Multi-Granularity Comprehensive Transportation Efficiency Analysis of Concrete

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Abstract. In the construction of hydroelectric dams, the efficiency of concrete transportation directly impacts the quality and timeline of the dam. Currently, concrete transportation scheduling still heavily relies on manual coordination, which makes it difficult to truly obtain the actual efficiency of the transportation equipment at each stage of concrete transportation. To more precisely evaluate the efficiency of concrete transportation in dams, this paper proposes a multi-granularity concrete transportation efficiency analysis algorithm (MCE). Our model comprehensively evaluates the efficiency of concrete transportation by utilizing the equipment utilization rate, equipment runtime rate, equipment work efficiency, and quality qualification rate. It can not only subdivide and analyze equipment effectiveness at different time scales, but also analyze efficiency from both the macro and specific equipment levels, providing a scientific basis for improving concrete transportation efficiency.

Keywords: Transportation efficiency analysis, Multi-granularity, Dam construction

1 Introduction

China is one of the richest countries in the world in terms of rivers, with more than 45,000 crisscrossing rivers. The huge river network provides unique natural conditions for the construction of water conservancy facilities in China, and makes China one of the countries with the largest number of reservoir dams in the world. As a type of dam that is both economical and safe and reliable, arch dams occupy a crucial position in the construction of hydropower projects. During the construction of arch dams, in order to pursue the benefits of early power generation, it is usually necessary to accelerate the construction progress of the dam to shorten the overall construction period. However, the arch dam concrete construction system is a complex dynamic

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system consisting of concrete production, transportation and pouring, and the three subsystems interact with each other to jointly determine the construction progress of the dam concrete. Problems in any one of the links will restrict the efficiency of dam concrete construction, and ultimately affect the construction progress.

In the water conservancy project concrete construction transportation scenario, large volume concrete is produced at the mixing plants, and the first stage of transportation is generally completed by the transport vehicle to the feeder plate through the traffic lines in the construction area. The transportation truck pours the concrete into the crane tank of the cable crane, and the cable crane lifts the concrete to the dam pouring location to complete the second stage of transportation. After unloading the concrete, the transport vehicle drive to the mixing plants, and the cable crane unloads the concrete and returns to the feeder plate, thus completing one cycle each. On-site concrete production and transportation activities are fast-paced, each link requires a compact connection, and there are problems such as long waiting time for transport vehicle loading, and long connection time for vertical transportation.

Therefore, it is of great significance to carry out the research on the production and transportation efficiency of dam concrete to optimize the equipment configuration of the construction system, reduce the cost of concrete construction, and accelerate the construction progress of the dam.

2 Related Works

In the research on concrete transportation efficiency analysis algorithms, there is currently limited literature both domestically and internationally. Most studies focus on comprehensive monitoring of the transportation process, analyzing transportation efficiency based on the monitoring results. Zhong et al. [1] researched intelligent control technology and solutions for the concrete transportation process in the construction of a 300m-high arch dam, conducting productive experiments to validate the feasibility of the intelligent control technology for concrete transportation. Wang et al. [2] proposed a monitoring framework and method for horizontal transportation of arch dam concrete based on a smart dam. They constructed an Internet of Things (IoT) integrated device in the concrete transportation environment to achieve real-time monitoring of the operational status of concrete transport vehicles. Xu et al. [3] addressing issues such as information isolation, difficulty in coordinated control, and safety control challenges in the transportation process of concrete for extra-high arch dams, established a comprehensive perception, real-time analysis, feedback warning, and dynamic tracking intelligent control system for concrete transportation. Guo [4] focusing on mechanical efficiency, conducted a detailed analysis of the composition of the concrete construction system for high arch dams, construction influencing factors, and general principles of mechanical configuration. Fan et al. [5] utilizing GPS positioning technology, tunnel interior positioning technology, and infrared technology, implemented real-time monitoring of concrete transport vehicles and cable cranes from the mixing floor to the unloading platform.

