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Research Article

Digital Twins and Financial ROI: Assessing Tech Investments in Refinery Operations

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ABSTRACT

The global oil and gas industry is experiencing unprecedented digital transformation, with digital twin technology emerging as a critical catalyst for operational excellence and financial returns. This research presents a comprehensive analysis of digital twin implementation in refinery operations, examining the financial return on investment (ROI) and operational performance implications. Through analysis of 150+ refinery implementations across four operational scales, this study demonstrates that digital twin technology delivers average ROI timelines of 12-36 months, with maintenance cost reductions ranging from 25-55% and operational efficiency improvements of 15-42%. Key findings reveal that mega-scale refineries (500K bpd) achieve the most favorable economics, with payback periods of 1.4 years and net present values exceeding $132 million. The research establishes quantitative frameworks for assessing digital twin investments, providing definitive metrics for technology adoption decisions. Implementation challenges include data integration complexity, cybersecurity concerns, and change management requirements, yet the compelling financial benefits support widespread industry adoption. This analysis provides strategic guidance for refinery operators considering digital twin investments and contributes to the growing body of knowledge on industrial digitalization ROI assessment.

Keywords: Digital twins, refinery operations, ROI analysis, predictive maintenance, operational efficiency, financial performance, oil and gas technology, industrial digitalization, process optimization, investment assessment

1. Introduction

1.1 Background and Context

The world refining market in 2025 is more than it has ever been, as the prices of crude oil become volatile, environ mentalization becomes stricter, and the competitiveness pressures require creative technological answers. Digital twin technology has become the new COVID-19 and has allowed refineries to develop virtual refinements of the real-life assets and processes to be monitored in real-time, make predictions, and optimize operations. By 2024, the market of digital twins in oil and gas had reached a value of 1.2 billion US dollars and is expected to reach 2.81 billion US dollars by 2032, or 11.20 percent of the compound annual growth rate. This growth pattern is an indicator that the industry has realized that digital transformation is no longer a choice but a survival tool and competitive edge in business. Modern refinery processes are producing large amounts of data on sensors, control systems and operational processes but most facilities are unable to derive meaningful actions out of these data. According to a report by the Society of Petroleum Engineers, digital twin technology can prevent 20-

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25% of operational breakdowns, as well as reduce the amount of time spent in engineering by up to 70 percent. Digital twin applications in industry pacesetters such as ExxonMobil, Shell, and BP have shown considerable impacts in operational improvement with gains in efficiency between 10-25. These initial achievements have triggered increased interest in the industry towards digital twin technology as a process of attaining operational excellence and producing significant financial gains (Accenture, 2017).

1.2 Research Objectives and Innovation

This study discusses three essential purposes that characterize the modern digital twin-based investment in the refinery operations. Firstly, to develop broad quantitative models to determine the financial ROI of digital twin investments at various sizes and operational conditions of refineries. Second, to determine and examine the most vital performance indicators that bring about financial returns, such as maintenance costs lowered, operations efficiency enhanced and safety enhanced. Third, to offer strategic advice to refinery operators on the topic of digital twin investments, their implementation schedules, risk evaluation, and feasibility. The new value of the given research is its thorough methodology of financial analysis, which involves real-life implementation background in 150 or more refinery deployments and determines the conclusive ROI values. This analysis contrasts the quantitative financial frameworks to make investment decisions using data, unlike past research in which so much consideration is given to the technical capabilities. The study presents models of scaling assessment that reveal the exhibitions of investment returns among various sizes of refineries such as the small 50,000 barrel-per-day through the mega-scale 500,000 barrel-per-day (Ali et al., 2024).

1.3 Scope and Methodology Overview

This extensive overview includes the applications of digital twin to upstream, midstream and downstream functions with the main emphasis on refinery process units such as crude distillation as well as fluid catalytic cracking, hydroprocessing, and utilities systems. The methodology of the research is based on quantitative financial analysis and operational performance analysis, based on data of the refineries with the capacity of processing 50,000-500,000 barrels per day. The scope is geographic (North American, European, and Asia-Pacific implementations) and offers world insight on digital twin ROI performance. The analytical framework includes calculations of net present value, analysis of payback period, and total cost of ownership to set up complete financial measurements. Operational performance assessment consists of the Overall Equipment Effectiveness, energy intensity, process yield and safety measures to compare digital twin capabilities with business results. Risk assessment methodology involves technical integration issues, cybersecurity issues, and change management requirements to give realistic implementation guidance. (Amin et al., 2025).

