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Evaluation and Dynamic Optimization of Big Data Technology in Engineering Project Resource Allocation

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Abstract: This paper focuses on the innovative application of big data technology in the field of engineering project resource allocation, deeply analyzing its core functional mechanisms in resource evaluation and dynamic optimization. By constructing an evaluation index system for resource allocation that integrates multi-source data, and combining data mining, machine learning, and deep learning algorithms, an intelligent dynamic optimization model for resource allocation is established. Taking a super-high-rise commercial complex construction project as a typical case, this paper details the full-process practice of big data technology from data collection and analysis to optimization decision-making, and quantitatively analyzes its significant effects in improving resource utilization efficiency, reducing project costs, and ensuring construction progress. The study shows that big data technology can provide scientific and precise decision-making basis for engineering project resource allocation, strongly promote the transformation of engineering project management towards intelligence and refinement, and provide new technical paths and practical references for industry development.

1. Introduction

In the project management system, resource allocation serves as a critical link, and its rationality and scientificity play a decisive role in project progress, cost control, and quality assurance. Traditional resource allocation models mostly rely on experience judgment and simple data statistics. When facing the characteristics of modern engineering projects such as large scale, complex structure, and strong dynamics, they gradually expose many drawbacks and struggle to meet the needs of refined management. With the vigorous development of big data technology, its excellent capabilities in massive data processing, in-depth analysis, and accurate prediction provide an innovative path for resource allocation in engineering projects. Through the systematic collection, in-depth mining, and scientific analysis of multi-source heterogeneous data generated throughout the entire life cycle of engineering projects, it is possible to accurately grasp resource needs and usage patterns, thereby achieving optimal resource allocation and bringing new development opportunities to engineering project management.

2. Application of Big Data Technology in Evaluation of Engineering Project Resource Allocation

2.1 Characteristics of Big Data Technology and Data Processing Flow

The "4V" characteristics of big data technology, namely Volume, Variety, Velocity, and Value, endow it with unique advantages in engineering project data processing. Throughout the entire life cycle of engineering projects, massive data is generated, from 3D model data in the design stage and real-time monitoring data in the construction stage to equipment maintenance data in the operation stage, with data scales reaching the TB or even PB level. Data types include structured data which are financial statements and material lists, and semi-structured data which are construction logs and progress reports, and unstructured data which are engineering drawings and video surveillance[1].

To effectively process these complex data, a specific data processing flow should be followed. First is data collection, which gathers various types of data related to engineering projects through multiple channels such as IoT sensors, project management information systems, and web crawlers. For example, not only can staff members deploy temperature and humidity sensors, pressure sensors, positioning sensors, and other devices on construction sites to achieve real-time collection of environmental data and equipment operating status data, but they can also use web crawlers to obtain external data such as price fluctuations of construction materials and changes in policies and regulations. The collected data is transmitted to a distributed storage system, such as the Hadoop Distributed File System (HDFS) or a cloud storage platform, for storage. Next comes data cleaning to remove duplicate, erroneous, and incomplete data, improving data quality. Then, through data transformation, data in different formats is unified and standardized for subsequent analysis. Finally, technologies such as data mining and machine learning are used to deeply analyze the processed data and extract valuable information.

2.2 Construction of Resource Allocation Evaluation Index System

Constructing a scientific and reasonable resource allocation evaluation index system is the key to achieving accurate evaluation. From the three dimensions of human resources, material resources, and financial resources, a comprehensive evaluation index system is established.

In the human resources dimension, indicators such as personnel skill matching degree, per capita labor productivity, and personnel allocation balance are set. The personnel skill matching degree is analyzed by establishing a skill requirement matrix and quantitatively comparing the skills required for construction tasks with personnel's actual skill certificates and project experience; per capita labor productivity is calculated based on the engineering quantity which is the number of tons of steel binding and cubic meters of concrete poured by personnel within a unit time ,and the input of labor costs; personnel allocation balance is used to evaluate whether there is idle or short personnel resources by analyzing the fluctuation curve of the number of personnel in different construction stages[2].

