

Analysis of Factors Causing Delays in the Clean Water Pipeline Network Project in Tangerang City

Yosep Suteja¹, Eri Marlapa²

^{1,2} Magister Management, Faculty of Economics and Bussines, Mercu Buana University, Jakarta, Indonesia.

DOI: <https://doi.org/10.56293/IJMSSSR.2025.5753>

IJMSSSR 2025
VOLUME 7
ISSUE 4 JULY – AUGUST

ISSN: 2582 – 0265

Abstract: The clean water pipeline network project plays a strategic role in improving community quality of life and supporting the achievement of Sustainable Development Goals (SDGs), particularly Goal 6 on the availability and sustainable management of clean water. However, project implementation often faces delays, leading to cost overruns, reduced quality, and decreased stakeholder satisfaction. This study aims to analyze the factors causing delays in project P2-DM001-RET-019 in Tangerang City, carried out by PT. XYZ. The research employs the DMAIC (Define, Measure, Analyze, Improve, Control) method, combined with the Critical Path Method (CPM), crashing technique, fishbone diagram, and 5 Why and 5W+1H analyses. Data were collected through document review, Focus Group Discussions (FGD), and field observations. Findings reveal four main factors contributing to delays: human (lack of experience and skills), machine (limited equipment availability), material (delays in delivery due to design and site condition discrepancies), and environment (community resistance). The application of the crashing method through additional labor reduced the project duration from 1,256 to 1,075 days (a time efficiency of 181 days or 14.44%) with a cost increase of 8.52%. Recommendations include selective recruitment, regular training, adequate equipment procurement planning, early technical design validation, and stakeholder engagement from the planning stage.

Keywords: project delay, clean water pipeline, DMAIC, fishbone diagram, CPM

1. Introduction

Based on preliminary observations, the pipeline installation work for the project experienced delays caused by several internal and external factors. The suspected external factors include coordination and permitting issues with local communities whose road access was affected by excavation activities, as well as unpredictable weather conditions. Internal factors include insufficiently competent and inexperienced human resources, and inadequate manpower planning from the Project Division.

The deviation or gap between the planned/estimated work duration and the actual duration in the field can be seen in the following chart:

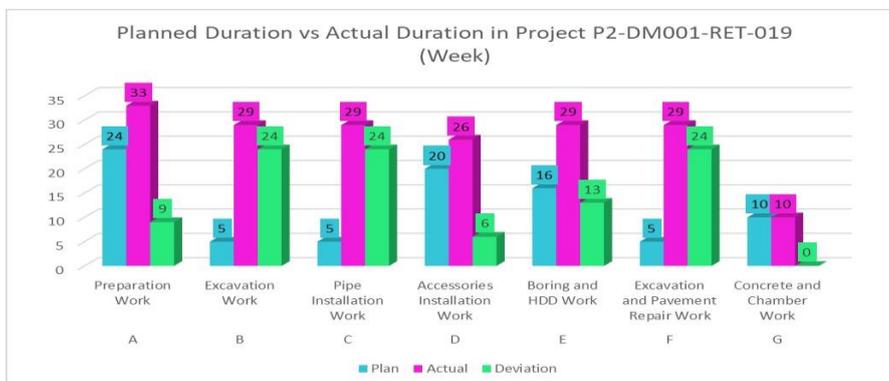


Figure 1. Planned Duration vs. Actual Duration for Project P2-DM001-RET-019

Source: Processed from PT. XYZ Report Data, 2023–2024

Clean water is one of the most fundamental resources for human life, directly influencing public health, economic productivity, and overall quality of life. The United Nations, through the Sustainable Development Goals (SDGs), has placed the provision of clean water and sanitation as a global priority under Goal 6: *Ensure availability and sustainable management of water and sanitation for all* (United Nations, 2015). The World Health Organization (WHO) reports that approximately 2.2 billion people worldwide still lack access to safely managed drinking water services, creating significant public health and economic challenges (WHO, 2022).

In Indonesia, rapid urbanization, population growth, and industrial expansion have increased the demand for reliable clean water distribution systems. However, the construction of clean water infrastructure, particularly pipeline networks, is often hindered by a combination of technical, managerial, and socio-environmental factors. Delays in infrastructure projects can have severe consequences, including extended deprivation of essential services, increased project costs, potential contractual penalties, reduced construction quality, and loss of stakeholder trust (Mahapatni, 2019; Nugroho & Raharja, 2022).