In the study of efficiency analysis, common methods include Overall Equipment Effectiveness (OEE) [6], Total Productive Maintenance (TPM) [7], Single Minute Exchange of Die (SMED) [8], Failure Mode and Effects Analysis (FMEA) [9], the Six Big Losses [10], and Theory of Constraints (TOC) [11]. OEE is a comprehensive indicator used to assess equipment performance, considering availability, performance, and quality. On the basis of OEE, some scholars have expanded the measurement time period from planned production time to calendar working time and added the index of equipment utilization, thus proposing the Total Effective Equipment Performance (TEEP) measurement system, which measures the proportion of total time that is truly productive. TPM is a manufacturing management technique that focuses on optimizing efficiency through equipment-centric improvements, aiming to maximize equipment utilization. SMED is a technique developed by Shigeo Shingo at Toyota in the early 1950s to address issues related to small batch production, reducing inventory, and enhancing the rapid response capability of production systems. FMEA is used to identify and evaluate equipment failure modes and their potential impacts on production efficiency, facilitating the implementation of preventive measures. The Six Big Losses provide an analytical method from the equipment perspective to assess production efficiency losses, including downtime, setup and adjustment losses, idling losses, speed losses, startup process defects, and defects during normal production. TOC is a management theory developed based on the optimization of production technology by Israeli physicist and management consultant Dr. Eliyahu M. Goldratt. TOC suggests that even in complex and sophisticated systems, there are constraining factors that may seem insignificant but limit the overall production capacity of the entire system.

This paper is based on the improvement of TEEP efficiency measurement theory to study the evaluation and analysis method of concrete transportation efficiency in hydropower dams, which evaluates the concrete transportation efficiency of each type of key equipment from four aspects, namely, equipment utilization rate, equipment runtime rate, equipment efficiency and quality qualification rate, respectively, so as to let the managers have a comprehensive grasp of the concrete transportation situation. In addition, it is also refined to analyze the efficiency of each related equipment in order to find out the key factors affecting the transportation efficiency and provide technical means for optimizing the concrete transportation efficiency.

3 Methods

As a key link in dam concrete construction, concrete transportation connects the two links of concrete production and pouring together, which is an important factor affecting the efficiency of dam construction. There are many factors affecting the transportation efficiency, this paper analyzes the operation rules of key equipment such as mixing plants, transport vehicle and cable crane in dam concrete pouring, establishes a production activity model as shown in Figure 1. Selects the parameters and indicators that can be counted to quantify the influencing factors in the actual production process at the dam construction site based on the activity model, and comprehensively summarizes a number of feasible assessment parameters to establish a quantitative concrete transport efficiency Indicators.

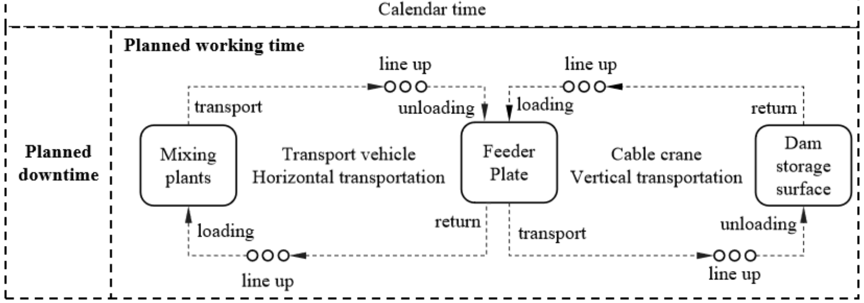

Fig. 1. Production activity model diagram

Based on the activity model, the metrics for evaluating concrete transport efficiency are determined to be equipment utilization rate, equipment runtime rate, equipment efficiency and quality qualification rate.

