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International
Journal
Of Modern Engineering Research (IJMER)

A Dynamic Model for Financial Risk Assessment in Mega Infrastructure Projects: An AI and Root Cause Analysis-Based System for Saudi Vision 2030

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Abstract

Background: *Saudi Vision 2030 hinges on the delivery of giga-projects, a pipeline of mega infrastructure developments unprecedented in scope and financial scale. Traditional financial risk analysis methodologies, founded on static experience-based models, are not adequate to address the dynamic, highly interlinked, and compound risks involved in these projects. This shortage is a serious threat to project viability, financial sustainability, and overall success of the national transformation agenda. Objective: This research proposes an innovative conceptual model of an "AI and RCA-Based Analytical System" (ARAS). The objective is to create a dynamic, data-driven system that not only can predict financial risks in real-time but also can diagnose the root causes of the risks. This study aims to demonstrate how such a system can provide decision-makers with proactive, actionable intelligence, and in the process, enhance capital efficiency and safeguard massive national investments.*

Methodology: *A constructive research methodology is followed to create the ARAS framework. The paper synthesizes literature on project finance, risk management, Artificial Intelligence (AI), and systems engineering in formulating the framework. The usefulness and applicability of the framework are subsequently demonstrated through in-depth analysis of two representative case studies, representing archetypal Saudi giga-project problems: a complex supply chain disruption and a public-private partnership (PPP) financing structure under stress.*

Results: *The research illustrates that the proposed ARAS system goes beyond the limitations of static models by the continuous ingestion and analysis of real-time project data. Its predictive ML module has the potential to identify emergent risks, such as potential cost overruns or liquidity shortfalls, weeks or months in advance. The integrated Root Cause Analysis (RCA) module, founded on causal inference techniques, can then trace these predicted risks back to their root causes, e.g., a specific supplier dependence or a contractual clause shortfall. This provides a level of foresight and diagnostic clarity that is currently unachievable.*

Conclusion: *The transition from static risk registries to a dynamic, AI-enabled analytical platform is a strategic necessity for the effective implementation of Vision 2030's giga-projects. The ARAS structure provides a blueprint for a next-generation paradigm of financial guardianship that supports project resilience, reinforces investor confidence, and ensures responsible custodianship of the Kingdom's financial resources in its most significant projects.*
Keywords: *Financial Risk Analysis, Artificial Intelligence, Giga-Projects, Saudi Vision 2030, Root Cause Analysis (RCA), Project Finance, Machine Learning, Public-Private Partnership (PPP).*

Date of Submission: 08-09-2025 Date of acceptance: 19-09-2025

I. Introduction

1.1. The Age of Giga-Projects and the Enhancement of Financial Risk

Saudi Arabia's vision 2030 is more than a policy document; it is a blueprint for a profound national reboot. At its heart is a portfolio of giga-projects—such as NEOM, the Red Sea Global, and Qiddiya—each a multi-billion-dollar project meant to act as an economic driver for diversification. These projects are characterized by their massive scale, long durations, technological advancement, and complex stakeholder ecosystems, with a dense web of international contractors, financiers, and government agencies.

While these projects promise enormous economic and social returns, they also represent a concentration of financial risk at the national level. A significant cost overrun or delay in a single giga-project can have ripple effects on the national budget, investor confidence, and the timeline of the overall Vision 2030 agenda. The reality that the capital involved is frequently bigger than the GDP of small nations means that traditional risk management practices are no longer sufficient.

1.2. The Problem: The Inadequacy of Static Risk Assessment

Traditional financial risk analysis of mega-infrastructure projects has long been under the dominance of conventional approaches such as Monte Carlo simulations, sensitivity analysis, and expert-based risk registers. These approaches, while helpful, suffer from one major weakness when dealing with giga-projects: they are largely static and periodic in nature.