From a project management perspective, the timely delivery of construction projects is a critical measure of success. The triple constraint framework time, cost, and quality emphasizes that a deviation in one dimension can disrupt the others (PMI, 2021). Delays in project schedules not only escalate costs but may also compromise quality due to accelerated work or reduced quality control. Previous studies in Indonesia's water supply sector (Kamarudin & Mustaffa, 2021; Rachmawati & Kurniawan, 2020) have shown that delays are commonly caused by factors such as inadequate workforce skills, poor equipment planning, material procurement issues, and insufficient stakeholder engagement.

Project P2-DM001-RET-019 in Tangerang City is a strategic infrastructure initiative aimed at expanding clean water access to meet increasing demand. Despite its importance, the project experienced significant schedule overruns in 2023, affecting its delivery timeline and increasing associated costs. These challenges highlight the need for a systematic and data-driven approach to identifying and addressing delay factors.

This research applies the DMAIC (*Define, Measure, Analyze, Improve, Control*) methodology, integrated with the Critical Path Method (CPM) and crashing techniques, alongside fishbone diagram and 5 Why analysis, to provide a comprehensive examination of delay causes. The study not only identifies the root causes but also proposes targeted improvement measures, aiming to contribute practical insights for project managers, contractors, and policymakers in the water infrastructure sector.

According to the chart above, it can be seen that the pipeline installation work on Project P2-DM001-RET-019 carried out by PT. XYZ experienced deviations from the planned duration. This was due to several activities encountering delays. Of the seven stages of work, only one stage was completed on time, namely excavation, pipe installation, and concrete and chamber work. Due to the delays in six other stages, PT. XYZ's initial target to complete the project in accordance with the contractual schedule was not achieved.

These observed deviations raise a critical question: *What specific factors were responsible for the delays, and how can they be systematically mitigated?* Addressing this question requires a detailed breakdown of the causes, categorized into manpower, machine, material, and environmental factors, followed by a targeted improvement strategy. The subsequent section, Factors Causing Project Delays, presents the analytical findings that serve as the foundation for formulating an effective delay mitigation plan.

2. Literature Review

2.1 Project Management and the Triple Constraint

Project management is defined by the Project Management Institute (PMI, 2021) as the application of knowledge, skills, tools, and techniques to project activities to meet project requirements. The triple constraint framework comprising time, cost, and scope/quality represents the core dimensions of project performance. A change in one of these dimensions inevitably impacts the other two (Nugroho & Raharja, 2022). In construction projects, delays in the schedule can lead to increased costs due to extended labor and equipment utilization, as well as potential reductions in quality caused by accelerated work or insufficient supervision (Mahapatni, 2019). The effective

balancing of these three constraints is therefore essential to achieving project success.

2.2 Project Delay: Definitions and Classifications

Project delay refers to the deviation between the planned project schedule and the actual progress achieved (M. Amperawan Kusjadmahad & Alifien, in Pramuji Singgih D.P., 2022). Delays can be classified into:

- **Non-excusable delays:** Caused by the contractor's own shortcomings, such as poor planning or inadequate resource allocation.
- **Excusable delays:** Resulting from factors beyond the control of both the contractor and the client, such as extreme weather conditions.
- **Compensable delays:** Attributable to the client's actions or inactions, which may result in compensation claims by the contractor.

Wahyudi (in Alaydrus & Hadjomuljadi, 2018) categorizes the causes of delays into workforce, material supply, equipment availability, managerial inefficiencies, financial constraints, design errors, environmental factors, and regulatory issues.

2.3 DMAIC in Construction Project Management

Define, Measure, Analyze, Improve, and Control is a Six Sigma methodology aimed at process improvement (George, 2002). In construction, the Define stage identifies the specific problem, Measure quantifies current performance, Analyze determines the root causes, Improve develops solutions, and Control ensures sustainability of improvements (Yousaf et al., 2013). Kamarudin & Mustaffa (2021) applied DMAIC in a Malaysian clean water supply project and successfully reduced delays by addressing inefficiencies in workforce management, equipment allocation, and stakeholder coordination. Lee & Lee (2019) found that DMAIC integration in water infrastructure projects improved schedule reliability and reduced rework.

2.4 Critical Path Method (CPM) and Crashing

CPM is a network-based scheduling technique used to identify the sequence of activities that determine the minimum project duration (Heizer, Render, & Munson, 2017). Activities on the critical path have zero float, meaning delays in these activities will directly affect the project's completion date. Crashing is a schedule compression method that reduces the project duration by adding resources such as labor, equipment, or overtime to critical path activities (Mahapatni, 2019). While crashing typically increases direct costs, it can be cost-effective when the financial impact of delays (e.g., penalties or opportunity losses) outweighs the additional expenses (Anugerah, Pratami, & Akbar, 2021).

