Evaluating the Time–Cost–Quality Trade-Off in the Design and Construction of Industrial Drinking and Demineralized Water Tanks: A Case Study from the Niger Delta, Nigeria

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Abstract
Construction projects frequently face competing requirements for timely delivery, budget control and conformance to specified quality. This study evaluates the time–cost–quality trade-off (TCQT) associated with the design and construction of industrial drinking-water and demineralised-water tanks for an oil and gas facility in Bonny Island, Rivers State, Nigeria. The study adopted an exploratory qualitative case-study design and relied on secondary evidence comprising published literature, industry sources and project planning/completion records. An inductive thematic analysis, informed by Braun and Clarke's six-phase approach, was used to identify recurring mechanisms through which project decisions influence time, cost and quality. The project records indicate a planned contract value of US$5,533,150.70 and an approved quality requirement of 94.54%; the final varied value increased to US$7,183,313.44, while reported achieved quality declined to 86.15%. The project milestones also experienced substantial schedule slippage, with reported milestone delays ranging from 444 to 730 days. Eight integrated themes emerged: timely completion with quality and budget compliance; critical-path and procurement management; KPI-based performance control; benefits and limitations of experienced permanent crews; proactive risk identification; non-linear relationships between resource loading and duration; scope-change effects on TCQT; and the strategic use of external expertise and digital tools. The findings indicate that accelerating work through additional resources does not automatically reduce overall duration because activity dependencies, bottlenecks and coordination constraints may limit productivity. The study therefore proposes an integrated TCQT decision framework combining scope definition, critical-path analysis, procurement planning, risk and contingency management, standardised KPIs, lean practices, BIM/digital coordination, stakeholder communication and controlled external support. The framework provides a practical decision structure for industrial water-tank projects where quality and functional integrity cannot be sacrificed merely to recover schedule or reduce initial cost.

Keywords: *Time–cost–quality trade-off; construction project management; industrial water tanks; demineralised water; critical path method; risk management; thematic analysis; Niger Delta; oil and gas.*

1. Introduction

The construction sector is characterised by complex interfaces among engineering design, procurement, labour, equipment, construction, commissioning and stakeholder requirements. Project success is commonly judged by the extent to which the required scope is delivered within an agreed period, budget and quality standard. In practice, however, these objectives are interdependent rather than independent. Shortening duration can require overtime, additional crews, expedited procurement or alternative construction methods; reducing expenditure can constrain resources or encourage lower-cost alternatives; and increasing quality assurance may require additional inspection, testing, specialist labour and higher-grade materials. Consequently, construction managers continuously make trade-off decisions rather than simply optimising a single project objective (Anuar & Ng, 2011; Wang et al., 2021).

The conventional time–cost trade-off (TCT) literature has established that reducing activity duration can increase direct cost, whereas prolonging work can increase time-dependent overheads. Critical Path Method (CPM) is widely used to identify activities whose delays can affect project completion, while PERT provides probabilistic estimates where activity durations are uncertain (Hegazy, 2002; Hinze, 2004). More recent TCQT research extends the conventional TCT perspective by treating quality as an explicit decision variable. This is particularly important because quality failures can produce rework, delay, safety exposure, operational underperformance and life-cycle cost, thereby converting an apparent short-term saving into a larger project loss (Orm & Jeunet, 2018; Pollack-Johnson & Liberatore, 2006).

Industrial water-tank projects are a useful context for examining TCQT because they combine structural, mechanical, piping, coating, instrumentation, testing and commissioning requirements. For drinking and demineralised water systems, material selection, corrosion protection, cleanliness, integrity testing and functional performance are not merely aesthetic concerns; they are essential to reliable operation. In an oil and gas facility, late completion of water infrastructure can also affect dependent operations and commissioning activities. The dissertation underpinning this article identified a practical project context in Bonny Island, Rivers State, Nigeria, and documented significant divergence between the approved baseline and final project outcome.

