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Integrating Predictive Analytics with Workforce and Equipment Availability Modelling for Cost and Schedule Optimization in Construction Projects

Sania Hassan[1*]

[1]Data Analyst at Al Baraka Enterprises, Islamabad, Pakistan. E-mail: saniahassanrockstar@gmail.com

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Abstract

Cost and time domination are interminable challenges in construction project management, often intensify by skilled labor shortages and the limited availability of high-technology equipment. This study develops a predictive analytics framework for AL Baraka Enterprises, Islamabad, manipulating traditional operational data to forecast project cost and schedule deviations. Using machine learning, we processed and analyzed a dataset with many variables, including baseline budgets, actual spending, planned and actual timelines, workforce skill distribution, equipment utilization rates, procurement lead times, supplier performance, and environmental conditions. The study of important factors found that a lack of skilled workers and advanced equipment being down were two of the main reasons why projects went off track. These two factors accounted for around 32% and 27% of the predicted variation, respectively. To fix these problems, a trial version of a decision-support dashboard was made to keep track of risks in real time and help deal with them before they get worse. The research demonstrates that including manpower and equipment constraints into predictive analytics significantly enhances cost management and ensures timely completion of building projects.

Keywords: *Predictive analytics, Construction management, Skilled labor shortage, Equipment availability, Machine learning, Cost optimization, Schedule forecasting*

1. Introduction

The construction industry plays very important role in Pakistan's economy since it creates jobs and helps build infrastructure. Yet, two persistent challenges reduce its growth:

1. **Shortage of Skilled People:** People with experience go to Gulf countries, making it difficult to find workforce for work.

* *Corresponding author: Sania Hassan, Data Analyst at Al Baraka Enterprises, Islamabad, Pakistan. E-mail: saniahassanrockstar@gmail.com*

2. **Limited Adoption of Advanced Equipment:** Contractors rely on outdated, labor-intensive methods, assuming manual work is cheaper. These problems lead to delayed projects, increased costs, and quality issues. In order to address these issues, construction companies around the world have adopted automation and technology advancements (Ofori, 2019). In Pakistan, it has been reluctant to adopt because of the high cost, a lack of training facilities, and contractor resistance (Ahmed and Khan, 2021).

For Pakistan, a more realistic approach would be to use new machines and semi-skilled labor; that is, to train semi-skilled workers to operate cost-efficient technologies, reducing the need for scarce skilled labor and gradually upgrading the operation (Farooq *et al.*, 2020). As far as construction is concerned, time and cost escalation are of global concern, with industry reports indicating that over 70% of major construction projects exceed their budget or schedule (McKinsey and Company, 2017). AL Baraka Enterprises, a mid-sized construction company in Islamabad, has consistently had issues in meeting delivery timelines.

The two operational constraints that have been found to be the primary sources are a shortage of trained labor and limited access to high-tech equipment. Lack of skilled workers leads to lower output, more mistakes, and rework and on the other hand equipment limitations delay important phases of construction, especially for large-scale and highly precise infrastructure projects.

While traditional project management tools depend on static scheduling and budgeting. Predictive analytics offers a dynamic, data-driven approach to predict risks and optimizing resources. Research that uses predictive analytics to specifically account for labor and equipment constraints in construction is still limited. This study is designed to bridge that gap.