2.5 Fishbone Diagram and 5 Why Analysis in Delay Identification

The fishbone diagram, also known as the Ishikawa diagram, is a visual tool for systematically identifying and categorizing the root causes of a problem (Nasution, 2015). In project delay analysis, causes are often grouped into categories such as manpower, machinery, materials, and environmental factors. The 5 Why technique involves repeatedly asking "why" to explore deeper causes of a problem until the fundamental issue is identified (Kuswardana, Mayangsari, & Amrullah, 2017). This combined approach has been shown to be effective in identifying and prioritizing delay factors in construction projects (Kurniawan, 2019).

3. Research Method

This study adopts a descriptive quantitative case study approach, focusing on project P2-DM001-RET-019 in Tangerang City, a clean water pipeline network construction project executed by PT. XYZ in 2023. The descriptive quantitative method was chosen to allow a detailed analysis of project delays based on empirical data, while the case study approach enables in-depth examination of specific project characteristics and challenges.

3.1 Data Collection

Two types of data were utilized:

- Primary data were gathered through Focus Group Discussions (FGD) with project stakeholders, including project managers, consultants, and field supervisors, as well as through structured brainstorming sessions and direct field observations of ongoing work.
- Secondary data were obtained from contract documents, project progress reports, work schedules, and official correspondence related to project implementation.

3.2 Analytical Framework

The research employed an integrated methodology combining DMAIC, Critical Path Method (CPM), crashing, fishbone diagram, and 5 Why analysis. The stages were as follows:

1. **Define:** Identification of project objectives, delay symptoms, and critical issues affecting the P2-DM001-RET-019 schedule.
2. **Measure:** Collection and quantification of current performance data, including planned vs. actual project timelines, cost breakdowns, and resource allocations.
3. **Analyze:**
 - Development of the project network diagram to determine the critical path using CPM.
 - Identification of critical activities with zero float.
 - Root cause identification using fishbone diagram and deeper exploration through 5 Why analysis to uncover fundamental issues.
4. **Improve:** Simulation of crashing scenarios to evaluate time-cost trade-offs, followed by the selection of the most feasible acceleration strategy.
5. **Control:** Formulation of recommendations and preventive measures to ensure delay reduction in future projects.

3.3 CPM and Crashing Application

The CPM analysis was conducted to identify the project's longest sequence of dependent activities, determining the minimum completion time. Crashing analysis was applied to critical path activities by increasing labor resources to reduce activity durations, while calculating the additional direct costs incurred. The cost slope formula was used to determine the optimal crashing decision, balancing the trade-off between reduced project duration and increased direct costs (Mahapatni, 2019).

3.4 Fishbone Diagram and 5 Why Analysis

The fishbone diagram categorized potential causes of delay into Manpower, Machine, Material, and Environment (3M+1E). The 5 Why analysis was then applied to each category to trace causal chains back to their root causes. This combined qualitative approach ensured that both surface-level and underlying issues were identified and addressed.

3.5 Validity and Reliability

To ensure validity, data from FGDs were cross-verified with documented project records. Triangulation between field observations, official reports, and stakeholder interviews was used to confirm the consistency of findings. Reliability was enhanced through the use of standardized data collection templates and analytical procedures applied consistently across all stages.

4. Results and Discussion

4.1 Results

Effective Time and Cost of Clean Water Pipeline Installation

1) Network Diagram and Critical Path (CPM)

After scheduling and coding each activity, interrelationships between activities were established to form a network plan. This approach ensures the correct sequence of the entire project, from initiation to completion. Since the project required time acceleration (*crashing*), the network used actual durations of delayed activities.

Table 1. shows the sequence of activities, predecessors, and durations used for the CPM analysis.

| Symbol | Work Description | Predecessors | Duration (Days) |
|--------|---------------------------------------|--------------|-----------------|
| A | Preparation Work | - | 224 |
| B | Excavation Work | A | 173 |
| C | Pipe Installation Work | B, E | 203 |
| D | Special Accessories Installation Work | C | 189 |
| E | Boring and HDD Work | B | 188 |
| F | Trench and Pavement Restoration Work | C, D | 209 |
| G | Concrete and Chamber Work | C | 70 |
| H | Completion Work | F | 0 |