The literature reviewed in the dissertation shows substantial development of mathematical and computational TCQT models, including multi-objective optimisation, fuzzy logic, genetic algorithms, particle-swarm optimisation and goal programming. Nevertheless, the practical translation of these models into project-level managerial decisions remains challenging because construction environments contain uncertain site conditions, procurement disruptions, scope changes, resource constraints and stakeholder pressures. The dissertation consequently identified a gap in practical, project-specific integration of TCQT with risk management, performance measurement and decision escalation, especially for industrial water-tank construction in the Nigerian Niger Delta.

1.1 Aim and Research Objectives

The aim of the study was to evaluate TCQT approaches and techniques and develop an improvement framework applicable to the design and construction of industrial drinking-water and demineralised-water tanks.

The objectives were to:

i. Evaluate improvement approaches for TCQT;
ii. Examine approaches for quantifying and standardising execution performance;

iii. Assess TCQT as a distinct construction improvement perspective;
iv. Incorporate risks and uncertainties affecting execution choices and project performance;
v. Develop and validate a practical TCQT decision framework for the project context.

1.2 Research Questions

i. What time, cost and quality outcomes would be required to complete the project on schedule and within budget under no-delay conditions?
ii. What factors determine the earliest practicable completion and its associated cost and quality implications?
iii. How can project acceleration be undertaken at minimum additional cost while maintaining a tolerable quality level?
iv. How do project risks affect schedule and budget performance?
v. When should project management seek additional expertise or support to recover time and cost performance?

1.3 Contribution and Novelty

The principal contribution is a practical integration of TCQT with project risk, performance measurement and decision escalation. Rather than treating time, cost and quality as isolated optimisation variables, the proposed approach links baseline definition, critical-path analysis, procurement, risk buffers, KPI monitoring, adaptive decisions and stakeholder communication. It also adapts the TCQT discussion to industrial water-tank projects, where quality failures can affect asset integrity and operational readiness. The dissertation explicitly identifies the need to consider corrosion, water-purity requirements and regulatory compliance within the trade-off framework.

2. Literature Review

2.1 Time–Cost–Quality Trade-off

TCT is based on the relationship between activity duration and cost. Under normal conditions, a contractor may use relatively inexpensive resources over a longer duration or deploy additional labour, equipment and overtime to shorten duration. The latter can increase direct cost and may introduce safety and quality risks. The optimum point is therefore not necessarily the shortest possible duration or the lowest activity cost, but the most advantageous project-level combination under the prevailing constraints (El-kholy, 2013; Jeunet & Orm, 2020).

TCQT extends this logic by explicitly recognising quality. Orm and Jeunet (2018) note that quality assessment is a major challenge because quality is multidimensional and cannot always be represented by a single measure. Construction quality can nevertheless be operationalised through conformance indicators, inspection results, defect rates, testing outcomes and activity-level quality weights. Pollack-Johnson and Liberatore (2006) demonstrated the importance of incorporating quality considerations into project time/cost decision-making, while El-Rayes and Kandil (2005) developed a TCQT approach for highway construction.

2.2 Scheduling and Schedule Compression

CPM is particularly relevant to the case because it identifies activity dependencies, float and the critical path. The dissertation notes that CPM is useful for pinpointing bottlenecks and prioritising resources, but it does not itself reduce delay; its value lies in identifying where managerial action is most likely to affect project completion. Schedule compression can then be considered through

fast-tracking or crashing. Fast-tracking overlaps suitable activities, whereas crashing adds resources or cost to shorten selected critical activities. Both methods require explicit consideration of quality and risk because parallel work and increased resource density can raise coordination and safety exposure (Ballesteros-Pérez, 2017; Webb et al., 2016).

2.3 Cost and Quality Management

Construction cost comprises direct and indirect components. Direct cost includes materials, labour, equipment and subcontractor resources, while indirect costs support project execution and management and can be time-dependent. Therefore, schedule delay may increase overhead even when direct activity costs remain unchanged. Quality management involves planning requirements, assuring that processes conform to the requirements and controlling outputs. In water-tank construction, quality controls should include material certification, fabrication/welding inspection, dimensional checks, coating inspection, pressure or integrity testing where applicable, cleanliness, functional testing and commissioning acceptance.