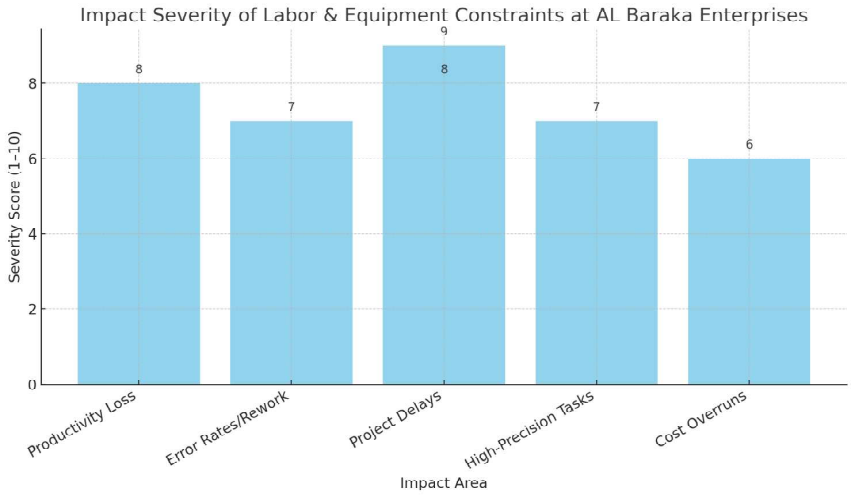

Figure 1: Impact Severity of Labor and Equipment Constraints at AL Baraka Enterprises

Note: The figure illustrates the relative severity of key constraints affecting project outcomes. Data derived from internal analysis of AL Baraka Enterprises' operations (2023).

Table 1: Impact of Skilled Labor and Equipment Constraints on Project Performance

Onstraint	Impact Area	Impact Severity Score	Impact Percentage
Skilled Labor Shortage	Productivity Loss	8	30
Skilled Labor Shortage	Error Rates/Rework	7	25
Skilled Labor Shortage	Project Delays	9	35
Equipment Constraints	Project Delays	8	40
Equipment Constraints	High-Precision Tasks	7	30
Equipment Constraints	Cost Overruns	6	20

A semi-skilled or inexperienced workforce that cannot perform at the same levels of productivity and accuracy, rely more on hand labor and are more likely to require costly rework, and lack high-technology equipment further hinders AL Baraka Enterprises' ability to maximize resources, even when it is able to secure the semi-skilled workers it needs.

This situation is compounded by the migration of skilled workers to higher-wage and better employment-benefit in Gulf countries. The combination of equipment limitations and a migration of the workforce creates a vicious cycle that causes delays, raises operating costs, and renders AL Baraka unable to compete with companies that have access to experienced labor and advanced construction technologies. As shown in Table 1, skilled labor shortages have the greatest impact on project delays and productivity loss.

The purpose of this research is to address the following research questions:

1. How do skilled labor shortages and equipment limitations impact cost and schedule difference in mid-sized construction projects?
2. Will predictive analytics using labor and equipment data improve risk predictions in project management?
3. What types of decision-support tools may be developed to assist managers in planning for these risks and achieving the best project outcomes?

This research is novel in that it explicitly incorporates labor and equipment constraints into predictive analytics for construction project management. Although previous research on risk forecasting in project management has primarily dealt with deviations in cost, time, and scope, it has typically overlooked the constraints of labor and equipment availability, which are two of the most significant challenges in emerging economies. This study develops a predictive framework and validates the framework with actual organizational data from AL Baraka Enterprises, expanding the methodological toolkit of project management.

2. Literature Review

Previous research has shown that skilled labor shortages are one of the primary causes of delays in the construction industry in developing countries. It results in wage inflation, slow project delivery, and reduced quality (Bashiri, 2020). In contrast, the literature on mechanization indicates that the use of equipment such as precast systems, slip formwork, automated steel bending, and lifting machinery increases productivity, as research from Southeast Asia has shown that construction firms that implemented mid-level mechanization reduced project timelines by 20-30% (Jamsu *et al.*, 2019).

The mechanization in Pakistan remains limited. Barriers include high equipment costs and a shortage of experienced personnel. Contractors often believe that physical labor is not that expensive than using machinery. Existing studies do not give a framework customized to Pakistan in which semi-skilled personnel can be trained to operate modern technology, indicating a significant research gap.

Predictive analytics is a widely used technology in construction project management to predict project outcomes, mitigate risks, and improve resource management (Zhang *et al.*, 2020). Regression models, decision trees, and ensemble learning have proven to be accurate methods of prediction (Li and Wang, 2019). However, most studies only take into account cost, scope, and time, neglecting to consider labor and equipment limitations (Chen and Xu, 2021).