In the material resources dimension, indicators include equipment availability rate, material loss rate, and material inventory turnover rate. The equipment availability rate is calculated by the ratio of the normal operation duration of the equipment recorded by the equipment operation monitoring system to the total duration; the material loss rate compares the theoretical material usage which is based on design drawings and construction process standards with the actual material consumption; the material inventory turnover rate reflects the turnover speed of materials from purchase and storage to receipt and outbound, and the calculation formula is the total amount of materials outbound / the average total inventory[3].

In the financial resources dimension, indicators cover fund availability rate, cost variance rate, and fund use efficiency rate. The fund availability rate counts the ratio of actual in-place funds to planned funds; the cost variance rate is calculated as (actual cost - budget cost) / budget cost $\times$100%; the fund use efficiency rate is measured by analyzing the relationship between fund investment and project output which is completed engineering quantity and output value growth.

2.3 Big Data-Based Evaluation Methods and Case Analysis

A super high-rise commercial complex project, with a construction area of 300,000 square meters, an investment of 5 billion yuan, and a construction period of 36 months, adopted the traditional resource allocation method in the early stage of the project. According to the data statistics of the first 6 months of the project, the phenomenon of idle workers was extremely prominent, with an average of 5 days of idle work per month. According to the calculation as shown in Figure 1, the total number of construction workers in the project is about 1,500, with an average daily wage of 300 yuan. Thus, the waste of labor costs caused by idle work is about 1.5 million yuan per month (1,500 $\times$300 $\times$5). In terms of material management, the overstock of steel inventory reached 12,000 tons. At that time, the average market price of steel was 2,500 yuan per ton, and the funds overstocked in steel alone amounted to 30 million yuan. However, some small-sized turnover materials such as scaffolding and formwork often suffered from supply shortages due to the lack of precise planning, which seriously affected the construction progress. In terms of equipment management, the project rented 200 various types of large-scale construction equipment, with an equipment idle rate as high as 30%. The average monthly rental cost of the equipment was 20,000 yuan, and the waste of rental costs caused by equipment idleness alone was 1.2 million yuan per month. This led to delayed construction progress, cost overruns, and extremely low efficiency in resource utilization[4].