1. Static Nature: Risk registers are typically completed at the beginning of a project and subsequently updated infrequently. They represent a snapshot in time but do not keep up with the dynamic, fluid nature of a ten-year construction project.

2. Data Latency: Analysis is often based on historical data and periodic reports, such that by the time a risk has been highlighted through these channels, it has very often already escalated into a major problem.

3. Symptom-Oriented: These methods are excellent for identifying what can go wrong (the risk event) but poor for diagnosing the complex, interlinked chain of events that is the why (the root cause). A cost overrun is a symptom; the root cause may be a deeply buried flaw in the initial geological survey or an untested assumption of dependence on a single volatile commodity market.

This passive and shallow risk assessment mode creates a dangerous blind spot for project financiers and government stakeholders, perpetually leaving them in a reactive state.

1.3. Research Objectives and the Proposed Solution

This study fills this significant gap by advocating a paradigm shift in financial risk assessment from a static, diagnostic, and reactive to a dynamic, diagnostic, and proactive system. The proposed solution is a conceptual framework of an "AI and RCA-Based Analytical System" (ARAS).

The primary objectives of this research are to:

1. Critically assess the limitations of traditional financial risk analysis frameworks within giga-project environments.
2. Formulate a holistic, multi-layered conceptual architecture for the ARAS, outlining its primary analytical modules and technological underpinnings.
3. Demonstrate the tangible value and operational utility of the ARAS through detailed, realistic case studies based on Saudi project archetypes.
4. Discuss how the introduction of such a system directly supports the strategic imperatives of good governance, transparency, and fiscal responsibility embedded in Vision 2030.
5. Discuss implementation challenges and strategic considerations in deploying the ARAS within the Kingdom's project management ecosystem.

II. Literature Review

2.1. Traditional Financial Risk Management in Infrastructure Projects

The literature on risk in project finance is extensive.

Notable risk categories include market risk (e.g., demand, price), credit risk (e.g., counterparty default), and operational risk (e.g., completion, cost overrun). Market risk is assessed through methodologies like the Capital Asset Pricing Model (CAPM), while Value at Risk (VaR) models estimate possible financial losses. Monte Carlo simulations are used widely to model the probability distribution of project outcomes through the simulation of thousands of scenarios with variable inputs (Flyvbjerg, 2009). Statistically rigorous as they are, these models are only as good as their assumptions and have a tendency to overlook "unknown unknowns" or non-linear, complicated interactions that are characteristic of megaprojects.

2.2. Root Cause Analysis (RCA) in Project Management

Evolved in engineering and quality management, RCA provides a methodical way of looking beyond a problem's symptoms to its root cause.

Techniques such as the Ishikawa (Fishbone) Diagram and Fault Tree Analysis are used to map potential causes. RCA in project management is typically conducted post-mortem, after failure has occurred, to generate "lessons learned" (Mahto& Kumar, 2021). Its application as a forward-facing, diagnostic tool in conjunction with real-time data feeds has been limited due to the challenge of performing such an analysis manually on an ongoing basis.

2.3. Advent of AI and Machine Learning in Finance and Risk Management

AI and Machine Learning have revolutionized the field of finance. ML models are nowadays ubiquitous for credit scoring, fraud detection, and algorithmic trading. In risk management, ML is already proving itself in being able to identify complex, non-linear patterns in large datasets that human analysts cannot see (Leo et al., 2019).

• Predictive Analytics: Supervised learning models (e.g., regression, gradient boosting) can be trained on historical project data to predict future outcomes like cost overruns or delays in schedules.

• Anomaly Detection: Unsupervised learning models can monitor real-time data feeds (e.g., sensor data from construction equipment, commodity price feeds) for abnormal patterns that are early warning signs of a larger problem emerging. Integrating these predictive features into the core of infrastructure project finance is a huge and untapped opportunity.

2.4. The Special Risk Profile of Saudi Giga-Projects

While it shares risks with all megaprojects, the Saudi giga-project risk profile is unique.