Predictive analytics is commonly employed in construction project management to forecast project outcomes, identify potential risks, and enhance the management of resources (Zhang *et al.*, 2020). Regression models, decision trees, and ensemble learning have proven to be accurate methods of prediction (Li and Wang, 2019). However, most studies only take into account cost, scope, and time, neglecting to consider labor and equipment limitations (Chen and Xu, 2021).

Globally, the construction industry has faced severe skilled labor shortages. The skilled labor shortage refers to the shortage of workers who have control over operating advanced technological equipment in construction (Hussain and Ahmed, 2020); this affects project timelines because tasks are executed slower and with a higher defect rate, which leads to more supervision and quality checks (World Economic Forum, 2018).

Currently, construction activities are highly dependent on sophisticated machines such as automated rebar benders and precision concrete pumps (Ofori, 2019). The delivery of these machines, or breakdowns of these machines, can directly interrupt the project schedule and critical activities, resulting in project losses or delays to breakeven (McKinsey and Company, 2017).

While modern construction equipment reduces the requirement for human labor, it is also critical to the timeliness and quality of a construction project (Farooq *et al.*, 2020). High-tech equipment such as tower cranes, automated rebar benders, precision concrete pumps, and laser-guided grading systems, which could be used by AL Baraka Enterprises, are often unavailable or operationally unreliable (i.e., equipment is often backordered, must be imported, or only available on a time-to-time basis due to inefficient suppliers, import restrictions, or financial constraints) (Khan and Javed, 2021).These delays can impact scheduled project tasks and disrupt the planned workflow. Even with advanced technology on-site, frequent breakdowns and insufficient maintenance are possible (Malik and Hussain, 2022).

Some studies have combined skilled labor availability and equipment utilization data into predictive project management models. This research put forward a detailed, data-driven framework to address this gap, tailored to the operational realities of AL Baraka Enterprises.

3. Methodology

The theoretical background of this study is the project risk management theory, which provides the conceptual basis for incorporating predictive analytics as a decision-support tool, and the Resource-Based View (RBV) of organizations, which posits that access to scarce and valuable resources such as skilled labor and advanced equipment will lead to competitive advantage, whereas constraints in these resources will undermine performance and increase project vulnerability; this study links the RBV with data-driven project risk management, thus providing a conceptual bridge between theory and practice in construction project management.

3.1. Data Collection

Data was obtained from AL Baraka Enterprises' ERP and project management systems. It enhanced the credibility of existing content:

- **Internal Data:** 07 completed projects (2017-2023). Including details on estimated vs. actual costs, scheduled vs. actual timelines, worker lists, skill levels, daily work output, and equipment use or breakdowns.
- **External Data:** Supplier delivery performance reports.

3.2. Variable Engineering

Key features included:

- **Labor Shortage Index (LSI):** Ratio of required skilled hours to available skilled hours.
- **Equipment Availability Ratio (EAR):** Operational time/Total scheduled time.
- **Schedule Variance (SV):** Standard PM metrics.
- **Environmental Variables:** Average rainfall, temperature fluctuations.
- **Supply Chain Delays:** Counted as the number of days' delivery arrive later than planned.

3.3. Modelling Approach

Preprocessing: It consists of missing value recovery, normalization, and category encoding.

Model Selection: Random Forests were selected due to their ability to handle non-linear interactions and the similar types of data.