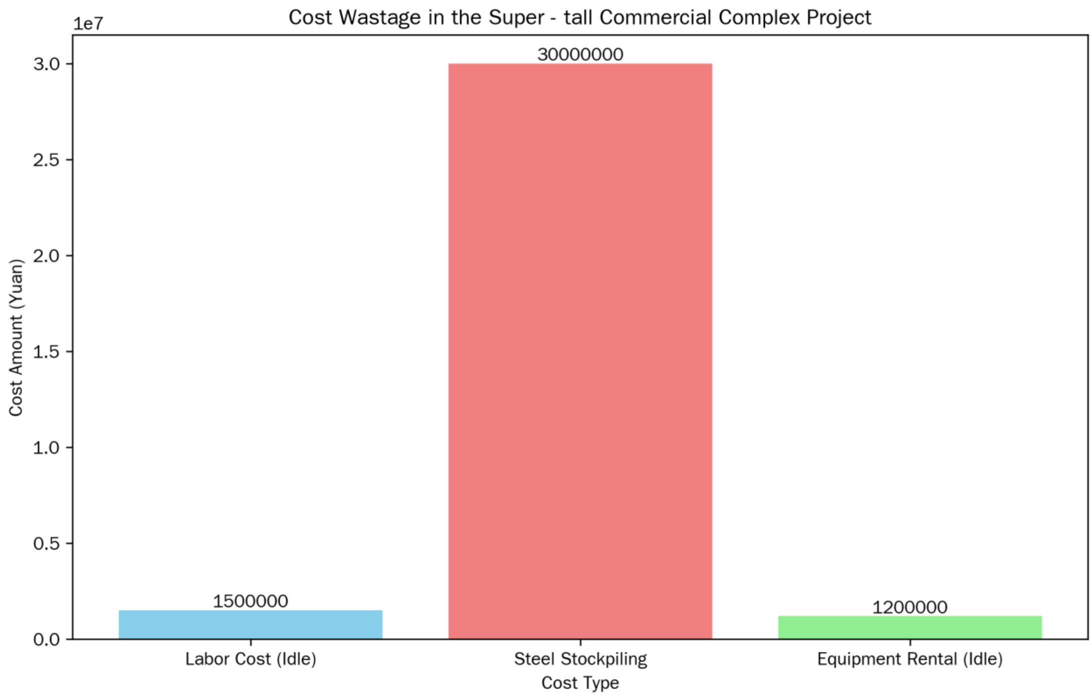

Figure 1 Cost Wastage in the Super-tall Commercial Complex Project

After introducing big data technology, more than 2,000 IoT sensors were deployed at the construction site, covering key construction machinery such as tower cranes, elevators, and concrete mixing equipment, to collect equipment operation parameters in real time; a project management information system was established to integrate data such as design drawings, construction progress plans, and material procurement contracts; through web crawler technology, external data such as the market prices of construction materials and the supply and demand of the labor market were collected daily, forming a project database containing structured, semi-structured, and unstructured data.

Using the constructed big data evaluation model, the early-stage resource allocation of the project was analyzed. In terms of human resources, it was found that there was a 20% gap in professional and technical personnel for electrical installation, resulting in the failure to complete processes such as electrical embedding on time, affecting the subsequent construction progress. Through the analysis of personnel skill certificates and project experience data, it was determined that electricians and electrical engineers with experience in high-rise building electrical installation needed to be supplemented. In terms of material resources, the steel inventory was seriously backlogged, mainly because the early procurement plan lacked accurate prediction of market price fluctuations and construction progress; while some small turnover materials such as scaffolding and formwork were often in short supply, affecting the continuity of construction. In terms of financial resources, the use of funds was scattered, and the fund guarantee for key construction links was insufficient. For example, in the core tube construction stage, the concrete pouring progress was slowed down due to the failure of funds to arrive[5].

Based on the analysis results, the LSTM algorithm was used to predict the resource demand in the subsequent construction stage, and the genetic algorithm was combined to optimize the resource allocation scheme. For human resources, 50 professional and technical personnel were deployed from other projects of the company to supplement key positions, and the work tasks and operation time of each team were dynamically adjusted according to the real-time construction progress and personnel work efficiency. In terms of material resource management, by analyzing historical steel price fluctuation data and market supply and demand trends, the steel procurement plan was adjusted, steel was purchased at the price trough, and a dynamic inventory management mechanism was negotiated with suppliers to replenish inventory in a timely manner when the inventory level was lower than the safety inventory. For small turnover materials, the lease plan was optimized by analyzing the price, service quality, and inventory status of different leasing companies through big data, reducing the lease cost. In terms of financial resources, the fund use plan was re-planned, funds were concentrated to ensure the core construction area, and the cost prediction model was used to monitor the cost of each construction link in real time. When it was found that there might be a risk of cost overrun in a curtain wall construction subcontracting link, timely negotiation was carried out with the subcontractor to adjust the contract terms and optimize the construction process[6][7].

The application of big data technology has brought significant results to the project. As shown in Figure 2, Figure 3, Figure 4, and Figure 5, the construction progress has changed from being 2 months behind schedule initially to being completed 1 month ahead of schedule, with the overall construction period shortened by 3 months. Through a comparative analysis of the construction schedule plan and the actual completion status, it is found that the construction tasks on the critical path were completed 10 days ahead of schedule on average, laying a foundation for the improvement of the overall project progress. The cost has been significantly reduced by 280 million yuan, with a decrease rate of 5.6%. An in-depth analysis of the composition of cost reduction shows that the labor cost was saved by approximately 80 million yuan due to reduced idle labor and reasonable allocation; the material cost was reduced by about 150 million yuan thanks to optimized procurement and inventory management; and the financial cost was saved by around 50 million yuan through precise fund scheduling and rational use. The average utilization rate of equipment has increased from 65% to 85%. According to the statistics on equipment operation data, the average daily operation duration of equipment has increased from 8 hours to 10 hours, effectively improving the equipment utilization efficiency. The material loss rate has decreased by 12%. Taking steel as an example, through optimized procurement and construction management, the steel loss has been reduced from 800 tons to 704 tons.

