructed based on the sequencing of interdependent activities and the adoption of fast-tracking opportunities for selecting engineering, procurement and commissioning phases. By overlapping compatible tasks, such as software development with partial hardware procurement, and early commissioning preparations with ongoing testing, an estimated timeline reduction of 5 months was achieved. By manufacturing replica cubicles, and the installation of project cubicles at the site can be significantly fast-tracked and the overall timeline of the project can be minimized by at least 5 months. The replica cubicles can be manufactured for the

customer for future use and can be part of the CAPEX of the supplier company. Moreover, parallel preparation of equipment RFQs and quotation activities can reduce the engineering and procurement timeline. This updated schedule offers a more resilient and responsive framework, balancing technical feasibility with operational risk and aligning with project delivery expectations.

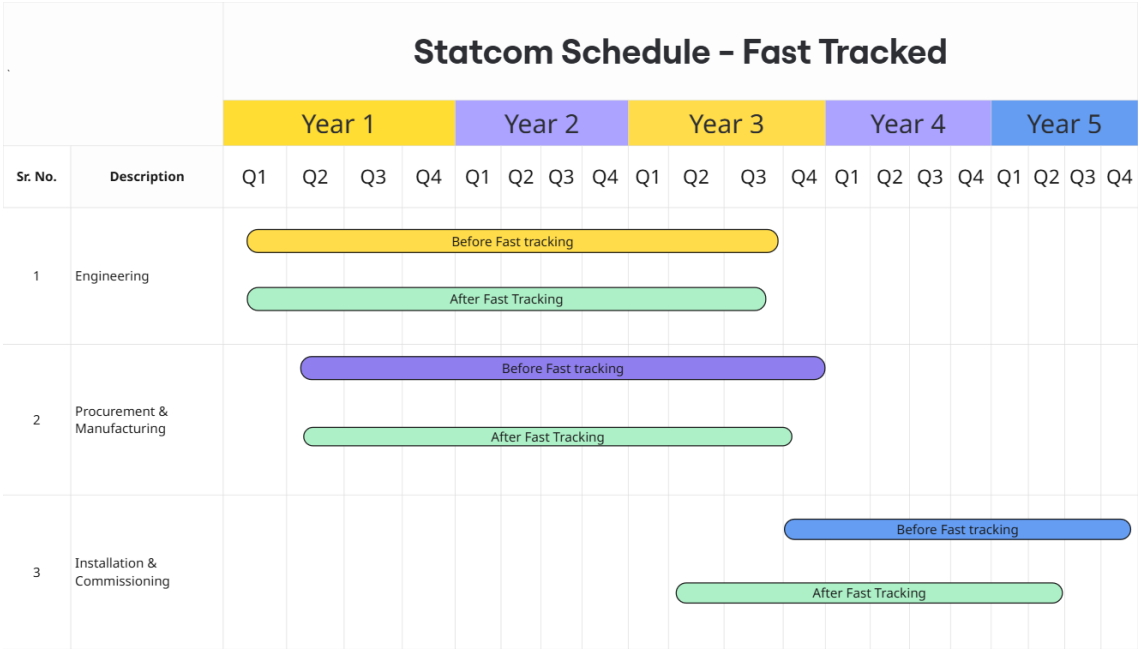


Figure 199. Revised fast-tracked Statcom schedule (by author)

6.3 Revised Theoretical Framework

The revised diagram illustrates the enhanced scheduling framework built on two main pillars: an optimized Work Breakdown Structure (WBS) and the application of the Critical Path Method (CPM). The WBS was refined to better represent all project components, particularly by defining the software discipline as a standalone element, improving clarity and traceability. The CPM method was used to correct logical flaws in the original schedule by ensuring proper activity relationships, float analysis, and accurate critical path identification. These improvements feed into the development of a more robust STATCOM EPC schedule, supported by structured project scheduling practices. From this

refined schedule, the analysis and interviews identified key bottlenecks across various disciplines.