These include environmental threats attendant to building in extreme desert and maritime conditions, geopolitical threats indigenous to the region, and enormous supply chain threats associated with the need to import vast quantities of specialized materials and labor. Additionally, the novelty and technological ambition of most projects (e.g., building a cognitive city like NEOM) pose unprecedented technological and adoption risks. Any risk assessment system that will be effective needs to be tailored to this specific environment.

III. The AI and RCA-Based Analytical System (ARAS) Framework

The proposed ARAS is a unified, multi-layered system for providing continuous, intelligent risk monitoring. It is composed of four principal modules.

3.1. Module 1: The Central Data Aggregation and Integration Layer

This foundation module is the nervous system of the system. It is a secure data lakehouse that is designed to ingest, cleanse, and structure massive volumes of heterogeneous data from a vast array of sources in real-time or near-real-time.

• Data Sources:

o **Internal Project Data:** Building Information Modeling (BIM) data, Primavera P6 project schedules, cost management systems (e.g., SAP), procurement records, and contractor progress reports.

o **External Market Data:** Real-time commodity price feeds (steel, concrete, energy), shipping and logistics cost indices, currency exchange rates, and interest rate data.

o **Unstructured Data:** News feeds, political risk reports, satellite images of the construction site, and even social media sentiment analysis regarding the project.

o **Physical Data:**IoT sensor data from the construction equipment (for predictive maintenance), environmental sensors (for weather risks), and worker safety monitors.

3.2. Module 2: The Predictive Financial Risk Identification Module (ML-Powered)

This module leverages the integrated data to foresee probable financial risks before they become cause for concern.

• **Cost Overrun Prediction:** Train a gradient boosting model (e.g., XGBoost) on real-time and past data to predict the probability of a cost overrun for specific work packages. Significant features can include material price volatility, contractor performance metrics, and change order frequency.

• **Schedule Delay Prediction:** The same model predicts the likelihood of delays that would trigger financial penalties or impact revenue-generating milestones.

• **Liquidity & Cash Flow Anomaly Detection:** An unsupervised learning model (e.g., an Isolation Forest) monitors cash flow statements and forecasts, raising alerts on variations from the expected patterns that can herald a future liquidity crisis.

3.3. Module 3: The RCA Causal Inference Module

When a high-probability risk is indicated by Module 2, this diagnostic module is invoked. The intent of this module is to address the "why" question.

• **Technology:** The module is based on a Bayesian Network, a probabilistic representation of the causal relationships between different variables. The network is initially structured based on expert knowledge (e.g., a supply chain expert knows that material delays can be caused by port congestion) and then continuously updated and refined by the real-time information.

• **Function:** If the ML module predicts a 70% chance of a cost overrun for the "structural steel" package next quarter, the RCA module will trace back the most probable cause paths.

It might conclude, for example, that the primary reason is not the global price of steel, but rather a combination of rising shipping insurance premiums in the Red Sea and a purported reduction in the productivity of a key supplier, thereby guiding decision-makers to the precise source of the problem.

3.4. Module 4: The Dynamic Risk Dashboard and Alerting Module

This is the user interface and communication layer of the system.

• **Dynamic Dashboard:** A real-time financial risk profile of the project is displayed on an interactive web-based dashboard. It is more than static "traffic light" reporting of a risk register. The user can see the trend over time in the probability of individual risks and can drill down through the output of the RCA module to determine causal drivers.

• **Intelligent Alerting:** Not only does the system create alerts, but it also provides context. An example of such an alert is: "Alert: Risk of 90-day delay in Phase 2 of Project Alpha has increased by 45% in the last week. RCA shows the primary driver is a 70% likelihood of a customs clearance bottleneck due to new import regulations. Recommended Action: Mobilize logistics team to seek alternative shipping routes."