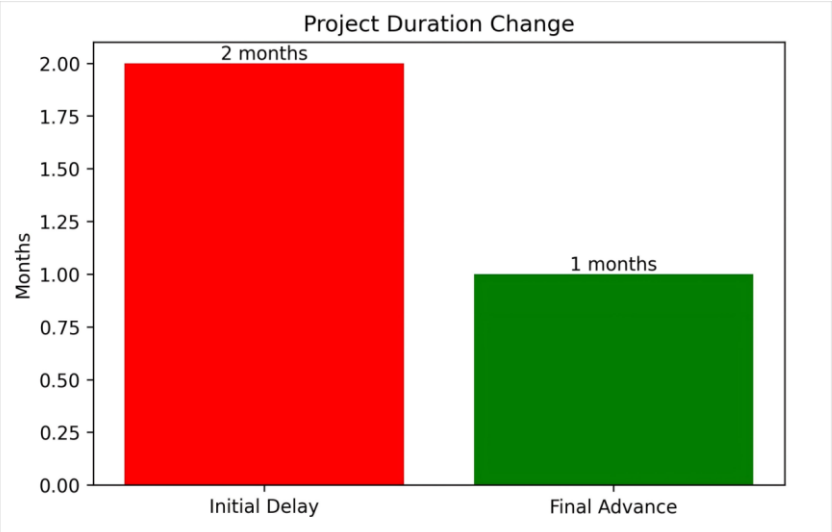

Figure 2 Project Duration Change

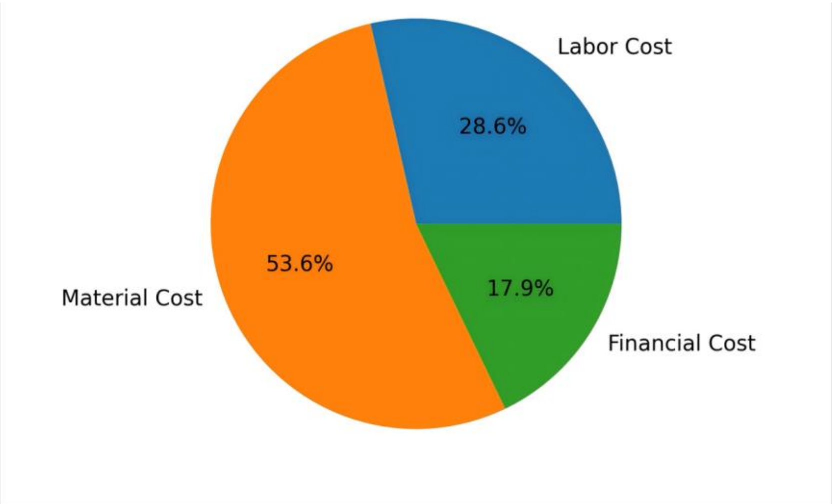

Figure 3 Cost Reduction Composition (in billions of yuan)