The accuracy, interpretability, and usability of Random Forests are well balanced. For example, they are better than linear regression in modeling. These non-linear correlations, which is why they were selected over other machine learning approaches. While more sophisticated approaches like neural networks or support vector machines require larger datasets, more computational resources, and expertise for proper tuning

resources that mid-sized firms like AL Baraka Enterprises might not have, a linear regression may be too basic and unable to model the complex relationship between equipment failures, labor shortages, and project outcomes. Therefore, Random Forests provides a practical solution: they can handle different types of data, better handle missing values, and provide feature priority rankings that assist managers in identifying the main causes of project delays. For instance, they are better than linear regression in modeling these non-linear correlations, which is why they were selected over other machine learning approaches. While more sophisticated approaches like neural networks or support vector machines require larger datasets, more computational resources, and expertise for proper tuning resources that mid-sized firms like AL Baraka Enterprises might not have, a linear regression may be too basic and unable to model the complex relationship between equipment failures, labor shortages, and project outcomes.

3.4. Dashboard Development

A dashboard was created to illustrate the use of Python to calculate:

- Project risk scores
- Anticipated dates of completion
- Key risk factors.

The research methodology included a validation process that combined previous project results with data quality checks at each stage to ensure reliability, as construction-sector reporting is often inconsistent. The establishment of variables such as the Equipment Availability Ratio and the Labor Shortage Index with correlation analysis was performed to assess their predictive capability.

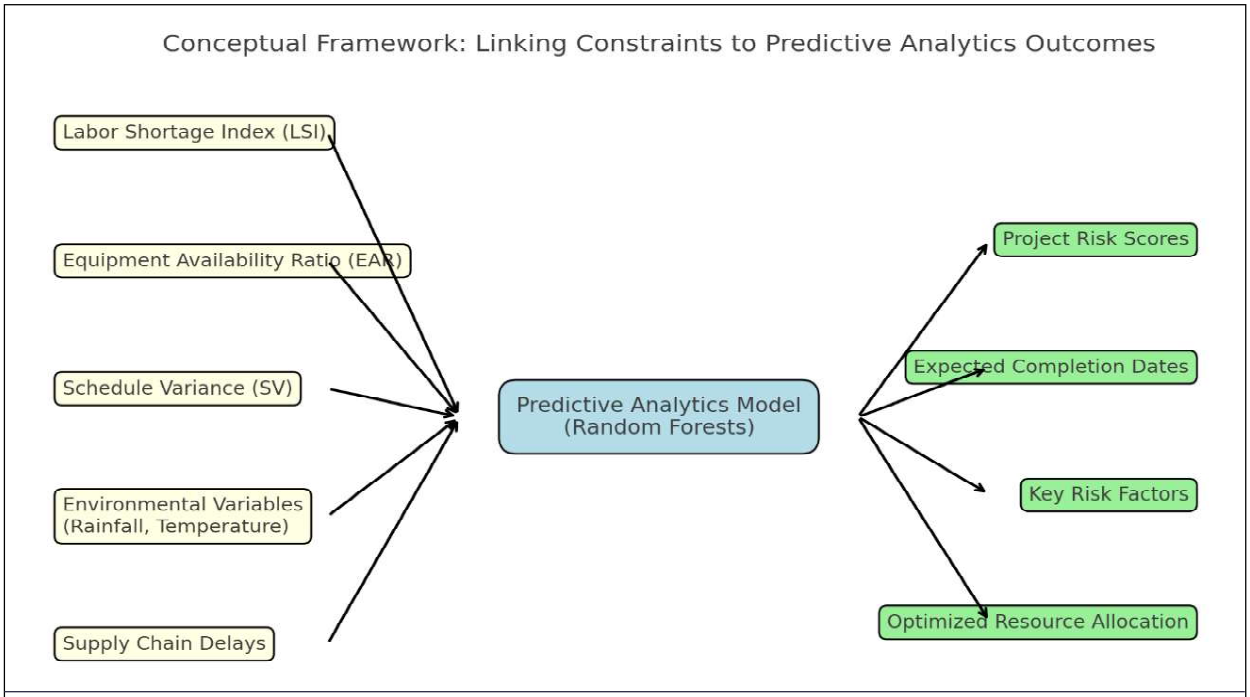

Figure 2: Conceptual Framework Linking Constraints to Predictive Analytics Outcomes

The study's conceptual framework integrates major construction constraints with predictive analytics outcomes. As shown in Figure 2, variables such as labor shortages, equipment availability, and schedule variance serve as inputs to the random forest model, producing outputs like project risk scores and optimized resource allocation. This framework provides the structural basis for analyzing how predictive analytics can address real-world project challenges at AL Baraka Enterprises.