Source: Author’s analysis, 2025

Table 2. Forward and Backward Pass Calculations

| Symbol | Duration | ES | EF | LS | LF | Total Float | Critical Path |
|--------|----------|------|------|------|------|-------------|---------------|
| A | 224 | 0 | 224 | 0 | 224 | 0 | Yes |
| B | 173 | 224 | 397 | 224 | 397 | 0 | Yes |
| C | 203 | 585 | 788 | 585 | 788 | 0 | Yes |
| D | 189 | 788 | 977 | 788 | 977 | 0 | Yes |
| E | 188 | 397 | 585 | 397 | 585 | 0 | Yes |
| F | 209 | 977 | 1186 | 977 | 1186 | 0 | Yes |
| G | 70 | 788 | 858 | 1116 | 1186 | 328 | No |
| H | 0 | 1186 | 1186 | 1186 | 1186 | 0 | Yes |

Source: Author’s analysis, 2025

From Table 2, the forward pass and backward pass calculations identified the critical path as A–B–C–D–E–F–H, with a total project duration of 1,256 days. All activities on this path have zero total float, meaning any delay will directly impact the project completion date. Only one activity (G) had a float of 328 days, classifying it as non-critical.

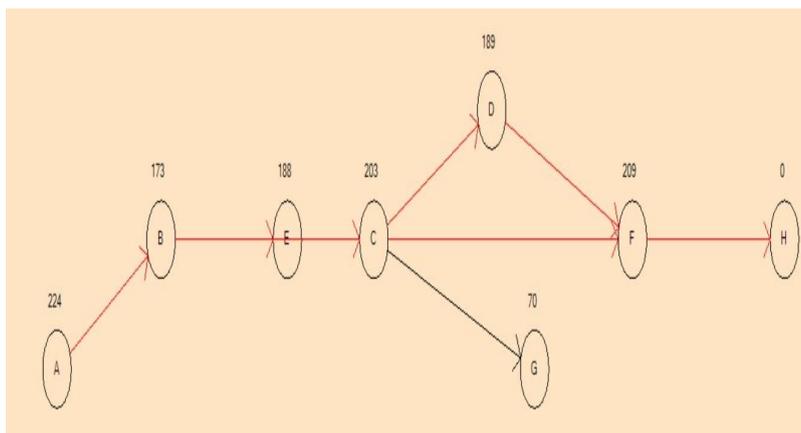


Figure 2. illustrates the network diagram, visually confirming the critical path sequence and interdependencies.

Source: Author’s analysis, 2025

2) Crashing of Critical Path Activities

To accelerate completion, the chosen method was adding manpower to critical activities. As shown in Table 4.3, every critical activity experienced a reduction in duration after the implementation of additional workers.

The overall project duration decreased from 1,256 days to 1,075 days, achieving a time efficiency of 181 days (14.44%). This reduction was significant because it allowed earlier project delivery while keeping productivity balanced across activities. However, the acceleration came with increased labor and mobilization costs, which needed further cost analysis.

Table 3. Crash Duration with Additional Manpower

| Symbol | Work Description | Predecessors | Volume | Duration | Normal Productivity/day | Initial Workers | Target Crash Duration | Additional Workers | Crashing Productivity | Actual Crash Duration |
|--------|-------------------------------|--------------|--------|----------|-------------------------|-----------------|-----------------------|--------------------|-----------------------|-----------------------|
| A | Preparation | - | 1 | 224 | 0.004 | 17 | 100 | 13 | 0.008 | 126 |
| B | Excavation | A | 5733 | 173 | 33.139 | 50 | 125 | 3 | 35.127 | 163 |
| C | Pipe Installation | B | 7716 | 203 | 38.010 | 50 | 150 | 3 | 40.290 | 192 |
| D | Accessories Installation | C | 1254 | 189 | 6.635 | 50 | 155 | 3 | 7.033 | 178 |
| E | Boring and HDD | B | 1983 | 188 | 10.548 | 50 | 160 | 4 | 11.392 | 174 |
| F | Trench & Pavement Restoration | C, D | 7716 | 209 | 36.919 | 50 | 180 | 4 | 39.872 | 194 |
| G | Concrete | C | 1 | 70 | 0.014 | 15 | 30 | 7 | 0.021 | 48 |

| Symbol | Work Description | Predecessors | Volume | Duration | Normal Productivity/day | Initial Workers | Target Crash Duration | Additional Workers | Crashing Productivity | Actual Crash Duration |
|--------------|------------------|--------------|--------|-------------|-------------------------|-----------------|-----------------------|--------------------|-----------------------|-----------------------|
| | & Chamber | | | | | | | | | |
| Total | | | | 1256 | | | | | | 1075 |

Source: Author’s analysis, 2025

3) Crash Cost Analysis

Table 4. details the additional wages, mobilization expenses, and the change in total project cost after crashing.