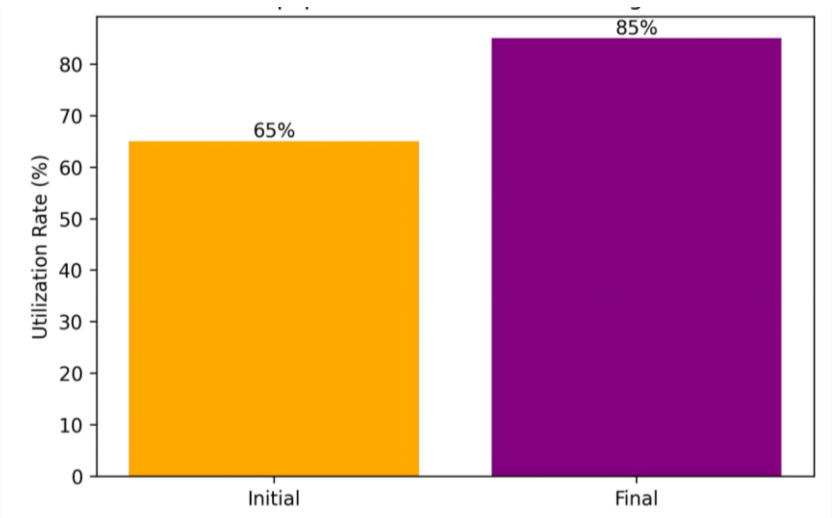

Figure 4 Equipment Utilization Rate Change

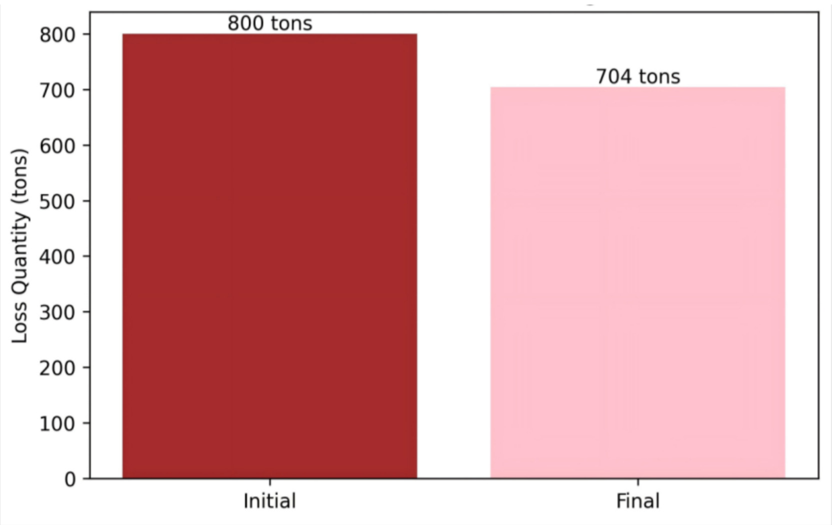

Figure 5 Steel Material Loss Change

3. Dynamic Optimization of Engineering Project Resource Allocation Based on Big Data

3.1 Dynamic Data Collection and Demand Forecasting

The deep integration of big data technology and IoT technology has realized the real-time dynamic collection of engineering project resource data. In a super-high-rise commercial complex project, more than 2,000 IoT sensors were deployed at the construction site, including tower crane hook visualization sensors, elevator load sensors, concrete mixer truck transportation status sensors, etc. These sensors collect real-time operation parameters of equipment which are including the lifting weight, slewing angle, and working hours of tower cranes, the running speed and stopping floors of elevators, material flow data which are including material entry time, quantity, storage location, equipment allocation records, etc., and personnel work dynamics which are personnel attendance, work location and task completion progress. At the same time, with the help of web crawler technology, external data such as the market prices of construction materials , the supply and demand of the labor market, and policy and regulation changes are captured daily[8].

In terms of resource demand forecasting, the Long Short-Term Memory (LSTM) algorithm has shown excellent performance. Taking the steel demand forecasting of this project as an example, the daily steel consumption data since the start of the project, construction progress plans, weather data which affects the construction progress and thus the steel use, market steel price fluctuation data, etc., were collected as training data. By learning the complex relationship between various factors and steel consumption in historical data, the LSTM model can accurately predict the steel demand for the next week or even a month. When it is predicted that the steel demand will surge by 40% within the next 15 days due to the strengthening of the core tube structure caused by design changes in a certain construction stage, it provides an important basis for dynamic resource optimization.

3.2 Dynamic Optimization Strategies and Algorithm Applications

The real-time monitoring and feedback mechanism is the basis for achieving dynamic resource optimization. The project management platform visually displays the collected real-time data and issues an alarm immediately when an abnormal situation occurs. For example, when it is monitored that the concrete pouring equipment in a certain area has been shut down continuously for more than 30 minutes, the system automatically analyzes the possible causes which are including equipment failure, material supply interruption, personnel deployment problems, etc., and pushes the alarm information to the mobile phones of relevant management personnel, and provides references to historical similar problem solutions[9].