2.4 Risk and Uncertainty

Construction projects operate under uncertainty arising from weather, site conditions, resource productivity, procurement lead times, design development and external events. The literature reviewed in the dissertation consistently links unmanaged risk with delay, cost overrun and quality deterioration. The study therefore treats risk as an explicit fourth decision dimension that modifies the feasible TCQT choices rather than as an afterthought.

2.5 Research Gap

The reviewed literature provides sophisticated optimisation models but relatively limited evidence on how such principles can be translated into practical decision gates for industrial water-tank projects. The dissertation specifically identified gaps in real-life application, stakeholder-weighted multi-criteria decision-making, and project-specific solutions that simultaneously address time, cost, quality, risk and regulatory conditions. This article addresses that gap through an integrated case-study interpretation of baseline/final project data and inductively derived management themes.

3. Methodology

3.1 Research Design and Philosophical Position

The research used an exploratory qualitative case-study design. An interpretive and inductive orientation was adopted because the purpose was to understand recurring relationships and managerial mechanisms in TCQT rather than statistically test a predetermined causal model. The underlying dissertation describes the design as exploratory and suitable for flexible synthesis of secondary information and development of tentative recommendations.

3.2 Study Context and Data Sources

The case concerned the design and construction of industrial drinking-water and demineralised-water tanks at a gas facility in Bonny Island, Rivers State, Nigeria. The study used secondary data from the project record before and after execution, supported by peer-reviewed literature, books, industry publications and other verified documentary sources. No human participants were recruited, and the analysis did not use interviews or questionnaires.

3.3 Analytical Procedure

Inductive thematic analysis was used to synthesise documentary evidence. The procedure followed the six phases associated with Braun and Clarke: familiarisation with the data; generation of initial codes; searching for themes; reviewing themes; defining and naming themes; and producing the analytical narrative. The dissertation records this process and explains that the themes were compared with the research questions and used to construct a practical TCQT improvement model.

3.4 Quantitative Descriptive Checks

Although the principal analytical method was qualitative, descriptive calculations were used to interpret the project record. Cost overrun was calculated as: [(final varied value − approved contract value) / approved contract value] × 100.

Quality change was expressed as the difference between baseline required quality and reported achieved quality.

Schedule deviation was examined at milestone level from the planned and actual completion dates. The reported project-model indicators (including SPI and CPI) were retained as documentary outputs and were not reclassified as conventional EVM indices because the available record does not provide a complete PV/EV/AC dataset for independent EVM reconstruction.

3.5 Trustworthiness and Ethics

Credibility was supported through comparison of the case evidence with established literature and by retaining the project-record values as reported. The dissertation states that trustworthiness was addressed through use of relevant academic materials, transparent synthesis and efforts to minimise interpretive bias. Ethical requirements were addressed through appropriate acknowledgement of sources; no participant consent was required because the study used secondary data without human participants.

4. Results

4.1 Baseline versus Final Project Performance

The baseline project had an approved contract sum of US$5,533,150.70 and an overall quality requirement of 94.54%. The seven major work packages comprised mobilisation, project management, engineering, procurement, site construction/installation, pre-commissioning/commissioning and demobilisation. The final varied value was US$7,183,313.44, with reported achieved quality of 86.15%.