The total project cost rose from IDR 1,323,950,000 to IDR 1,436,850,000 (an 8.52% increase). This additional expense was considered acceptable given the substantial time savings achieved.

The cost–time trade-off indicates that the acceleration strategy was cost-effective, as the cost slope for each activity remained within reasonable limits compared to the potential contractual and operational benefits of earlier completion.

Table 4. Crash Cost with Additional Manpower

| Sym bol | Work Descri ption | Volu me | Durat ion | Normal Productiv y/day | Targ et Crash Durat ion | Addi tional Work ers | Crashin g Product ivity | Actua l Crash Durat ion | Additi onal Wages | Extra Mobiliz ation | Normal Cost | Crash Cost |
|------------|-------------------------------|------------|--------------|------------------------------|-------------------------------------|-------------------------------|----------------------------------|-------------------------------------|-------------------------|---------------------------|----------------|---------------|
| A | Preparation | 1 | 224 | 0.004 | 100 | 15 | 0.008 | 126 | 37,500,000 | 1,500,000 | 95,200,000 | 134,200,000 |
| B | Excavation | 5733 | 173 | 33.139 | 125 | 3 | 35.127 | 163 | 9,375,000 | 300,000 | 216,250,000 | 225,925,000 |
| C | Pipe Installation | 7716 | 203 | 38.010 | 150 | 3 | 40.290 | 192 | 11,250,000 | 300,000 | 253,750,000 | 265,300,000 |
| D | Accessories Installation | 1254 | 189 | 6.635 | 155 | 3 | 7.033 | 178 | 11,625,000 | 300,000 | 236,250,000 | 248,175,000 |
| E | Boring and HDD | 1983 | 188 | 10.548 | 160 | 4 | 11.392 | 174 | 16,000,000 | 400,000 | 235,000,000 | 251,400,000 |
| F | Trench & Pavement Restoration | 7716 | 209 | 36.919 | 180 | 4 | 39.872 | 194 | 18,000,000 | 400,000 | 261,250,000 | 279,650,000 |
| G | Concrete & Chamber | 1 | 70 | 0.014 | 30 | 7 | 0.021 | 48 | 5,250,000 | 700,000 | 26,250,000 | 32,200,000 |

| Symbol | Work Description | Volume | Duration | Normal Productivity/day | Target Crash Duration | Additional Workers | Crashing Productivity | Actual Crash Duration | Additional Wages | Extra Mobilization | Normal Cost | Crash Cost |
|--------|------------------|--------|----------|-------------------------|-----------------------|--------------------|-----------------------|-----------------------|------------------|--------------------|---------------|---------------|
| TOTAL | | | 1256 | | | | | 1075 | 109,000,000 | 3,900,000 | 1,323,950,000 | 1,436,850,000 |

Source: Author’s analysis, 2025

Delay Factors in Clean Water Pipeline Installation

The analysis identified four main categories of delay causes, based on the 3M + 1E framework:

1. Man (Labor) – Several workers lacked the necessary experience and technical skills, such as butt fusion welding. This was linked to non-selective recruitment processes and limited pre-project training programs.
2. Machine (Equipment) – The number of welding machines was insufficient for the workload, forcing sequential rather than parallel work, leading to bottlenecks.
3. Material – Late delivery of fittings and accessories, mainly due to discrepancies between design specifications and actual site conditions, with no pre-construction test pits conducted.
4. Environment – Community resistance arose when pipeline routes crossed private property or when residents were unaware of the long-term impact of groundwater depletion.
- 5.

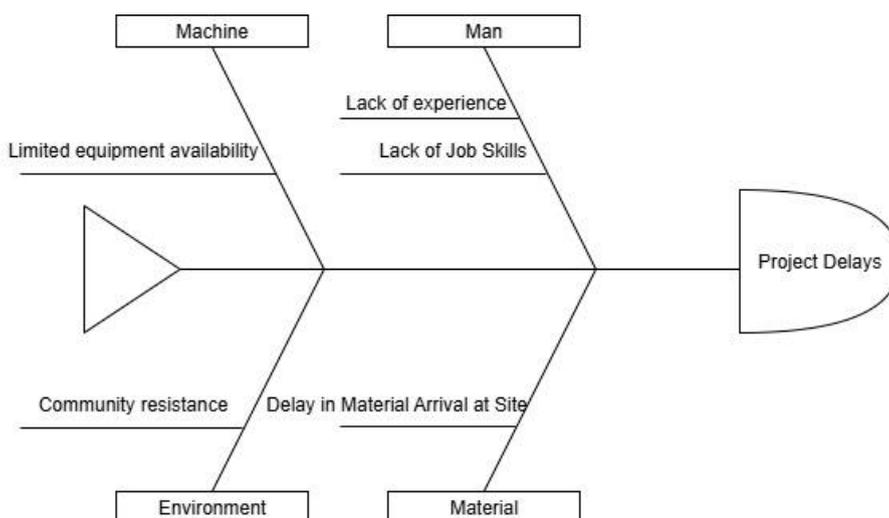


Figure 3. presents the fishbone diagram summarizing these root causes.