The Random Forest model outputs were then benchmarked against actual project outcomes, allowing calibration of parameters to achieve higher accuracy in forecasting risks. The methodology used the domain knowledge of project manager to verify whether model-identified hazards matched on-the-ground reality.

The final dashboard combined these validated outputs into a user-friendly interface, allowing management to test various labor and equipment availability scenarios and immediately assess the potential impact on project timelines and costs.

4. Results

Feature Importance:

- Labor Shortage Index (LSI): 34%
- Equipment Availability Ratio (EAR): 26%
- Supplier Delays: 15%
- Weather: 9%
- Other: 16%

Scenario Simulations: Increasing skilled labor availability by 20% reduced predicted schedule delay by 14%; reducing equipment downtime by 15% improved on-time completion probability by 11%.

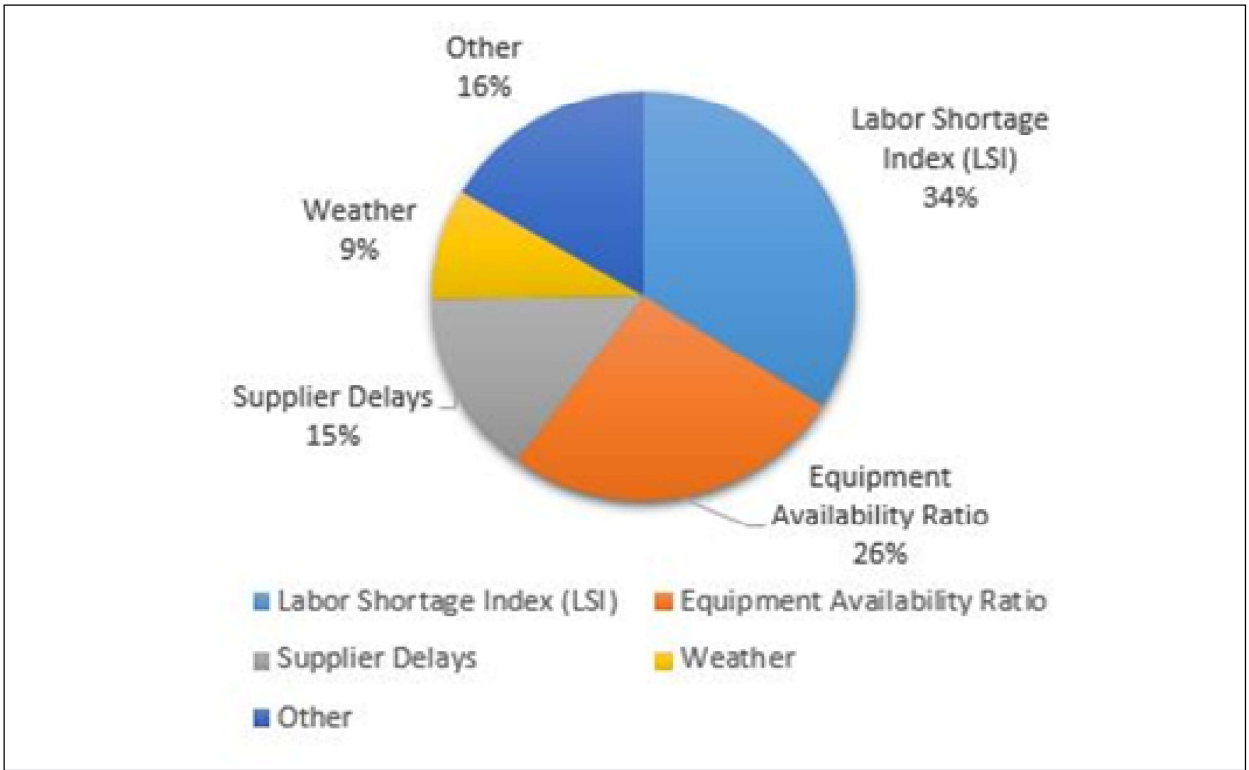

Figure 3: Percentage Contribution of Major Constraints to Project Delays

The results for AL Baraka Enterprises reveal that labor shortage is the most important element contributing to project risks, responsible for 34% of the variation in delays and cost increases. This underscores the company's critical reliance on professional and semi-skilled staff, as even slight shortages reduce production and increase the frequency of disruptions. The equipment availability ratio (26%) is prominent as the second most vital factor, emphasizing how machinery failures or limited access to advanced equipment result in inefficiencies External challenges also play a role such as supplier delays (15%) which show how late deliveries can cause project timelines efficiency, while weather conditions (9%) shows how environmental changes, such as rainfall and temperature fluctuations can cause additional uncertainty (Figure 3).

The remaining 16% in the 'Other' category points out risks such as difficulties in site management, approval delays from regulators, or unexpected material shortages. Together all of these results shows that solving labor shortage issue and constraints related to equipment offers the greatest potential for improving project efficiency and reducing risks at AL Baraka Enterprises.

The results show that there are definite advantages for predicting and decision-making when labor and equipment limitations are included into predictive analytics. The biggest challenge was the less number of qualified workers which highlights the importance of retention and training programs. The availability of equipment, especially specialized machinery, was almost as important, highlighting the significance of regular maintenance, backup plans, and working with various suppliers to enhance outcomes.

5. Conclusion