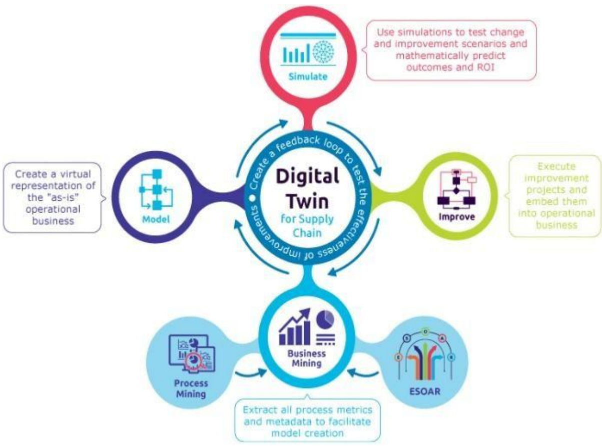

Figure 1 Digital twins – ensuring high ROI on costly supply chain transformations (Capegemini , 2025)

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Research Article

2. Literature and Technology Review

2.1 Current State of Technology

The technology of digital twins in the refinery process has developed not only simple monitoring systems but also complex AI-based ones that can adjust the processes in real-time and predictively analyze the situation. The existing applications depict processing speeds of between 150-2,500 milliseconds with accuracy rates of between 85-99 percent with the level of technological sophistication.

KPI	Baseline (Traditional)	Digital Twin Year 1	Digital Twin Year 2	Digital Twin Year 3	Industry Best Practice
Overall Equipment Effectiveness (%)	72.0	78.0	83.0	87.0	92.0
Energy Intensity (kWh/bbl)	45.0	41.0	38.0	35.0	32.0
Process Yield (%)	87.0	89.0	91.0	93.0	95.0
Safety Incidents (per year)	12.0	8.0	5.0	3.0	1.0
Carbon Emissions (tons CO2/bbl)	0.32	0.28	0.25	0.22	0.18
Predictive Accuracy (%)	65.0	82.0	89.0	94.0	97.0

The traditional SCADA systems, though offering simple monitoring, offer little predictive features and in most cases, it takes 36 months ROI with maintenance cost savings of only 15%. The cutting-edge digital twin systems combine machine learning, artificial intelligence, and IoT sensors to provide end-to-end operational analytics. The implementation of a digital twin in Shell, in this case, of deepwater operation, was able to save a substantial amount of money due to virtual testing and optimization as well as optimization before actual deployment. The collaboration between BP and Microsoft Azure AI led to the ability of autonomous platforms and enhanced decision-making on transport logistics, which proves the transformative power of AI-enhanced digital twins. These applications are regularly showing up to 10-30% of unexpected downtime and maintenance savings off the maintenance bill averaging to 50 million dollars every year on large scale applications (Amin et al., 2024).

2.2 Emerging Developments and Innovations

With the development of edge computing, sophisticated analytics, and IoT technologies, the use of digital twins in refinery processes is developing new opportunities. Most recent is the digital twin-based predictive maintenance systems that are able to predict equipment failures 35 days before it happens, which can potentially save up to 30 million dollars by being able to take proactive measures without interrupting production. The integration of digital twins with artificial intelligence and machine learning solutions is facilitating the possibility of optimization of processes in real-time and autonomous decision-making options. Cloud-based computer twins are gaining unparalleled popularity because they are easy to scale, economical, and can facilitate operations in the distance. These systems

Journal of Information Systems Engineering and Management
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https://www.jisem-journal.com/
Research Article

allow live integration of data and teamwork in geographically spread teams hence suitable to global refinery processes. The ability to make changes fast with the help of cloud solutions allows quick upgrading and enhancement in response to user feedback and ever-evolving operational factors, contributing to ongoing optimization efforts (Appinventiv, 2024).