Based on the bottleneck analysis, the diagram outlines recommendations tailored to different project phases—engineering, procurement, installation, and commissioning to improve scheduling efficiency to complete the project within the contractual timeline. The diagram also highlights fast-tracking opportunities, enabling the overlapping of tasks to shorten the project timeline. Together, these elements support the development of an accelerated project schedule that is more efficient, practical, and aligned with actual execution needs.

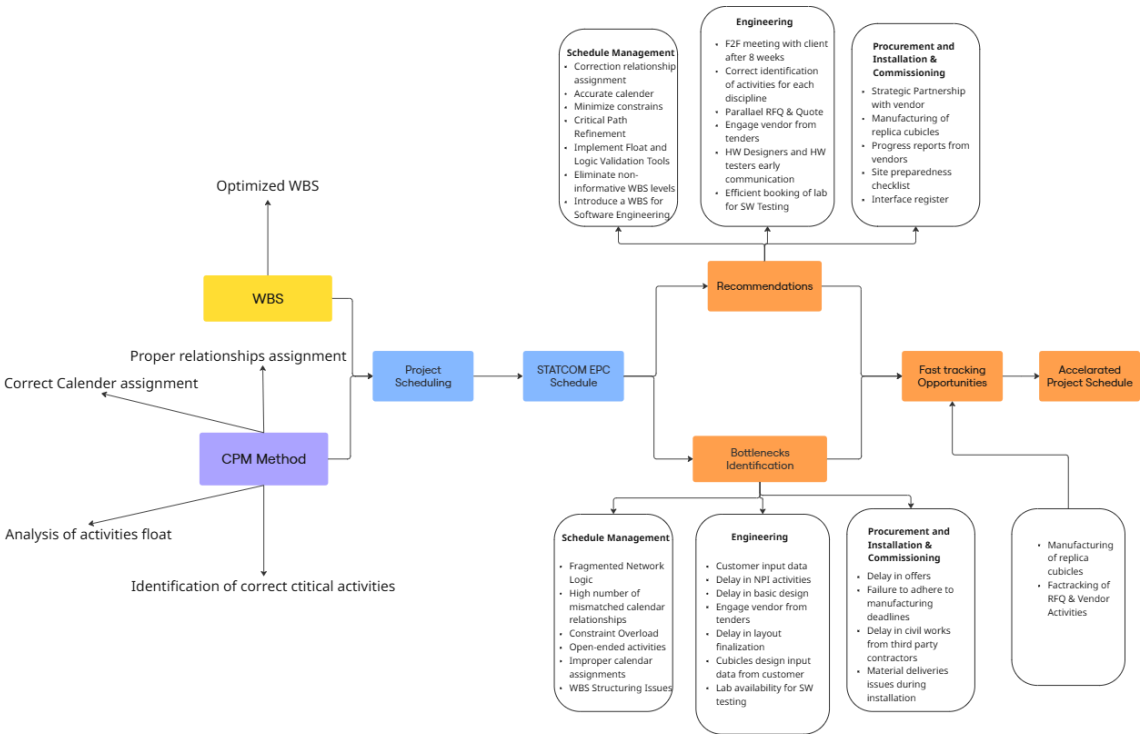


Figure 20. Revised theoretical framework (by author)

7 Conclusion

This research investigated strategies for optimizing project schedules and mitigating delays in EPC projects, with a specific emphasis on the STATCOM project. Through a comprehensive literature review and qualitative insights from project stakeholders, the study identified common scheduling bottlenecks and evaluated the applicability of established techniques such as the Critical Path Method (CPM), crashing, and fast-tracking. The case analysis revealed that reconfiguring the Work Breakdown Structure (WBS) and refining activity dependencies led to accurate critical path with zero total float and a notable compression of the project timeline. These outcomes underscore the importance of precise schedule planning and proactive delay management in improving project performance. By bridging theoretical scheduling models with practical execution strategies, this study contributes valuable knowledge to the field of project management, particularly within the context of technically complex EPC undertakings.

The practical implications of this research are significant for professionals managing large-scale EPC projects, especially those involving sophisticated power systems like STATCOM. The findings demonstrate how targeted schedule optimization techniques can lead to measurable improvements in project efficiency, offering a roadmap for practitioners to identify and address scheduling challenges early in the project lifecycle.