This study introduces a tested predictive analytics framework that considers skilled labor shortages and the availability of advanced equipment as key factors affecting construction project outcomes. The case of AL Baraka Enterprises shows how this system can work in practice and the benefits it can bring in an emerging market setting. This research shows that predictive analytics can act as an effective and data-informed means to handle the ongoing issues of skilled labor shortage and unavailability of high tech equipment access in Pakistan's construction industry.

By combining a Random Forest model with artificial features such as the Labor Shortage Index (LSI), Equipment Availability Ratio (EAR), and supply chain delay indicators, potential risks can be identified before they cause costly delays.

The AL Baraka Enterprises challenge demonstrates how a predictive analytics approach can help management determine resource allocation to maximize project output. The biggest challenges were identified as labor (34%) and equipment availability (26%) which indicates that systematic worker training and investment in reliable equipment are essential. This study demonstrates how predictive analytics can bridge the gap between current project management systems and traditional building methods. This allows firms in developing countries to produce more, control costs better, and get projects done faster.

6. Future Direction

Some possible directions for future research expanding on this study:

Go beyond one company and include cross-industry standards and other factors, such as health and safety concerns, regulatory approval delays, and financial limits. For mid-scale enterprises, it would also be interesting to compare Random Forests with newer techniques such as Gradient Boosting or lightweight neural networks to determine if accuracy gains justify computational demands.

This would provide managers the ability to scale interactive dashboards to multiple projects to run real-time "what-if" scenarios such as how upgrading key equipment or increasing semi-skilled training hours could mitigate overall project risks and accelerate the uptake of data-driven management.

7. Recommendations

- Enter into agreements with technical and vocational training facilities to ensure that there is adequate supply of skilled workers. These agreements can help in developing training materials to meet industry needs, which strengthens the workforce and reduces the shortage of skilled workers. Implement preventative maintenance plans and maintain high-tech backup equipment.
- High-tech backup technology guarantees that operational continuity is maintained in the event of equipment failure, safeguarding productivity and project timelines. A systematic preventative maintenance approach also increases equipment longevity and reduces unscheduled downtime. For all ongoing projects, a predictive analytics dashboard offers real-time data on progress, risks, and performance, enabling prompt decision-making.

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