A 5 Why analysis further confirmed that the root causes were non-selective recruitment, inadequate training, poor equipment planning, lack of design validation, and insufficient stakeholder engagement during planning.

Corrective Actions (5W+1H)

Based on the 5W+1H analysis in Table 4.6, corrective actions were formulated as follows:

- Man: Implement selective recruitment with competency-based criteria and partner with accredited training institutions. Conduct periodic technical training with vendors to ensure skill readiness.
- Machine: Develop a detailed equipment plan early in the project, including buffer units to avoid delays due to breakdowns or shortages.
- Material: Perform design validation and test pits before procurement to match material specifications with field conditions.
- Environment: Engage community leaders and local authorities from the planning stage to build trust and

avoid land disputes. Government agencies should conduct public awareness campaigns on the environmental risks of excessive groundwater use.

These actions are preventive in nature and are recommended for adoption **in future projects to reduce the risk of delays, improve time performance, and optimize project costs.**

4.2 Discussion

1. Factors Causing Project Delays

The analysis identified four primary categories contributing to delays in the P2-DM001-RET-019 clean water pipeline project manpower, machine, material, and environment each with specific sub-causes and direct implications for the project schedule.

- **Manpower:** The absence of selective recruitment processes meant that workers with insufficient technical proficiency, particularly in specialized techniques like butt fusion welding, were assigned to critical tasks. This lack of skill contributed to a higher frequency of installation errors and rework, directly prolonging activity durations. The problem was exacerbated by the absence of structured, pre-mobilization technical training. These findings are in line with Kurniawan (2019), who identified inadequate technical competence as one of the main drivers of schedule slippage in Indonesian pipeline projects.
- **Machine:** Only two welding machines were available for a project of significant scale, forcing critical activities to be performed sequentially instead of in parallel. This created a bottleneck on the critical path, leading to cumulative delays. This mirrors Kusnadi & Supriyadi (2021), who emphasized that underestimating equipment needs in the planning stage is a recurring cause of delays in water pipeline infrastructure.
- **Material:** Material delivery delays stemmed from design discrepancies between the engineering drawings and actual site conditions, compounded by the lack of test pits prior to work commencement. This meant that procurement adjustments had to be made mid-project, stalling progress. Rachmawati & Kurniawan (2020) similarly found that late material delivery is often linked to insufficient pre-construction field validation.
- **Environment:** Social resistance emerged when pipeline routes crossed private property or disrupted local access, with many residents lacking awareness of the long-term consequences of groundwater depletion. Without early and transparent engagement, these issues escalated into work stoppages. Alsharif & Alzahrani (2020) have shown that proactive community involvement during project planning significantly reduces such socio-environmental delays.

Collectively, these findings reaffirm the triple constraint principle (PMI, 2021; Nugroho & Raharja, 2022), where schedule deviations have cascading effects on cost and, potentially, quality.

2. Effectiveness of DMAIC, CPM, and Crashing in Delay Mitigation

The combined use of DMAIC and CPM allowed for both a diagnostic and corrective approach to delay management:

- In the Define and Measure stages, CPM analysis revealed that the critical path consisted of activities A–B–C–D–E–F–H, all with zero float, indicating no tolerance for delay.
- In the Analyze stage, fishbone diagram and 5 Why analysis pinpointed the root causes of delay in each 3M+1E category.
- In the Improve stage, the crashing technique adding skilled labor to critical activities was applied. This reduced the project duration from 1,256 to 1,075 days, saving 181 days (14.44%).
- The acceleration increased costs by 8.52%, from IDR 1,323,950,000 to IDR 1,436,850,000, which is considered a justifiable trade-off given the significant time recovery. This finding aligns with Anugerah, Pratami, & Akbar (2021), who demonstrated that labor-based crashing is an efficient solution when contractual deadlines and operational needs outweigh modest cost increases.

This approach not only recovered lost time but also provided a quantifiable time-cost trade-off model for project

managers, enabling informed decision-making for similar future projects.