Future research could build upon these insights by incorporating emerging technologies such as AI-driven predictive scheduling, and real time progress tracking, which have the potential to further enhance planning precision and responsiveness. Additionally, comparative studies across different types of EPC projects or geographic regions could provide a deeper understanding of contextual factors influencing scheduling success, thereby enriching the global body of project management knowledge.

Reference

Abuwarda, Z., & Hegazy, T. (2019). Multi-dimensional optimization model for schedule fast-tracking without over-stressing construction workers. *Canadian Journal of Civil Engineering*, *46*(12), 1160–1173. https://doi.org/10.1139/cjce-2018-0544

Al-Momani. (2000). Construction delay: A quantitative analysis | Request PDF. *ResearchGate*. https://doi.org/10.1016/S0263-7863(98)00060-X

Anubhav Sharma. (2024, February 16). *(21) Schedule Compression Technique: Fast Tracking Vs Crashing | LinkedIn*. https://www.linkedin.com/pulse/schedule-compression-technique-fast-tracking-vs-crashing-sharma-vlz3f/

Bragadin, M. A., & Kähkönen, K. (2016). Schedule health assessment of construction projects. *Construction Management and Economics*, *34*(12), 875–897. https://doi.org/10.1080/01446193.2016.1205751

C. R. Kothari. (1990). *Research Methodology C R Kothari (Eng) 1.81 MB*. http://dl.saintgits.org/jspui/bitstream/123456789/1133/1/Research%20Methodology%20C%20R%20Kothari%20%28Eng%29%201.81%20MB.pdf

Cibi. (2024, December 5). *What is a bottleneck? Causes, tips, and examples*. Qntrl Blogs. https://www.qntrl.com/blog/bottleneck-examples-and-solutions.html

Ezra, P. N., Egedegbe, F. E., Nwafor, C. N., Obasi, I. N., & Okonta, C. A. (2024). Project Management Using Critical Path Method (CPM) and Project Evaluation and Review Technique (PERT). *International Journal Of Mathematics And Computer Research*, *12*(12), Article 12. https://doi.org/10.47191/ijmcr/v12i12.03

Fu, W., Liu, S., & Srivastava, G. (2019). Optimization of Big Data Scheduling in Social Networks. *Entropy*, *21*(9), 902. https://doi.org/10.3390/e21090902

Gilbert, D. L. (2024). *Effective Project Management Strategies for Identifying and Addressing Projects' Complexities and Improving Projects' Success Rates*.

Hansen, H. (2012, March 20). The Management for EPC Projects. *Hansen's Kammer*. https://hansenkammer.wordpress.com/2012/03/20/the-management-for-epc-projects/

Hendrickson, C., & Au, T. (1989). *Project management for construction: Fundamental concepts for owners, engineers, architects, and builders*. Prentice Hall.

Herroelen, W., & Leus, R. (2005). Project scheduling under uncertainty: Survey and research potentials. *European Journal of Operational Research*, *165*(2), 289–306. https://doi.org/10.1016/j.ejor.2004.04.002

Ilker Etikan. (2016). (PDF) Comparison of Convenience Sampling and Purposive Sampling. *ResearchGate*. https://doi.org/10.11648/j.ajtas.20160501.11

industrialaudit. (2015, September 4). How To: Categorize and Report Project Construction Delays [Industrialaudit]. *Workface Efficiency®*. https://industrialaudit.com/construction-delays/

James Chen. (2024, July 28). *What Is a Neural Network?* Investopedia. https://www.investopedia.com/terms/n/neuralnetwork.asp

John Lowe & Henry Odeyinka. (2002, October). (PDF) A Factor Approach to the Analysis of Risks influencing Construction Cost Flow Forecast. *ResearchGate*. https://www.researchgate.net/publication/228458225_A_Factor_Approach_to_the_Analysis_of_Risks_influencing_Construction_Cost_Flow_Forecast

Jyh-Bin Yang. (2017). (PDF) Reviewing Construction Schedule Float Management. *ResearchGate*. https://doi.org/10.2174/1874836801711010001