The Genetic Algorithm is widely used in dynamic resource scheduling. Taking equipment scheduling as an example, factors such as equipment type, quantity, working time, maintenance cycle, and current location are used as the chromosome encoding of the Genetic Algorithm. First, a population of initial equipment scheduling schemes is randomly generated, and through operations such as selection, crossover and mutation, after multiple rounds of iterative calculation, the scheduling scheme that minimizes equipment use cost and maximizes efficiency while meeting the project construction progress and quality requirements is sought. In this super-high-rise project, through the optimization of equipment scheduling by the Genetic Algorithm, the average idle rate of tower cranes was reduced from 25% to 10%, and the equipment lease cost was reduced by 12%.

3.3 Practice and Effects of Dynamic Optimization in the Case

In this super high-rise commercial complex project, a series of dynamic optimization measures were implemented based on the results of big data analysis,as shown in Figure 6, Figure 7, Figure 8 and Figure 9. In terms of human resources, 50 formworkers and steel fixers with experience in super high-rise construction were urgently deployed from other projects of the company to supplement the core tube construction teams. Moreover, according to the real-time construction progress and personnel work efficiency, the work tasks and operation hours of each team were dynamically adjusted. A dynamic evaluation model for personnel work efficiency was established to score the work performance of personnel in each team in real time. Task allocation was adjusted based on the scoring results to motivate personnel to improve work efficiency. For example, teams with high work efficiency were appropriately assigned more tasks and given certain rewards; for teams with low work efficiency, the reasons were analyzed, and targeted training or personnel adjustments were carried out.

In the management of material resources, a JIT (Just-In-Time) supply mode was established through negotiations with steel suppliers. Based on the steel demand predicted by the LSTM model, production and transportation were arranged in advance to reduce inventory backlog. In the process of implementing the JIT supply mode, an information sharing mechanism was established with suppliers to transmit real-time steel demand forecast data and construction progress plans, ensuring that steel was supplied on time and in the required quantity. For small-sized turnover materials, a shared rental platform was adopted to optimize the rental scheme. Through big data analysis of factors such as prices, service quality, inventory status, and distance from the construction site of different rental companies, the optimal rental scheme was selected to reduce rental costs.

In terms of financial resources, a cost prediction model was used to monitor the cost of each construction link in real time. When it was found that there might be a risk of cost overrun in a certain curtain wall construction subcontracting link, negotiations were conducted with the subcontractor in a timely manner to adjust the contract terms and optimize the construction process. A hierarchical mechanism for cost risk early warning was established, with different levels of early warnings set according to the degree of cost deviation, and corresponding countermeasures were taken for different levels, such as adjusting the budget and optimizing the scheme. For example, when the cost deviation rate reaches 5%, a yellow warning is issued to remind relevant personnel to pay attention to cost changes; when the cost deviation rate reaches 10%, a red warning is issued, and the cost adjustment plan is immediately activated.

Through the application of big data technology in the dynamic optimization of resource allocation, the project has achieved remarkable results. In terms of construction progress, the overall construction period of the project was shortened from the original planned 1,200 days to 1,110 days, completing the construction task 90 days ahead of schedule, which created conditions for the project to be put into operation in advance, and it is estimated that the rental income can be generated 120 million yuan in advance. In terms of cost control, the total cost of the project was reduced from 5 billion yuan to 4.72 billion yuan, with a decrease rate of 5.6%. Among them, the labor cost was saved by 80 million yuan (by reducing idle labor through reasonable personnel deployment), the material cost was reduced by 150 million yuan (by optimizing material procurement and inventory management), and the financial cost was saved by 50 million yuan (by reducing financing costs through precise fund scheduling). In terms of resource utilization efficiency, the average equipment utilization rate increased from 65% to 85%, reducing equipment rental expenses; the material loss rate decreased from the industry average of 8% to 5.6%, saving a large amount of construction materials. Further analysis of the project's economic benefits shows that the rental income generated by the early completion and the profit increase brought by cost reduction have significantly improved the project's return on investment and enhanced the enterprise's competitiveness in the market. From the industry perspective, the successful practice of this project has provided valuable experience for other similar engineering projects and promoted the application and exploration of big data technology in the entire construction industry.