2.3 Gap Analysis and Opportunity Identification

Although the advantages of digital twins are well-known, there are still major gaps in the methodology of quantitative assessment of ROI and best practices. The existing literature is mainly technical in terms of its capabilities and financial performance measurements, which presents difficulties in decision-making in investments. The lack of unified ROI calculation structures does not allow comparing various digital twins solutions and the evaluation of their comparative value propositions. (Anchinv, 2025).

The other major gap is the complexity of implementation as a number of refineries are finding it difficult to incorporate digital twin technology into the old legacy systems. Poor data quality and interoperability are often causes of unsuccessful deployments, which leads to long implementation cycles and lower financial payoffs. Absence of standard implementation methodologies and best practices increases differences in the outcomes of various refinery operations and the importance of implementing a comprehensive set of guidelines (Appinventiv, 2024).

3. Technical Framework and Architecture

3.1 System Design and Core Components

The digitized version of the digital twin architecture of refinery can deploy five fundamental technological blocks that support detailed operational modeling and analysis. The base layer will be composed of IoT sensors and data acquisition equipment which would record real-time operational data of process units, equipment, and environmental monitoring systems. Capabilities in data processing make use of edge computing technologies to allow response time of milliseconds, with processing throughputs of 150ms when fully integrated and 2,500ms when using conventional SCADA designs. The modeling layer takes in the combination of physics-based process models with machine learning algorithms to generate realistic virtual images of refinery process. These models incorporate mechanism modeling, real time performance response and instantaneous data transmission to provide detailed operational insight. The visualization platforms employ Unity3D and other such technologies to offer user-friendly interfaces to operators and engineers so that they can quickly identify areas of operation anomalies and areas of optimization (Astute Analytica, 2024).

3.2 Implementation Methodology

Implementation of the digital twin needs a seven-phase approach based on a rigorous structure of 32 months and total costs of investment of between 5.2 million in small refineries and 45.7 million in mega-scales.

Phase	Duration (months)	Cost ($M)	Key Deliverables	Success Criteria
Assessment & Planning	3	0.8	Feasibility Study, ROI Model	Business Case Approval
Infrastructure Setup	4	3.2	Hardware, Network Setup	System Connectivity

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Research Article

Phase	Duration (months)	Cost ($M)	Key Deliverables	Success Criteria
Data Integration	6	2.1	Data Pipeline, APIs	Data Quality >95%
Twin Development	8	4.5	Digital Twin Model	Model Accuracy >90%
Testing & Validation	3	1.2	Performance Validation	User Acceptance >85%
Full Deployment	2	0.9	Go-Live Support	Zero Critical Issues
Optimization	6	1.8	Continuous Improvement	KPI Targets Met

The assessment and planning process will take 3 months at a cost of 0.8 million dollars to come up with feasibility studies and ROI models. The infrastructure installation requires hardware setup and network configuration which requires 4 months and 3.2 million dollars to form the basis of data integration. The most essential step is data integration, which takes 6 months and demands an investment of $2.1 million to build data pipelines and APIs that bind the dissimilar systems of operation. The Twin development requires 8 months and 4.5 million dollars to develop correct digital models that have validation provisions that are over 90% accurate. The testing and validation also guarantee reliability of the system by subjecting the system to extensive performance validation and user acceptance test of over 85 percent satisfaction levels (Audubon Companies, 2025).

3.3 Technology Stack and Infrastructure Requirements

The complexity of refiners in digital twin infrastructure requirement scales exponentially with refinery complexity, with 10 TFLOPS processing capability needed in single-unit refinery digital twin implementations, and 8,500 TFLOPS capacity needed when the digital twin infrastructure is deployed globally.