The equipment utilization rate Ru measures the rationality of the planned work schedule and reflects the proportion of planned work time Tp to calendar time Tc. Tc can be characterized by different scales such as hours, days, weeks, months, seasons, etc. The Ru is calculated as:

$$R_u = T_p / T_c \tag{1}$$

The equipment runtime rate Rt measures the time losses due to short-term equipment shutdowns, equipment failures, and similar factors, reflecting the equipment's time utilization. In this paper, it is defined as the ratio of effective working time Te to planned working time Tp. Te is closely related to planned downtime Td. It is evident that there are various factors contributing to downtime losses, mainly equipment failures, insufficient raw material supply, energy interruptions, etc. Since these factors are often unpredictable or uncertain, the equipment utilization rate exhibits variability within an assessment period. After considering the uncertain factors contributing to downtime losses, the formula for calculating the equipment utilization rate is defined below:

$$R_t = T_e / T_p = \ T_p - T_d \ / T_p \tag{2}$$

The equipment efficiency Re reflects the performance of the equipment, primarily considering losses attributed to performance. The main causes of these losses may include factors related to the equipment itself, human factors, environmental factors, scheduling factors, etc. Equipment efficiency is the ratio of actual workload O to the designed average workload M. The designed average workload is determined by the staff based on the on-site environment and equipment conditions, reflecting the equipment's normal working level in an ideal environment. The definition of equipment efficiency Re is as follows:

$$R_e = O/M \tag{3}$$

The quality qualification rate Rq measures the quality losses during equipment operation, reflecting the effective working conditions of the equipment. In actual operations, concrete mixtures may become non-compliant due to reasons such as production and transportation, and non-compliant concrete mixtures need to be scrapped according to standards. The Rq is calculated as:

$$R_q = N_q/N \tag{4}$$

where Nq is the number of qualified products, N is the total number of produced products.

Based on equations (1) to (4), the calculation formula for the Multi-particle Concrete Transportation Efficiency Analysis Algorithm (MCE) in this paper is obtained as follows:

$$MCE_i = R_{ui} R_{ti} R_{ei} R_{qi} \tag{5}$$

In the formula, MCEi represents the comprehensive efficiency of each specific equipment. In order to conduct efficiency analysis for each key transportation link from a macro perspective and control the overall efficiency of concrete transportation, the average efficiency MCEavg and the minimum efficiency MCEmin for various types of equipment can be calculated based on the results of the efficiency analysis for specific equipment. The calculation formulas are as follows:

$$MCE_{\mathrm{avg}} = \sum\nolimits_{i=1}^{k} MCE_i \tag{6}$$

$$MCE_{\min} = \inf \;\; MCE_1, MCE_2, \ldots, MCE_i \tag{7}$$

4 Experiment

This paper analyzes the transport monitoring data of Hydropower Station A. Hydropower Station A is located in the mainstream of the upper reaches of the Jinsha River, with a normal reservoir water level of 2889.00 meters and a corresponding storage capacity of 10.80 billion cubic meters.

The analysis primarily focuses on the efficiency of the entire transportation process, starting from the departure of the transport vehicle from the mixing plant's outlet to the transportation of concrete to the feeder plate, transferring the concrete to the cable crane's material tank, and then returning to the mixing plant's outlet. According to the MCE algorithm, it is necessary to calculate the production efficiency of the mixing plants, the transportation efficiency of the transport vehicle, and the transportation efficiency of the cable crane.

In this paper, the pouring data of one day in 2023 is selected for data processing and analysis. The pouring configuration for this period includes 2 mixing plants, 7 transport vehicles, and 4 cable cranes. Based on the transportation data and the formulas (6) and (7) of the algorithm model in this paper, the efficiency evaluation values for different time periods in a day can be obtained.

Based on efficiency evaluation values, the average efficiency trend curve for each type of equipment (Figure 2) and the trend curve for the minimum efficiency (Figure 3) are obtained.