Kabirifar, K., & Mojtahedi, M. (2019). The impact of Engineering, Procurement and Construction (EPC) Phases on Project Performance: A Case of Large-scale Residential Construction Project. *Buildings*, *9*(1), Article 1. https://doi.org/10.3390/buildings9010015

Ketsopoulou, I., Taylor, P., & Watson, J. (2021). Disruption and continuity in energy systems: Evidence and policy implications. *Energy Policy*, *149*, 111907. https://doi.org/10.1016/j.enpol.2020.111907

Khandpur, R. S. (2006). *Printed circuit boards: Design, fabrication, assembly and testing*. McGraw-Hill.

Kumar, P., & Raj, P. (2015). *Delay Analysis of Projects and Effects of Delays in the Mining/Manufacturing Industries*.

Landau, P. (2024, July 19). *Fast Tracking: Schedule Compression in Project Management*. ProjectManager. https://www.projectmanager.com/blog/project-management-fast-tracking

Mark Nagata & Neil Mutschler. (2019). *How Retained Logic, Actual Dates, And Progress Override Deal With Out-Of-Sequence Progress*. https://www.traunerconsulting.com/how-retained-logic-actual-dates-and-progress-override-deal-with-out-of-sequence-progress/

markwideresearch. (2025, January). *Static Synchronous Compensator (STATCOM) Market 2025-2034 | Size,Share, Growth*. https://markwideresearch.com/static-synchronous-compensator-statcom-market/

maximizemarketresearch. (2025, March). STATCOM Market – Global Industry Analysis and Forecast (2024-2030) by Type, Application and Region. *MAXIMIZE MARKET RESEARCH*. https://www.maximizemarketresearch.com/market-report/global-statcom-market/70411/

Merriam & Tisdell. (2016). *L-G-0003719584-0007575839*. https://download.e-bookshelf.de/download/0003/7195/84/L-G-0003719584-0007575839.pdf

Moon, E. (2020). *Delays in Global Engineering Procurement and Construction Projects*.

Mukul Burghate. (2018, June). *(PDF) Work Breakdown Structure: Simplifying Project Management*. ResearchGate. https://www.researchgate.net/publication/345762461_Work_Breakdown_Structure_Simplifying_Project_Management

Niazi, G. A., & Painting, N. (2017). Significant Factors Causing Cost Overruns in the Construction Industry in Afghanistan. *Procedia Engineering*, *182*, 510–517. https://doi.org/10.1016/j.proeng.2017.03.145

Peng, W., Ma, J., Chen, X., Ji, Y., Sun, J., Ding, J., & Zhang, D. (2020). Optimization of the Schedule for the Whole Process in Hot Strip Manufacturing. *Metals*, *10*(6), 717. https://doi.org/10.3390/met10060717

Project Management Institute (Ed.). (2007). *Practice standard for scheduling*. Project Management Institute.

Rao, P., Crow, M. L., & Yang, Z. (2000). STATCOM control for power system voltage control applications. *Power Delivery, IEEE Transactions On*, *15*, 1311–1317. https://doi.org/10.1109/61.891520

Runtime, O. (2024, January 31). Testing & Iteration: Core Aspects of Design Thinking. *Jaro Education*. https://www.jaroeducation.com/blog/testing-iteration/

Ruwanpura, J., Ahmed, T. N., Kaba, K., & Mulvany, G. P. (2006). Project planning and scheduling and its impact to project outcome: A study of EPC projects in Canada. *AACE International Transactions*, *2006*, PS.20.1-PS.20.9.

Sajjad Kabir. (2016). (PDF) METHODS OF DATA COLLECTION. In *ResearchGate*. https://www.researchgate.net/publication/325846997_METHODS_OF_DATA_COLLECTION

Sami Ur Rehman, M., Shafiq, M., Thaheem, M. J., & Albattah, M. (2022). *A Case Study of Implementing Project Management Processes in EPC Contracts*.