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4. In-Depth Illustrative Case Study Analysis

Case Study 1: Supply Chain and Cost Overrun in a Remote Giga-Project

• **Scenario:** A major component of a giga-project is being constructed in a remote desert location, which includes a long and complex supply chain for custom-made composite materials ordered from Europe. The project's financial model is highly sensitive to material prices as well as construction timelines.

• **Classical Risk Assessment:** The initial risk register identified "disruption to supply chain" as a medium-probability, high-impact risk. The mitigation was to have a 30-day buffer of materials on site. The risk is reviewed quarterly.

• The Unfolding Problem: A minor geopolitical upheaval in a key maritime transit chokepoint causes shipping insurance premiums to spike by 300%. Meanwhile, one of the two qualified suppliers of the composite material experiences a labor strike. Both of these occurrences, transpiring between quarterly updates, are not explicitly factored into the project's financial forecasting. The 30-day cushion is consumed, the building halts, and the project experiences a massive cost overrun and six-month delay.

• **ARAS Framework Application:**

Data Ingestion (Module 1): ARAS is continuously ingesting real-time data on shipping insurance premiums, news feeds about geopolitical events, and production news from the suppliers.

Predictive Identification (Module 2): Weeks ahead of buffer consumption, the ML model detects the abrupt, correlated increase in both supplier lead times and insurance costs. It warns of a 90% probability of budget overrun in the "composite materials" work package within the next 60 days.

RCA Causal Inference (Module 3): The dashboard alert is triggered. The RCA module immediately identifies the two independent events (insurance spike, labor strike) as the converging root causes. It calculates that the strike at a single sole supplier explains 70% of the potential schedule delay, indicating a critical supplier dependency risk that had been minimized.

Proactive Decision-Making (Module 4): Through this early, granular intelligence, project leaders can take proactive action weeks in advance. They can authorize air-freighting a small but vital batch of material to avoid a complete work shutdown and immediately begin negotiating with the second supplier to ramp up production, dramatically minimizing the financial and schedule impact.

Case Study 2: Public-Private Partnership (PPP) Financing Under Market Stress

• **Situation:** A new smart city's utility infrastructure (5G, water, power) is being financed by a private consortium under a complex Public-Private Partnership (PPP) arrangement. The financing for the private consortium is structured as an issuance of a series of bonds over several years. The profitability of the project for the government partner is dependent on the achievement of certain user adoption rates of the new utility services by specific dates.

• **Traditional Risk Assessment:** There is a basic sensitivity analysis in the financial model for interest rate changes. The risk of low user take-up is noted, with the mitigation of a marketing campaign at some unspecified future date.

• **The Unfolding Problem:** A global inflation surprise prompts central banks to raise interest rates much faster than anticipated. This suddenly increases the private consortium's cost of capital on their next bond issue, threatening their ability to fund the next phase of construction. Meanwhile, an alternative technology emerges that makes the planned 5G service less attractive than initially modeled, jeopardizing the user adoption projections.

• Application of the ARAS Framework:

o **Data Ingestion (Module 1):** ARAS is tracking real-time global interest rate futures, central bank reports, and technology news feeds that contain mention of the competing technology. It is also ingesting preliminary data from a pilot program on user interest in the 5G service.

o **Predictive Identification (Module 2):** The ML module's liquidity prediction for the private consortium is that there is a high probability of a funding deficit at the next major construction milestone due to the rising interest rates. A second model, relying on the pilot program data and news sentiment analysis, predicts that the initial user adoption targets for the 5G service will fall short by 40%.

o **RCA Causal Inference (Module 3):** The RCA module bridges these two projected risks. It demonstrates that the potential funding deficit (Root Cause A) will delay the launch of the 5G network, which will further worsen the user adoption rate (Symptom B), ultimately endangering the government's entire revenue model for the project (Financial Impact C).

o **Proactive Decision-Making (Module 4):** The ARAS dashboard provides the government stakeholders with a clear, data-driven forecast of the future, interlinked problems. This enables them to proactively engage the private consortium in exploring financial restructuring options (e.g., loan guarantees, refinancing) before a crisis. It also provides objective evidence of the need to change the technology strategy for the utility service to be viable, safeguarding the long-term financial viability of the PPP.