Work package	Approved value (US$)	Final varied value (US$)	Planned/actual completion	Reported delay (days)	Quality achieved (%)
Mobilisation	276,933.05	376,933.05	13 Apr 2021 / 20 May 2022	572	87.50
Project management	553,375.10	753,375.10	15 Sep 2021 / 25 Jan 2023	704	85.00
Engineering	276,500.00	426,500.00	19 May 2020 / 28 Apr 2021	444	85.00
Procurement	1,659,733.70	2,009,733.70	23 Jul 2021 / 18 Nov 2022	621	86.67

Construction/installation	2,213,108.85	3,013,271.60	26 Jul 2021 / 13 Jan 2023	605	83.88
Pre-commissioning/commissioning	498,000.00	518,000.00	13 Sep 2021 / 03 Jan 2023	502	80.00
Demobilisation	55,500.00	85,500.00	15 Sep 2021 / 03 Aug 2023	730	95.00
Total	5,533,150.70	7,183,313.44	—	—	86.15

Table 1 indicates a cost increase of US$1,650,162.74, equivalent to approximately 29.82% above the approved contract sum. The reported quality outcome fell by 8.39 percentage points from the 94.54% baseline requirement to 86.15%. The largest reported milestone delay was 730 days for demobilisation, while engineering recorded the smallest milestone delay at 444 days. These values demonstrate that the case experienced a simultaneous deterioration in schedule, cost and aggregate quality performance rather than a simple one-dimensional time overrun.

4.2 Model Indicators

Planned days	Total days reported	SPI (reported)	CPI (reported)	Schedule variance (days)	Schedule efficiency	Availability	Cost/schedule index
610	1182	1.3611	0.7347	572	1.9377	6.2295	2.0958
760	1464	1.3614	0.7345	704	1.9263	7.3684	2.0959
273	717	1.5425	0.6483	444	2.6264	-62.6374	2.1908
675	1296	1.2109	0.8258	621	1.9200	8.0000	2.0367
455	1060	1.3616	0.7345	605	2.3297	-32.9670	2.0960
183	685	1.1004	0.9088	502	3.7432	-174.3169	2.0092
90	820	1.5405	0.6491	730	9.1111	-711.1111	2.1897

The dissertation's model-result table reports activity-level indicators including SPI, CPI, schedule variance, schedule efficiency and other indices. The reported CPI values below 1.0 are consistent with adverse cost efficiency in conventional EVM interpretation, but the SPI values above 1.0 should be treated cautiously because the underlying calculation basis is not fully documented in the dissertation. Accordingly, this article uses the milestone dates and cost/quality totals as the principal direct evidence of project performance.

4.3 Inductively Derived Themes

Code	Theme	Core interpretation
T1	Integrated completion objective	Timely completion within budget and quality requirements protects client satisfaction and project-team reputation.
T2	Critical-path and procurement control	CPM identifies critical activities and bottlenecks; procurement planning should protect critical-path work from material delays.
T3	KPI-based performance governance	Standardised KPIs translate time, cost, quality and safety expectations into measurable management information.
T4	Experienced permanent crews	Experienced crews can reduce learning curves, rework and coordination loss, but prolonged repetition can create complacency, fixed costs and reduced innovation.
T5	Proactive risk identification	Early identification of design, procurement, weather, labour, regulatory and site risks reduces the probability and impact of TCQT disruption.
T6	Non-linear resource–duration relationship	Adding labour or equipment does not guarantee proportional duration reduction because dependencies, congestion and bottlenecks constrain productivity.
T7	Scope-change control	Scope additions create ripple effects across time, cost, resources and quality and should be subject to formal change control.
T8	Adaptive external support and digitalisation	External experts, consultants and digital tools can strengthen complex decision-making, benchmarking, risk management and coordination when internal capacity is insufficient.

5. Discussion

5.1 Why the Case Demonstrates a Genuine TCQT Problem

The case is important because the final outcome did not show a conventional "pay more to finish earlier" pattern. Instead, cost increased while the project still experienced major schedule slippage and a lower aggregate quality result. This suggests that a substantial portion of additional expenditure did not create equivalent schedule value. The result supports the literature's argument that the relationship between resource quantity and activity duration is not linear in complex projects (Feylizadeh et al., 2018; Zhang et al., 2014). Where work is constrained by design release, procurement lead times, access, interfaces, testing or predecessor activities, adding labour to a downstream activity may create congestion rather than recovery.