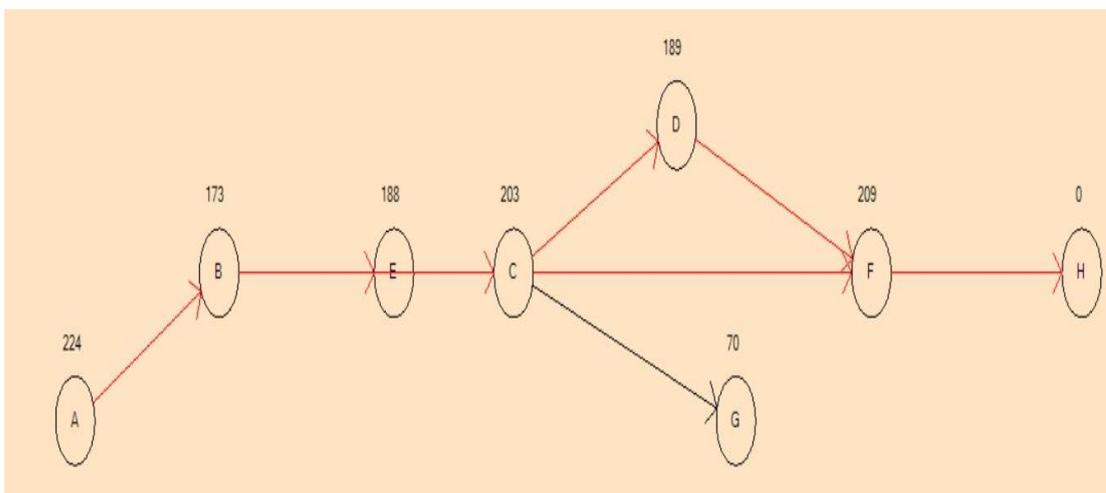


Figure 4. Network Diagram Before Crashing

Source: Processed by the Author, 2025

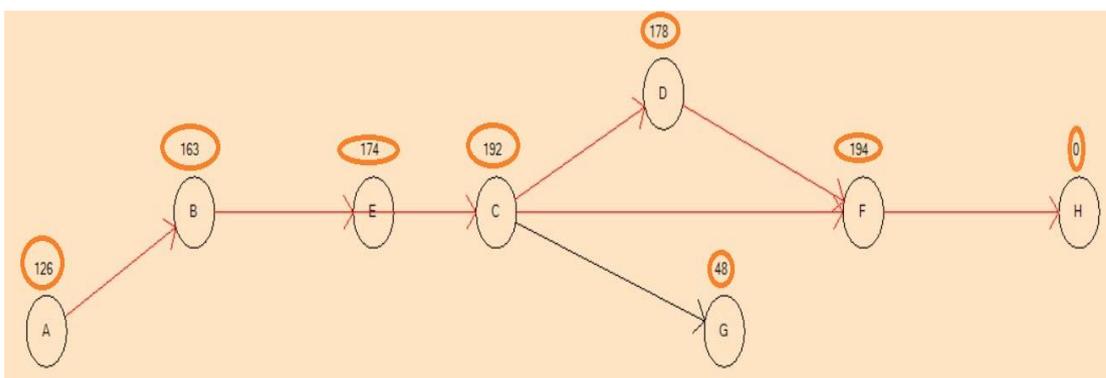


Figure 5. Network Diagram After Crashing

Source: Processed by the Author, 2025

3. Relevance to Project Management Theory and Previous Studies

This research confirms that integrating DMAIC with CPM offers a comprehensive framework for delay management. It corroborates Kamarudin & Mustafa (2021) and Lee & Lee (2019), who concluded that DMAIC is adaptable beyond manufacturing, offering structured problem-solving for construction projects.

Unlike many previous studies that focus on qualitative identification of delay causes, this research extends the literature by:

- Providing quantitative measurement of delay impacts through CPM.
- Applying cost slope analysis to determine the most cost-effective acceleration strategy.
- Linking root cause identification directly to corrective actions and measurable schedule recovery.

The findings also highlight the Indonesian construction context, where human resource quality, equipment availability, and stakeholder management remain critical success factors. While such issues are not unique to Indonesia, their resolution often requires a tailored approach that considers local labor markets, procurement systems, and community engagement practices.

5. Conclusion and Recommendations

Conclusion

This study analyzed the causes of delays in the P2-DM001-RET-019 clean water pipeline network project in Tangerang City, applying an integrated methodology of DMAIC, Critical Path Method (CPM), and crashing, supported by fishbone diagram and 5 Why analysis.