IV. Discussion: Strategic Value for Vision 2030

The adoption of the ARAS framework is not merely an exercise in project management maturity, but a strategic governance tool that aligns directly with the underlying principles of Vision 2030.

5.1. Enhancing Fiscal Responsibility and Governance

Vision 2030 has an extremely strong emphasis on government efficiency and fiscal sustainability. Giga-projects represent the largest capital expenditure in the nation's history. With an unprecedented level of foresight over financial risk, ARAS enables a more effective and accountable deployment of capital. It allows government agencies and the PIF to shift from passive financiers to active, data-driven custodians of these national investments, with the confidence that public funds are invested with maximum impact and minimal wastage.

5.2. Building Investor Confidence and Attracting FDI

To succeed, the giga-projects must attract huge foreign direct investment. International investors and financiers demand world-leading levels of transparency and risk management. The adoption of a system like ARAS would be a powerful message to the global investment community that Saudi Arabia is committed to world-class project monitoring. It provides the data-driven comfort to de-risk these mega-investments, which would render them more attractive to international capital and, very likely, lower the cost of financing.

5.3. Implementation Challenges and Strategic Considerations

• **Data Culture and Availability:** The single biggest challenge is the availability of high-quality, real-time data. This will require a cultural shift across all project stakeholders—from contractors to government agencies—towards radical data transparency. Standardized data formats and enforceable data-sharing clauses in contracts would be necessities.

• **The "Explainability" Imperative:** For top-level decision-makers to trust the output of an AI system in such high-risk environments, the system cannot be a "black box." The integration of the RCA module and the utilization of Explainable AI (XAI) techniques are paramount to trust establishment and to maintaining human oversight at the center of the decision process.

• **Building Human Capital:** The ARAS approach demands a different kind of professional who is thoroughly familiar with project finance, data analytics, and the specific engineering or commercial field of the project. A national strategy for building this custom talent through university curricula and professional training will be essential to the long-term success of this approach.

V. Conclusion and Future Research

The era of giga-projects demands an equivalent revolution in the tools with which we manage their mega financial risks. The passive, intermittent, and symptom-focused methods of the past are no longer adequate to the dynamic, interconnected, and high-stakes world of Saudi Arabia's Vision 2030 projects.

This research has proposed the AI and RCA-Based Analytical System (ARAS) as a conceptual model for a new generation of risk management.

By capitalizing on the predictive power of AI and the diagnostic wisdom of RCA, the ARAS framework offers a path forward to transform risk management into a compliance-to-strategy, rearview-to-foreview exercise and a strategic activity of value creation and protection. The case studies demonstrate its clear potential to guarantee the foresight to deal with complexity, to maximize capital, and ultimately to increase the Kingdom's highest-priority ventures' chances of success.

- **Recommendations for Policymakers:**

1. Initiate a pilot to develop and trial a Minimum Viable Product (MVP) of the ARAS on a single significant current project in order to demonstrate its value and develop its architecture.
2. Establish a central Project Data Standards Authority in the PIF or its equivalent to mandate data formats and exchange protocols for all giga-projects.

• Avenues for Future Research:

1. Empirical studies to quantify the financial benefits (ROI) of employing such a system compared to traditional methods.
2. Research into integrating Generative AI into the ARAS system to produce narrative risk reports and recommended mitigation strategies in natural language automatically.
3. Exploration of the legal and contractual framework required to enable AI-driven project monitoring and data sharing in multi-party project environments.

By embracing this technological and methodological quantum leap, not only will Saudi Arabia be able to safeguard its mega investments, but it can also create a new global benchmark for the intelligent and responsible delivery of large-scale infrastructure projects.

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