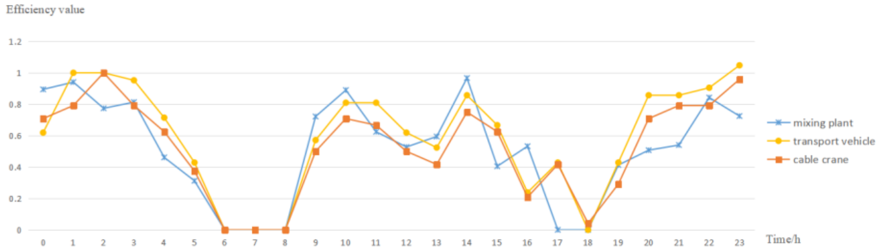

Fig. 2. Average efficiency trend curve

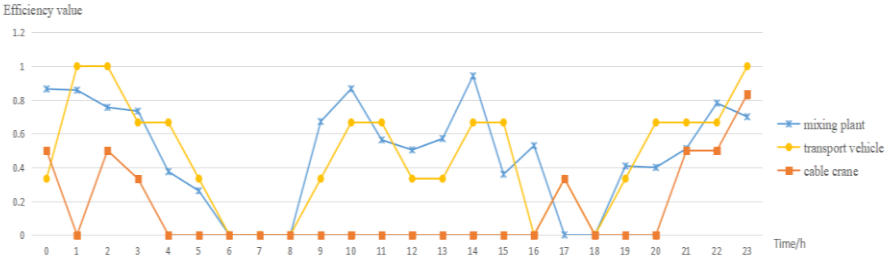

Fig. 3. Minimum efficiency trend curve

From the change curves in Figures 2 and 3, it can be observed that during the pouring process on this particular day, the normal overall efficiency of the mixing plants is around 80%. Before normal shutdowns (shift changes, meal breaks, etc.), the efficiency relatively decreases.

The comprehensive efficiency of the transport vehicles fluctuates with the changes in the mixing plant. Overall, the configuration of the transport vehicles can meet the transportation needs of the current concrete production, and the transportation efficiency is generally below the average efficiency. Even if the pouring strength is further improved, it can still meet the needs of concrete transportation. It is worth noting that at some point there will be an efficiency value greater than 1. This is because the comparison is based on the average transportation volume of the equipment under ideal conditions, rather than the maximum transportation volume.

The comprehensive efficiency of the cable cranes is relatively high. Considering the limit efficiency and the actual production situation, among the 4 cable cranes, one is mainly used for auxiliary transportation and on-site lifting work.

Overall, the production efficiency of the mixing plants, as well as the transportation efficiency of transport vehicles and cable cranes, is generally below the design standards and can meet the normal pouring needs.

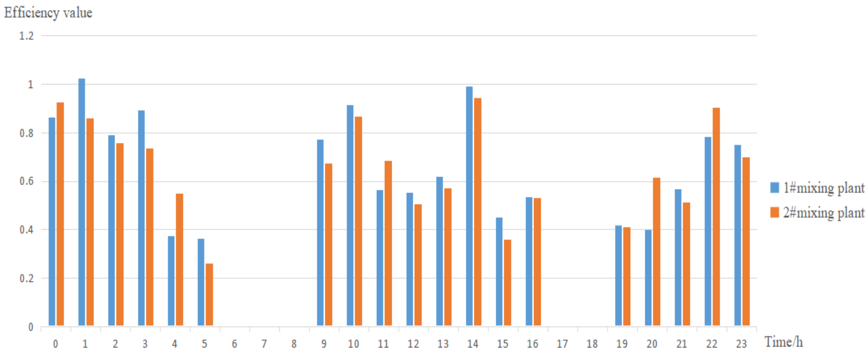

Fig. 4. Comparison chart of production efficiency between two mixing plants

Figure 4 shows a comparison chart of the production efficiency of the two mixing plants. From the figure, it can be observed that the production efficiency of the two mixing plants is similar and generally below the designed average efficiency, indicating that there is still room for improvement in production efficiency. Even if the pouring strength is improved in the future, the concrete production efficiency can still ensure normal pouring.