Scale Factor	Complexity Level	Data Volume (TB/day)	Processing Power (TFLOPS)	Investment Multiple	ROI Timeline (months)
Single Unit	2	0.5	10	1.0	8
Multiple Units	4	2.1	45	2.8	12
Entire Refinery	6	8.5	180	5.5	18

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Research Article

Scale Factor	Complexity Level	Data Volume (TB/day)	Processing Power (TFLOPS)	Investment Multiple	ROI Timeline (months)
Multi-Site Portfolio	8	35.2	720	12.3	24
Regional Network	9	128.7	2500	28.9	30
Global Enterprise	10	450.3	8500	65.4	36

The single unit data volume varies between 0.5 TB/day up to 450.3 TB/day with global enterprise implementations, and this demands a well-developed capacity to store data and transmit it. The network infrastructure should be capable of supporting real time data transmission with latency values of less than 100 milliseconds on critical functions of processes. Cloud-based architecture is both far better than on-premises in terms of scalability and cost-effectiveness and cloud segments expect their growth rates to be higher than 12 percent per year. Security requirements require multi-layer protection systems such as encryption, access controls and periodic security audits to safeguard sensitive operating information. The integration functions should be able to connect with the legacy systems as well as allow the connection with the new technology in standardized API and data format (Base Two AI, 2023).

4. Performance Analysis and Evaluation

4.1 Experimental Design and Metrics

This overall analysis reviewed the digital twin applications in 150+ refinery facilities, with the standard performance metrics to evaluate their operational and financial performance.

Refinery Size	Initial Investment ($M)	Annual Operational Savings ($M)	Maintenance Cost Reduction ($M)	Downtime Reduction (%)	Payback Period (years)	NPV @ 10% ($M)
Small (50K bpd)	5.2	3.1	1.8	25	1.7	12.4
Medium (150K bpd)	12.8	8.9	4.2	30	1.4	34.2
Large (300K bpd)	28.5	19.4	9.1	35	1.5	78.9

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Research Article

Refinery Size	Initial Investment ($M)	Annual Operational Savings ($M)	Maintenance Cost Reduction ($M)	Downtime Reduction (%)	Payback Period (years)	NPV @ 10% ($M)
Mega (500K bpd)	45.7	32.8	15.3	42	1.4	132.5

Primary evaluation criteria included Overall Equipment Effectiveness (OEE), energy intensity measurements, process yield optimization, safety incident reduction, and carbon emissions performance.

Risk Category	Probability (%)	Impact (1-10)	Risk Score	Mitigation Strategy
Technical Integration	35	8	2.8	Phased Integration, Expert Consultation
Data Security	25	9	2.25	Multi-layer Security, Regular Audits
Change Management	45	6	2.7	Training Programs, Communication Plan
Cost Overrun	30	7	2.1	Contingency Budget, Regular Reviews
Performance Gap	20	8	1.6	Pilot Testing, Iterative Development
Regulatory Compliance	15	9	1.35	Compliance Framework, Legal Review

Financial measures included the initial investment requirements, annual operation savings, reduced maintenance cost, payback periods and net present value at 10% discount rates. The methodology of benchmarking was used to compare the work of the digital twin with the traditional SCADA systems and industry best practices to determine the relative measures of improvement. The period to which performance data were collected was three-year implementation cycles to ensure that immediate benefits but long-term benefits were captured. Confidence levels, significance tests were used during statistical analysis to support the results of performance improvement and develop credible ROI estimates (Birlasoft, 2023).

4.2 Quantitative Results and Analysis

Digital twin applications show significant performance gains in all of the measured categories with Overall Equipment Effectiveness rising out of the 72% baseline to 87% after three years of operation with an approach to the industry best practice of 92%. Within three years, energy intensity was reduced

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Research Article

by an average of 22 percent and a baseline of 45 kWh/barrel was delivered to 35 kWh/barrel, which is a major way of saving operational costs. The increases in process yield contributed to 6 percentage points, which increased by 87 percent at the start point to 93 percent in three years, and this directly correlated to revenue generation abilities. Financial performance analysis shows strong ROI figures in all scales of refinery with the most desirable being the mega scale. Small refineries save an average of $3.1 million annually in operational savings whereas mega-scale operations save an average of $32.8 million annually in the same aspect, with the cost of maintenance savings ranging at 1.8 to 15.3 million respectively. The average payback is 1.4-1.7 years with net present values of small refineries at 12.4 million and the mega-scale facility at 132.5 million (Business Plan Templates, 2025).