5.2 Critical Path and Procurement as TCQT Levers

The thematic findings position CPM as a decision-support mechanism rather than a delay-removal mechanism. The project manager can identify activities with little or no float, determine procurement items that control those activities, and establish recovery options before the critical

path is affected. The dissertation similarly concludes that CPM is highly impactful for timeline management but must be accompanied by bottleneck identification and proactive controls. This finding is consistent with research on schedule optimisation and construction project control (Hegazy & Menesi, 2010; Petroutsatou, 2022).

5.3 Quality Should Be a Constraint, Not a Residual

A central implication is that quality should not be treated as the variable sacrificed when time or cost pressures arise. The final reported quality of 86.15% was below the 94.54% baseline requirement. For industrial water tanks, quality loss may manifest through defective fabrication, coating problems, leakage, contamination risk, rework or commissioning failure. A robust TCQT model should therefore impose minimum quality and safety thresholds and permit time/cost optimisation only within those boundaries. This interpretation is aligned with the literature on quality-integrated project optimisation (El-Rayes & Kandil, 2005; Orm & Jeunet, 2018).

5.4 Scope Management and Change Control

Thematic evidence indicates that scope changes can trigger additional engineering, procurement, labour and construction requirements. When the completion date is not moved and additional resources are introduced to absorb the new work, the project can experience cost escalation and quality compression. Therefore, the correct managerial response is not simply to “work harder” but to quantify the effect of each proposed change on the three project objectives and associated risks. Formal change evaluation should identify the time impact, cost impact, quality implications, risk exposure and resource requirements before approval.

5.5 Risk, Contingency and Decision Escalation

The findings support an integrated risk approach. The dissertation identified design changes, material shortages, labour strikes, regulatory changes, weather and unforeseen site conditions as significant risks. These risks should be linked directly to time and cost contingencies. A practical decision rule is to escalate when forecast performance crosses predetermined thresholds—for example, persistent schedule variance on critical-path activities, forecast cost overrun beyond contingency, repeated quality non-conformances or a risk whose residual exposure exceeds the team's authority. External expertise should be engaged before the project reaches a point at which recovery becomes prohibitively expensive.

5.6 Lean Construction, Prefabrication and BIM

The dissertation concludes that lean construction, integrated project delivery, prefabrication/modularisation and BIM are promising improvement approaches. For tank projects, prefabrication can shift repetitive fabrication and inspection activities into controlled environments, potentially reducing site congestion and improving consistency. BIM can support multidisciplinary coordination, constructability review and visualisation of interfaces. Lean practices such as pull planning, just-in-time material delivery and continuous improvement can reduce waiting, excess movement, rework and material waste. These approaches should, however, be selected based on project-specific feasibility rather than assumed to be universally optimal.

6. Proposed Integrated TCQT Decision Framework

Based on the eight themes, the study proposes a practical eight-stage management cycle. The framework converts the dissertation's conceptual model into decision gates that can be embedded in project controls.

Stage	Management action	Primary outputs	TCQT purpose
1. Define	Freeze scope, functional requirements, quality criteria and acceptance standards.	Approved scope baseline; quality plan; WBS.	Prevents avoidable scope-driven time/cost growth.
2. Plan	Develop integrated schedule, resource plan and procurement strategy.	CPM network; procurement schedule; resource histogram.	Protects critical activities and long-lead materials.
3. Quantify	Estimate normal, accelerated and contingency scenarios.	Time/cost options; quality thresholds; risk allowances.	Makes trade-offs explicit before execution.
4. Protect	Establish risk register, buffers and contingency reserves.	Risk responses; time/cost buffers; recovery options.	Absorbs foreseeable uncertainty without destabilizing the baseline.
5. Execute	Apply lean methods, prefabrication where feasible and controlled work packaging.	Look-ahead plans; work packages; inspection/test records.	Reduces waste while protecting quality.
6. Monitor	Track CPI/SPI where EVM data are available plus quality, safety and procurement KPIs.	Dashboard; trend analysis; exception report.	Detects emerging TCQT deviation early.
7. Decide	Evaluate changes and recovery options using time, cost, quality and risk criteria.	Change decision; recovery plan; escalation decision.	Selects the least damaging intervention rather than the fastest intervention.
8. Learn	Capture lessons, update benchmarks and refine future estimates.	Lessons learned; benchmark database; revised standard rates.	Improves future TCQT predictability.