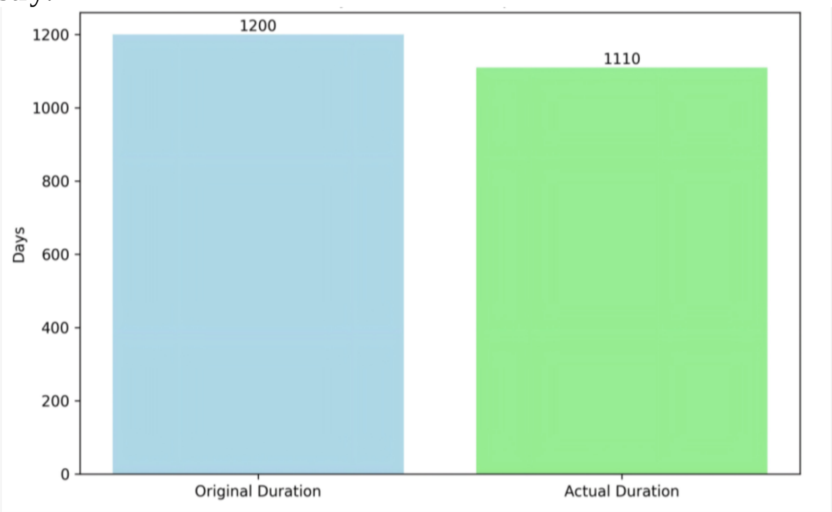

Figure 6 Project Duration Comparison

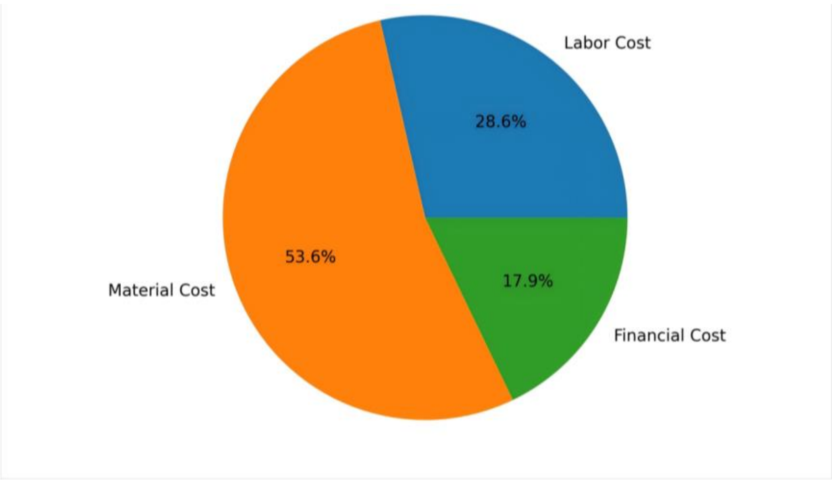

Figure 7 Composition of Total Cost Reduction

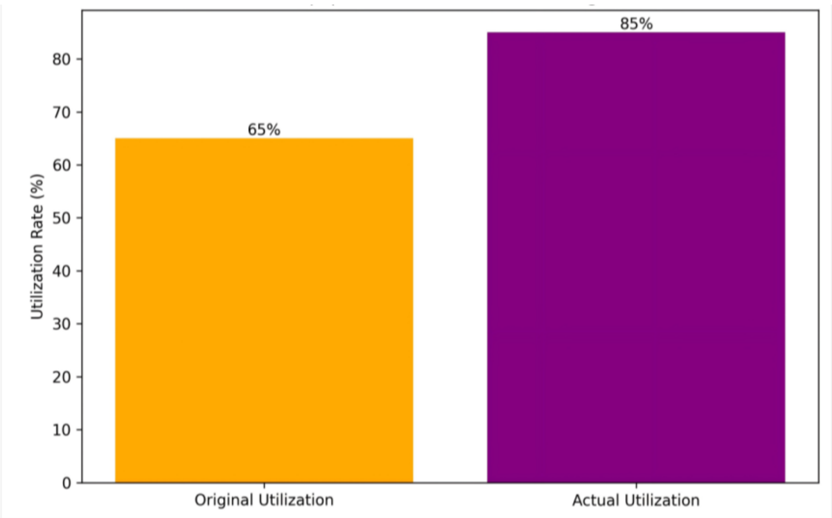

Figure 8 Equipment Utilization Rate Change

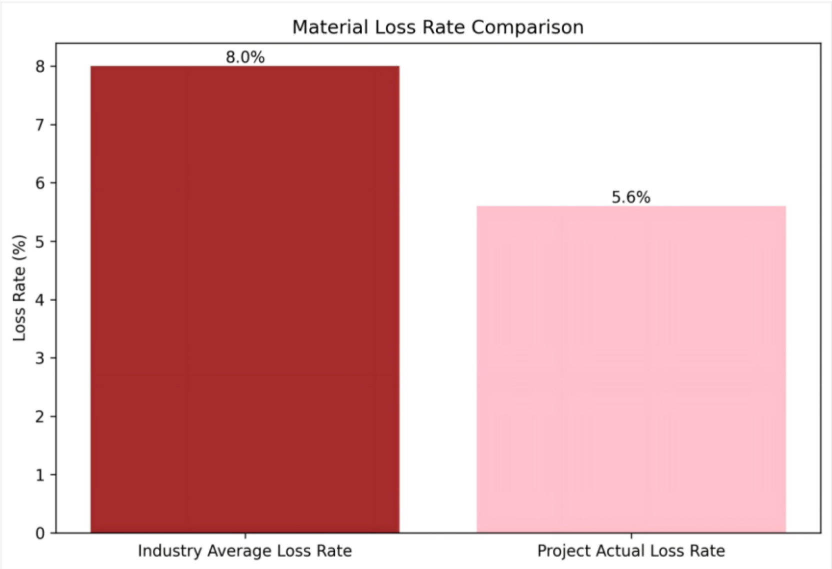

Figure 9 Material Loss Rate Comparison

4. Case Analysis and Summary

The successful application of big data technology in this super-high-rise project has laid the foundation for evaluation and optimization through multi-source data integration, accurately grasped resource allocation through a comprehensive index system, and achieved efficient deployment through advanced algorithms and management strategies. However, it has also exposed some problems. Some management personnel have a low acceptance of big data technology and lack the awareness of data analysis and application, which affects the promotion and application of the technology; there are certain loopholes in data security management, and the core project data faces the risk of leakage; the data interaction with external units is not smooth enough, affecting the comprehensiveness and timeliness of information[10].

Compared with other similar projects, this project has certain advantages in the depth and breadth of big data technology application. In terms of data collection, the number and types of deployed sensors are more, and the coverage is wider, which can obtain more comprehensive project data; in terms of algorithm application, the LSTM algorithm and the Genetic Algorithm are effectively combined, and the optimization effect is more significant. However, there is still room for improvement in data sharing and cross-departmental collaboration. For example, the data sharing mechanism with design units and supervision units is not perfect, resulting in delays and errors in information transmission. In the future project implementation process, communication and cooperation with all parties should be strengthened, a unified data sharing platform should be established, and real-time data sharing and collaborative application should be realized.

5. Conclusion

This study confirms the important value of big data technology in the evaluation and dynamic optimization of engineering project resource allocation. It effectively solves the drawbacks of the traditional model and realizes efficient resource utilization and precise control. However, in practical applications, it still faces challenges such as inconsistent data standards, security and privacy protection, and a shortage of professional talents. In the future, it is necessary to accelerate the formulation of engineering project big data standards and specifications to promote data interconnection; strengthen the research and development of data security protection technologies, such as using blockchain technology to realize trustworthy storage and transmission of data; and cultivate compound talents through channels such as professional courses in colleges and universities and internal training in enterprises. With the development and improvement of technology, big data technology will promote the intelligent transformation of engineering project management and provide technical support for the high-quality development of the construction engineering industry.

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