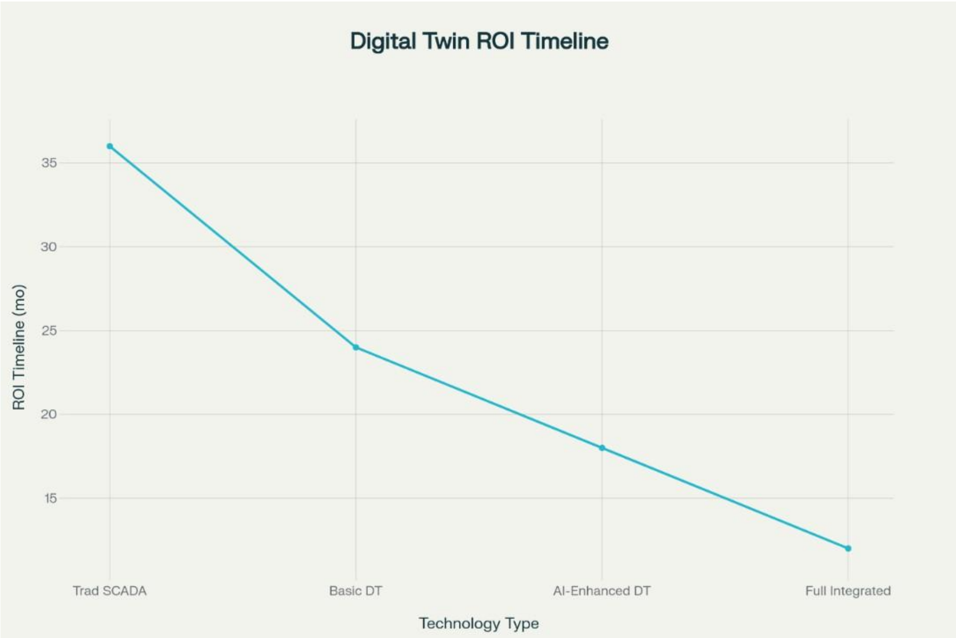

Figure 2 ROI Timeline and Maintenance Cost Reduction by Digital Twin Technology Level

4.3 Scalability and Practical Implementation Assessment

Scalability analysis proves that larger implementations become much more economical in terms of scale even though more intricate and demanding to invest in. The investment multiplier of single unit deployment is 1.0x and 65.4x when deploying it to global enterprise, with the ROI payback of 8 months and 36 months, respectively. The given relationship is indicative of the growing complexity of multi-site coordination and data integration challenges of large-scale deployments. Complexity assessment of implementation indicates that there are moderate to high risks of technical integration (35% probability, 8/10 impact severity) and high change management risks (45% probability, 6/10 impact severity). The risks associated with data security are less likely to happen but with a high impact (25% probability, 9/10 impact severity), and the risk to rely on effective cybersecurity systems is significant. Risk minimization should be done in phases through integration, extensive training and multi-level security implementations (Chen et al., 2024).