Samreen Fiza. (2022, January). *(PDF) Flexible AC Transmission System*. ResearchGate. https://www.researchgate.net/publication/381110754_Flexible_AC_Transmission_System

Santos, J. L. dos, & Sampaio, R. R. (2023). Integrating Project Management, Software Development, and Knowledge Management Models: A Case Study in a Public ICT Services Organization. *Social Networking*, *12*(1), Article 1. https://doi.org/10.4236/sn.2023.121001

Sembiring, N., & Putra, A. (2020). Scheduling evaluation in construction projects using the critical chain project management method. *IOP Conference Series: Materials Science and Engineering*, *830*, 032091. https://doi.org/10.1088/1757-899X/830/3/032091

Shaker. (2014, March). (PDF) Improving the voltage profile and reactive power of the wind farm based fixed speed wind turbine with using STATCOM. *ResearchGate*. https://doi.org/10.1109/EVER.2014.6844127

Sharma, S., Gupta, S., Zuhaib, M., Bhuria, V., Malik, H., Almutairi, A., Afthanorhan, A., & Hossaini, M. A. (2024). A Comprehensive Review on STATCOM: Paradigm of Modeling, Control, Stability, Optimal Location, Integration, Application, and Installation. *IEEE Access*, *12*, 2701–2729. IEEE Access. https://doi.org/10.1109/ACCESS.2023.3345216

skyquest. (2025, January). *Statcom Market Trends, Size, Share & Forecast | 2032*. https://www.skyquestt.com/report/statcom-market

Static Synchronous Compensator: GE Grid Solutions. (n.d.). Retrieved March 11, 2025, from https://www.gevernova.com/grid-solutions/powerd/catalog/statcom.htm

statsndata. (2025, March). *1 new message*. https://www.statsndata.org/report/static-synchronous-compensator-statcom-market-24236?utm_source=chatgpt.com

Stolevski, D. (2022, April 27). Linear Scheduling Vs Critical Path Method—The Art of Project Scheduling. *ScheduleReader*. https://www.schedulereader.com/linear-scheduling-vs-critical-path-method-the-art-of-project-scheduling/

Subramanian, S., Wasnik, R. V., Singh, H., Kamal, F. R., & Takieddine, O. H. (2019, November 11). *Early Engagement in FEED to Overcome Engineering Challenges – Delivering Fast Track EPC Projects*. Abu Dhabi International Petroleum Exhibition & Conference. https://doi.org/10.2118/197210-MS

Suresh, D., & Sivakumar, Dr. A. (2019). Impact of Schedule Management Plan on Project Management Effectiveness. *International Journal of Engineering and Advanced Technology*, *9*, 3350–3355. https://doi.org/10.35940/ijeat.A1515.109119

Talukder, Islam, & Mahi. (2023, October). (PDF) Implementation, Challenges and Advancement of Agile Project Management in Modern Projects. *ResearchGate*. https://www.researchgate.net/publication/375597437_Implementation_Challenges_and_Advancement_of_Agile_Project_Management_in_Modern_Projects

Terry Ruas. (2020, January). *(PDF) Software Engineering: A Practitioner's Approach 9 th Edition*. ResearchGate. https://www.researchgate.net/publication/365946272_Software_Engineering_A_Practitioner's_Approach_9_th_Edition

Vetoshkin, L., & Müller, Z. (2021). Dynamic Stability Improvement of Power System by Means of STATCOM With Virtual Inertia. *IEEE Access*, *9*, 116105–116114. IEEE Access. https://doi.org/10.1109/ACCESS.2021.3106236

Wang, H., & Gao, F. (2024). Research on project schedule optimization model construction and engineering efficiency improvement method. *Applied Mathematics and Nonlinear Sciences*, *9*(1), 20242554. https://doi.org/10.2478/amns-2024-2554

Yi, D., Lee, E.-B., & Ahn, J. (2019). Onshore Oil and Gas Design Schedule Management Process Through Time-Impact Simulations Analyses. *Sustainability*, *11*, 1613. https://doi.org/10.3390/su11061613

Yokoyama, H., & Goto, H. (2016). Resolution of Resource Contentions in the CCPM-MPL Using Simulated Annealing and Genetic Algorithm. *American Journal of Operations Research*, *6*(6), Article 6. https://doi.org/10.4236/ajor.2016.66044