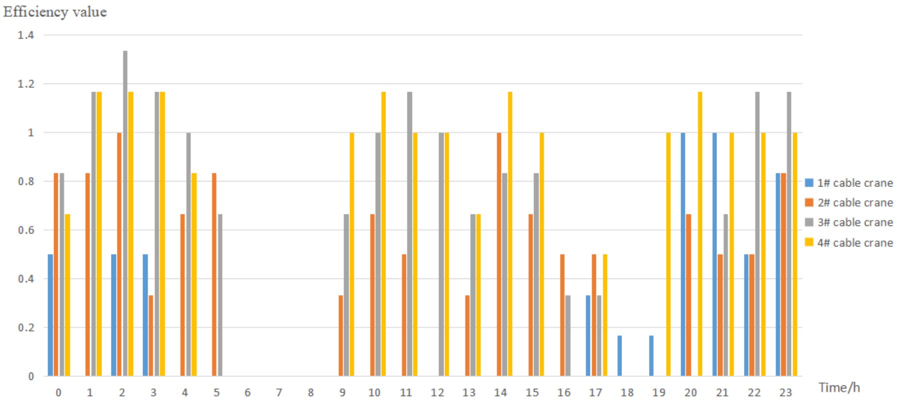

Fig. 5. Comparison chart of transportation efficiency of 4 cable cranes

Figure 5 presents a comparison chart of the transportation efficiency of the four cable cranes. As indicated in the figure, there is an issue of uneven scheduling in cable crane transportation. Cable crane 3# and 4# have a relatively high transportation intensity, while cable crane 1# and 2# have a lower transportation intensity. To enhance transportation efficiency, a reevaluation and rearrangement of cable crane scheduling can be considered.

Taken together, the main factor currently restricting overall transportation efficiency is the cable crane transportation process. Although the overall transportation efficiency of cable cranes is below the designed average efficiency, due to uneven cable cranes scheduling, some cable cranes operate at an excessive efficiency, while the remaining cable cranes have low transportation efficiency. This not only hinders the improvement of pouring efficiency, but also leads to accelerated loss of some cable crane equipment, which not only poses safety risks but also increases the cost of dam construction.

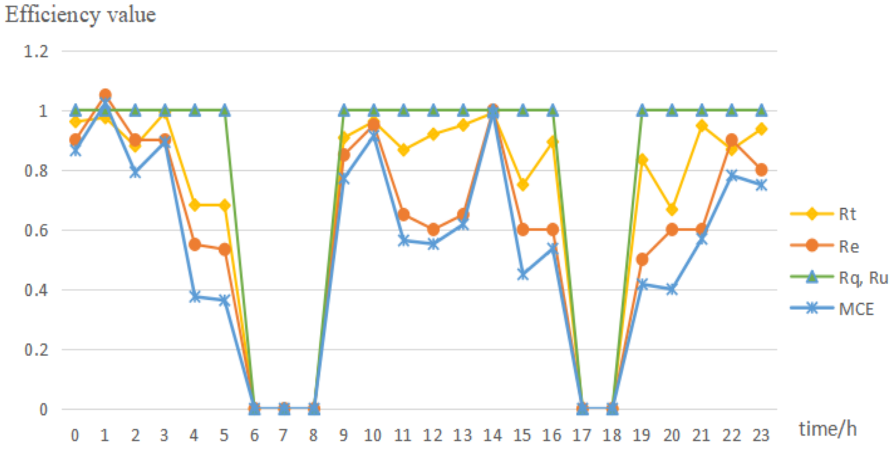

Fig. 6. Trend chart of various evaluation indicators for mixing plant 1#

Additionally, a detailed analysis can be conducted for each individual piece of equipment, as illustrated in Figure 6, which represents the detailed analysis results for Mixing Plant 1. As shown in the figure, during the concrete pouring process on this day, the quality qualification rate Rq for all batches during normal production periods is 1, indicating that the produced concrete mixtures meet the requirements with no quality losses. The value of equipment utilization rate Ru is either 0 or 1, because transportation time is arranged in hours. If you want to analyze efficiency in more detail, it can be subdivided into 30 minutes or less according to the actual situation. During the planned working periods, the equipment runtime rate Rt is relatively high, generally exceeding 80%, and the equipment's working time is generally sufficient. The equipment efficiency Re shows a relatively large fluctuation, changing overall in accordance with the variation in the equipment runtime rate.

5 Conclusion

The MCE efficiency analysis model provides a comprehensive analysis of the entire process of concrete transportation in dam construction. It allows for the analysis of equipment efficiency from both an overall and individual. This dual-dimensional approach enables managers to have a macro-level understanding of efficiency while also conducting detailed analyses for each piece of equipment. This assists managers in objectively analyzing the factors that contribute to the underutilization of efficiency.

Acknowledgments

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