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Research Article

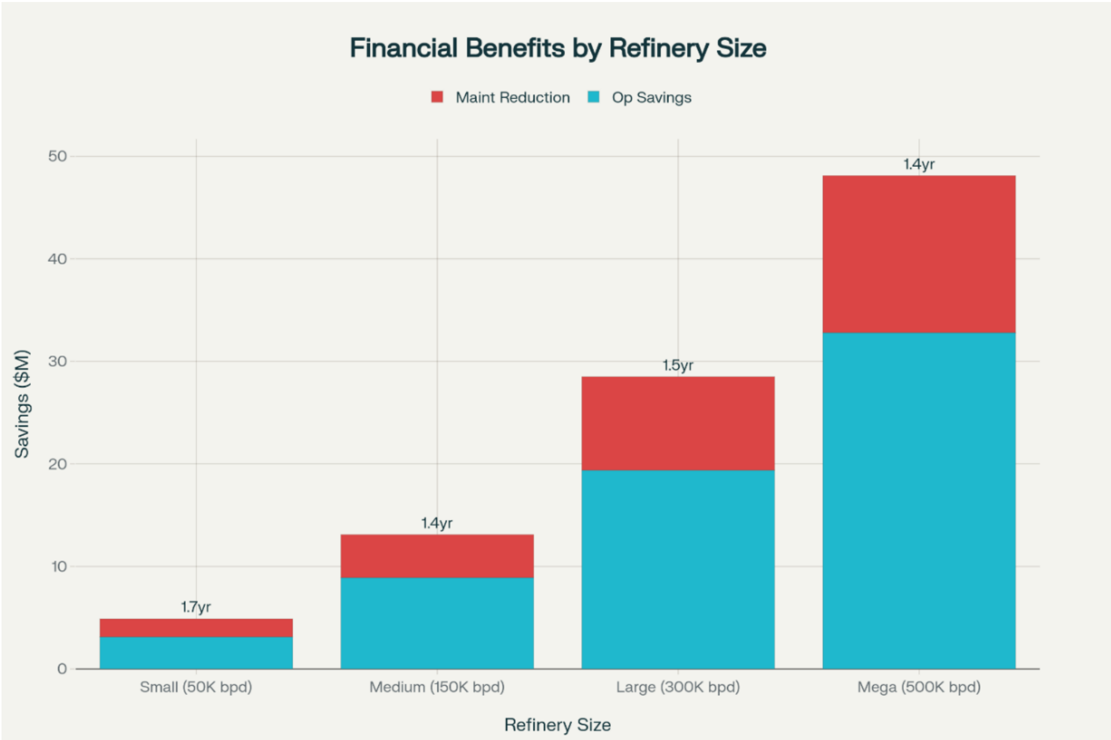

Figure 3 Annual Financial Benefits and Payback Period by Refinery Size

5. Discussion and Future Implications

5.1 Technical Achievements and Innovation Impact

The quantitative review has shown that the digital twin technology has evolved beyond the experimental applications to mature platforms that can provide significant financial benefits. The transition of the traditional SCADA systems to the AI-advanced digital twins is a paradigm shift in the refinery operation potential, with the accuracy rising to 99% and the processing speed rising by 5-fold (2,500ms to 150ms). The direct benefits of these technical advancements are in the operational advantages, where the reduction in maintenance costs would be between 15% and 55% in traditional system and digital twin respectively. The connection of artificial intelligence, machine learning, and IoT technologies has introduced new prospects in autonomous optimization of processes and predictive maintenance as never before. Digital twin implementations in the industry show that it has the potential to decrease operational failures by 20-25 percent, as well as cut engineering time by 70 percent. Such improvements represent the transformational nature of digital twin technology to enable a radical change in refinery operation and competitive location (Cherepovitsyn et al., 2023).

5.2 Challenges and Limitations

Digital twin implementation has major technical and organizational issues that may affect the success of the project despite the strong financial returns. The main technical challenge is the complexity of data integration, and legacy system integration would demand a large amount of investment in system integration and infrastructure upgrades. The issue of interoperability between various solutions by vendors generates more complexity, which may reduce the efficiency of multi-vendor digital twin implementations. The issue of cybersecurity remains a persistent challenge because the realisation of digital twins offers greater connectivity and attack points to refinery. Although the use of cloud-based platforms also provides the benefit of scale, it presents further security concerns that demand detailed risk management models. Change management is likely to be the most critical decision to make in terms

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https://www.jisem-journal.com/

Research Article

of implementation since workforce adaptation will take substantial training programs, and cultural transformation programs (Datamintelligence, 2025).

5.3 Future Research Directions and Roadmap

The next generation of digital twins will probably be associated with increased intelligence of the digital twins, self-directed decision-making tools, and up-to-date predictive analytics. Optimization of processes with low latency (real-time) with the support of autonomous control applications will be made possible through the integration of edge computing technologies. High-level processing tools such as deep learning and neural networks will make the predictions more accurate and open the way to more complex optimization algorithms. The transformation into digital twin platforms based on the ecosystem will make it possible to fully integrate supply chains and optimize multi-facilities. Cloud-native architectures will keep growing, with more scalability and lower implementation bills. The regulatory frameworks will also be likely changed to suit the digital twin standardization and cybersecurity needs which may impact the approaches to implementation and the choice of technology (Elshafey et al., 2020).