6.1 Recommended KPI Set

Dimension	KPI	Interpretation / decision trigger
Time	Schedule variance; critical-path slippage; SPI	Identifies emerging completion-date risk.
Cost	Cost variance; CPI; forecast at completion	Identifies budget erosion and need for corrective action.
Quality	NCR rate; first-pass yield; defect density/DPMO; test acceptance rate	Prevents schedule recovery from being achieved by quality degradation.
Procurement	Long-lead item delivery variance; expediting rate; material availability	Links supply-chain performance to critical-path activities.
Risk	High/critical residual risks; contingency drawdown	Signals when management reserves or external support may be needed.
Safety	Recordable incidents; high-potential events; permit deviations	Prevents unsafe schedule compression.
Change	Design-change frequency; approved change value; schedule impact of changes	Quantifies scope-driven TCQT effects.
Productivity	Planned vs actual installation rate; labour productivity	Detects resource-loading inefficiency.

7. Managerial and Engineering Implications

For project managers, the key implication is that TCQT decisions should be made at the project-system level rather than activity-by-activity. A decision to add a crew is justified only when the affected activity is critical, the activity is resource-sensitive, the additional resources can work without congestion, and the quality/safety controls remain effective. For engineering managers, design maturity and interface control are essential because late design changes can propagate directly into procurement and construction. For procurement managers, long-lead materials and equipment should be prioritised according to critical-path exposure rather than simply purchase value. For quality managers, inspection and testing should be integrated into the schedule so that quality gates do not become hidden sources of delay. For sponsors, decision thresholds and escalation routes should be defined early so that support is mobilised before recovery costs become excessive.

8. Limitations and Future Research

The study has several limitations. First, it is based on secondary documentary evidence and therefore does not include interviews with project managers, engineers, contractors or client representatives. Second, the case represents one industrial water-tank project, limiting statistical generalisation. Third, the available project record does not contain sufficient activity-level earned-value information to independently reconstruct conventional EVM metrics for every work package. Fourth, the qualitative thematic analysis depends on the quality and completeness of the documentary evidence. Future studies should combine this framework with primary interviews, multiple Nigerian case studies and quantitative multi-objective optimisation. A future model could assign stakeholder-weighted utilities to time, cost, quality, safety and risk and use simulation or evolutionary optimisation to generate a Pareto frontier of feasible project strategies.

9. Conclusion

This study examined the time–cost–quality trade-off in the design and construction of industrial drinking-water and demineralised-water tanks using a qualitative case-study and inductive thematic approach. The project record demonstrates substantial divergence from the baseline: the approved value of US$5.533 million increased to US$7.183 million, approximately 29.82% above the original contract sum, while reported quality decreased from 94.54% to 86.15%. Major work packages experienced reported delays of 444–730 days.

The analysis shows that the central TCQT challenge is not simply a shortage of money or labour. Rather, project outcomes are shaped by the interaction of scope stability, critical-path dependencies, procurement reliability, risk, resource productivity, quality controls, stakeholder decisions and management capability. Eight themes were identified and integrated into a practical decision framework. The framework emphasises early scope definition, critical-path/procurement protection, quantified trade-off analysis, risk buffers, KPI-based monitoring, lean execution, controlled schedule compression, formal change management, digital coordination and timely access to external expertise.

The study concludes that project acceleration should be selective and evidence-based. Additional resources should be applied only where they can influence critical-path duration without creating congestion, excessive cost or quality deterioration. Quality should be treated as a minimum constraint, not a residual variable that can be sacrificed for schedule recovery. The proposed framework therefore offers a practical foundation for improving TCQT decision-making in future industrial water-tank and comparable EPC construction projects in Nigeria and similar high-complexity environments.

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