Zakaria, Z. (2025). *Critical Path Method (CPM) in Project Management*. ProjectManager. https://www.projectmanager.com/guides/critical-path-method

Zamri Zakaria, Md Nazri Othman, Hidayat Zainuddin, Mohd Jahidi Rosdi, & Alaa Razzaq Khallawi. (2024). Systematic Review of Risks in Energy Performance Contracting (EPC) Projects. *Journal of Advanced Research in Applied Sciences and Engineering Technology*, *48*(2), 235–250. https://doi.org/10.37934/araset.48.2.235250

OpenAI. (2025). ChatGPT (GPT-4.0 Mini) [Large language model]. OpenAI. https://openai.com/

Consensus. (2023). Consensus: AI-powered research summarizer [AI tool]. https://consensus.app/

Typeset Inc. (2023). SciSpace (formerly Typeset) [AI research assistant]. https://typeset.io/

Canva Pty Ltd. (2023). Canva [Online design platform]. https://www.canva.com/

Appendices

Appendix 1: Introduction Letter

Asad Rafique
MSc Strategic Project Management Student
University of Vaasa
School of Technology and Innovations

March 04, 2025

Dear Recipient,

I am student at University of Vaasa's Strategic Project Management programme and currently working on my master's thesis. My thesis topic is 'Review of Statcom EPC Project Schedule and Optimization of the overall timeline and it aims to gather information how is the Statcom project schedule is prepared and how its timeline can be shortened by identifying the bottlenecks and using fast tracking methods.

I am looking for interviewees to gather information for the study regarding schedule bottleneck, activities relationships and opportunities to expedite the schedule. To take part as an interviewee, you do not have to be an expert to cover every part of EPC schedule. It is desired that interviewee has a general understanding of Statcom project execution in their discipline, and some level of interest in project management.

The interviews will most likely be conducted during Mar and Apr 2025. The interview date and time can be decided on the availability and mutual agreement. The length of the interview is approximately 40 to 60 min. Please be informed that the identity of the interviewee will not be revealed in the thesis.

You can send your questions and concerns to the following e-mail address:

x7433743@student.uwasa.fi

Best Regards,

Asad Rafique

Appendix 2: List of Interviewees

Interviewee	Role	Experience	Interview Duration
1	Manager - System Design	22	44 Minutes
2	Lead Engineer - System Design	20	44 Minutes
3	Engineer- System Design	3	44 Minutes
4	Team Leader – EM Design	18	40 Minutes
5	Lead Engineer – EM Design	12	40 Minutes
6	Engineer – EM Design	5	40 Minutes
7	Manager - HW Design	21	42 Minutes
8	Lead Engineer - HW Design	15	42 Minutes
9	HW Engineer - HW Design	2	42 Minutes
10	Manager - SW Design	24	60 Minutes
11	Lead Engineer - SW Design	18	60 Minutes
12	SW Tester - SW Design	7	60 Minutes
13	Manager - Procurement	14	40 Minutes
14	Lead officer - Procurement	6	40 Minutes
15	Manager - Projects	16	60 Minutes
16	Technical Manager - Projects	18	60 Minutes

Background Information:

Interview type: Focused-group interview (6)

Number of Intervieews: 16

Industry: STATCOM industry.

Appendix 3: Interview Questionnaire

1. Can you briefly describe your professional background and experience in managing EPC STATCOM projects?
2. What are the major activities in your discipline. Also, these activities are critical.
3. What scheduling tools or techniques do you currently use for managing project timelines?
4. Do you think the current total float of the major activities presents the true picture?
5. How effectively do you find Critical Path Method (CPM) being used in the schedules?
6. What are the most common causes of delays in STATCOM EPC projects based on your experience?
7. Can you identify specific bottlenecks in project scheduling that frequently impact project timelines?
8. How do activity interdependencies affect project timelines in EPC projects?
9. Are there any opportunities to fast track any activity in the schedule.
10. What recommendations would you suggest for improving the activities timeline in future STATCOM EPC projects?