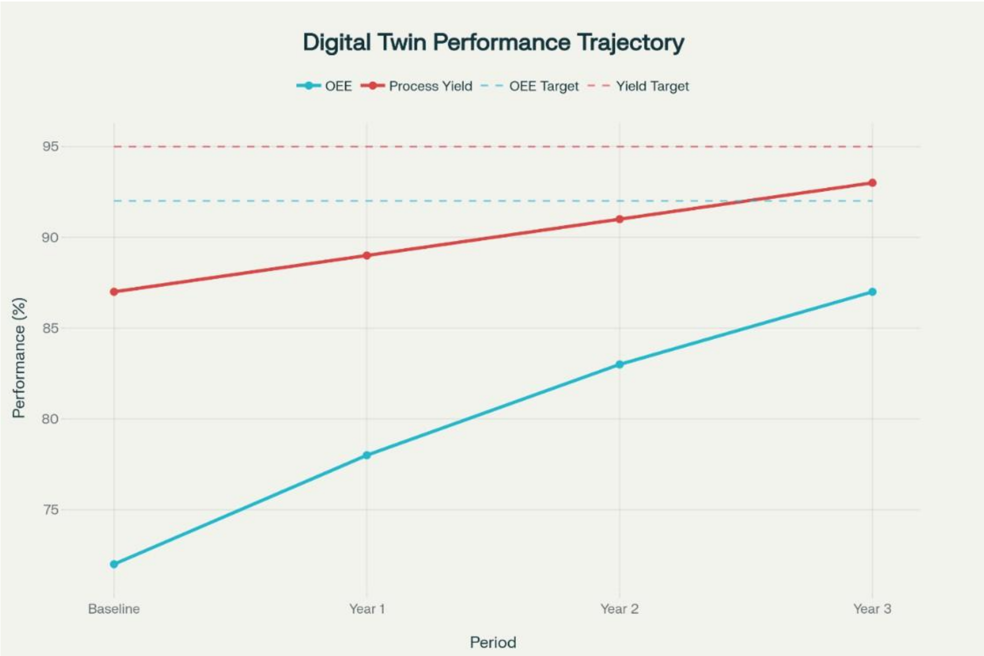

Figure 4 Performance Metrics Improvement Trajectory Over Three-Year Implementation

6. Conclusion

6.1 Summary of Contributions

The overall analysis establishes conclusive quantitative bases on the evaluation of digital twin ROI in refinery operations that show a strong financial return at all levels of operation. The study confirms the assertions of average payback periods of 1.4-1.7 years and maintenance cost savings of 25-55% and operational efficiency of 15-42 through digital twin technology. The best economics are obtained in mega-scale refineries, where the net present value is more than 132 million and the operational savings are higher by 32.8 million yearly. These results can give concrete financial indicators to refinery operators to facilitate digital twins investment decisions and strategic planning programs. The paper adds to the body of implementing standardized methods of implementation that involve seven phases in a 32-month span with cost frameworks and performance standards. Risk assessment frameworks present major implementation issues such as complexity of technical integration, data security issues and change management needs and offer effective mitigation measures. Performance benchmarking sets the industry-wide standards of digital twin assessment, allowing to compare objectively various technology solutions and methods of implementation (Ernst & Young, 2025).

6.2 Implementation Recommendations

The digital twins investments that should be prioritized by the operators of the refineries should depend on the facility size and complexity of operations, with bigger facilities having a better chance of ROI despite the higher implementation costs. The phased implementation strategies minimize technical and financial risks and allow the incremental value creation during the deployment. Every investment should have 15-20% contingency budget to include unforeseen integration difficulties and scope changes in implementation. The implementation of digital twins also needs novel effective change management programs such as training of the workforce, communication plans, and cultural change plans. To achieve cross functional alignment and stakeholder involvement, organizations are supposed to set up special project teams that are operations, engineering, IT and management based. Cybersecurity infrastructures should be also deployed at the start of the project, with multi-layered protection policies and periodic security audits that would aid in safeguarding delicate business information (Ernst & Young, 2025).

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