The results identified four primary factors contributing to delays:

1. Manpower – Non-selective recruitment and lack of specialized technical training, resulting in lower productivity and frequent rework.
2. Machine – Insufficient welding equipment, causing sequential rather than parallel operations on critical path activities.
3. Material – Delayed delivery due to design-site discrepancies and absence of pre-construction validation.
4. Environment – Community resistance stemming from land disputes and low awareness of groundwater sustainability.

The CPM analysis revealed the critical path (A–B–C–D–E–F–H) with zero float, indicating that any delay in these activities directly impacts the project completion date.

The application of crashing by adding skilled labor to critical activities reduced the project duration from 1,256 to 1,075 days, achieving a 14.44% time saving (181 days) at an 8.52% cost increase.

These findings confirm the relevance of the triple constraint principle and align with previous studies such as Kurniawan (2019), Rachmawati & Kurniawan (2020), and Alsharif & Alzahrani (2020). The study extends existing literature by combining DMAIC's structured root cause analysis with CPM and crashing's time-cost optimization, producing both diagnostic and corrective solutions for project delay management.

Recommendations

Managerial Recommendations:

- 1. Human Resources:**
 - Implement selective recruitment processes with clear competency criteria.
 - Conduct structured technical training for all workers before mobilization, particularly in specialized tasks like butt fusion welding.
- 2. Equipment Planning:**
 - Allocate adequate machinery for high-volume critical activities, with buffer capacity to mitigate breakdown risks.
- 3. Material Management:**
 - Perform early design validation and conduct test pits prior to procurement to ensure material specifications match field conditions.
- 4. Stakeholder Engagement:**
 - Initiate community consultations and coordinate with local leaders during the design stage to reduce social resistance.
- 5. Project Monitoring:**
 - Integrate DMAIC and CPM into regular project reviews, enabling proactive identification of performance gaps and timely corrective action.

References

1. Alaydrus, A., & Hadjomuljadi, S. (2018). *Manajemen konstruksi: Teori dan praktik*. Jakarta: Erlangga.
2. Alsharif, M. H., & Alzahrani, J. I. (2020). Analyzing the impact of stakeholder engagement on project delays in water supply projects. *Journal of Construction Engineering and Management*, 146(4), 04020025. [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0001771](https://doi.org/10.1061/(ASCE)CO.1943-7862.0001771)

3. Anugerah, R., Pratami, Y., & Akbar, A. (2021). Designing project schedule using crashing method to compress the Fiber to The Home project schedule. *Jurnal Teknik dan Manajemen*, 12(1), 44–52.
4. George, M. L. (2002). *The Lean Six Sigma pocket toolbook*. New York: McGraw-Hill.
5. Heizer, J., Render, B., & Munson, C. (2017). *Operations management: Sustainability and supply chain management* (12th ed.). Pearson Education.
6. Kamarudin, S., & Mustaffa, N. (2021). Application of DMAIC methodology in construction project management: A case study on water supply projects. *International Journal of Construction Management*, 21(11), 1061–1073.
<https://doi.org/10.1080/15623599.2019.167539>
7. Khoiroh, A. (2018). Analisis percepatan proyek konstruksi menggunakan metode crashing. *Jurnal Teknik Sipil dan Lingkungan*, 10(2), 87–94.
8. Kurniawan, A. (2019). Analisis penyebab keterlambatan proyek konstruksi menggunakan metode DMAIC. *Jurnal Teknik Sipil*, 26(2), 91–102.
9. Kusnadi, Y., & Supriyadi, A. (2021). Assessment of delays in water pipeline projects using DMAIC methodology. *Jurnal Teknik Sipil*, 28(1), 47–56.
10. Mahapatni, R. (2019). Cost and time optimization in project management: An application of crashing techniques. *International Journal of Project Economics*, 4(1), 25–34.
11. Nasution, M. N. (2015). *Manajemen mutu terpadu (Total Quality Management)*. Jakarta: Ghalia Indonesia.
12. Nugroho, R., & Raharja, S. (2022). Manajemen risiko biaya proyek konstruksi. *Jurnal Rekayasa Sipil*, 19(1), 77–88.
13. PMI. (2021). *A guide to the Project Management Body of Knowledge (PMBOK® guide)* (7th ed.). Newtown Square, PA: Project Management Institute.
14. Rachmawati, D., & Kurniawan, B. (2020). Evaluating the causes of delays in water pipeline projects: A case study in Jakarta. *Jurnal Teknik Sipil*, 27(1), 33–44.
15. Yousaf, M., Umer, M., & Hassan, R. (2013). DMAIC methodology for Six Sigma implementation. *International Journal of Scientific & Engineering Research*, 4(10), 126–133.