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Dynamic Cost Calculation Model for Handling Equipment Based on Markov Chains

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Abstract: Traditional equipment cost calculation methods use the deterioration value method, assuming constant equipment status and a linear uniform deterioration process. These methods fail to meet actual operational needs when issues such as faults and maintenance differences exist. Therefore, it is necessary to utilize Markov chain theory to construct a dynamic cost model including three states: excellent, medium, and inferior, with state transition probability matrices representing the uncertainty of equipment deterioration. The Markov chain model can more accurately reflect the impact of equipment state transitions on equipment life-cycle costs, providing a more accurate dynamic analysis for enterprise equipment life-cycle management and better reflecting the differences in the probabilities of each state and the costs of each state.

Keywords: Port handling equipment; Markov chain; State transition; Cost optimization.

1 INTRODUCTION

As a global logistics hub, the efficient operation and maintenance of port handling equipment (such as forklifts, quay cranes, and yard cranes) directly affect cargo turnover efficiency and enterprise costs. According to the China Port Statistical Yearbook 2023, the equipment maintenance cost of above-scale ports accounts for 32% of the operating expenses, in which the cost calculation and status management of forklifts have become a difficulty in port asset management due to their high-frequency operation and complex working conditions. The traditional deterioration value method is based on the assumption of "single state-linear deterioration", ignoring the sudden state changes of equipment caused by maintenance differences and sudden faults, resulting in a cost prediction deviation rate often exceeding 15%, which is difficult to meet the demand for precise management of smart ports. Aiming at this pain point, this study constructs a Markov chain model including three states: excellent, medium, and inferior, and describes the deterioration trajectory of forklifts in high-load and high-corrosion environments through state transition probability matrices. The research results not only provide data support for the maintenance strategy optimization of port forklifts (such as planning the replacement of inferior state equipment in advance), but also expand the application scenarios of Markov chains in transportation infrastructure management, helping to realize the equipment management upgrade from "experience-driven" to "data-driven". Through theoretical modeling, case verification, and industry adaptation analysis, this paper provides a new paradigm for port equipment life-cycle cost management, which has significant engineering application value and promotion prospects.

2 THEORETICAL FRAMEWORK AND APPLICATION LIMITATIONS OF TRADITIONAL EQUIPMENT COST CALCULATION METHODS

2.1 *CORE PRINCIPLES OF THE DETERIORATION VALUE METHOD*

Linear deterioration: Equipment performance deteriorates linearly with the increase of service life, and the deterioration increment λ is a constant value.

Single state assumption: All equipment belongs to the same technical level, and the different deterioration speeds of different equipment due to differentiation are ignored.

No state transition assumption: The state of the equipment will not change suddenly with time, and the deterioration process is continuous and predictable.

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According to this assumption, the formula for calculating the annual average total cost of a forklift is:

$$C(T) = K_0/T + \lambda T/2 \quad (1)$$

In formula (1)： $K_0$is the original value of the forklift (yuan); T is the service life (years); λ is the deterioration increment. The first term in formula (1) is the annual average purchase cost (decreasing with the increase of service life), and the second term is the annual average deterioration cost (increasing with the increase of service life). The service life corresponding to the minimum value of the sum of the two is the economic life of the equipment.

Example 1: A port purchases 100 new forklifts for the handling of a certain cargo in the next two years. The original value of a single new forklift K_0 = 80,000 yuan, and the deterioration increment of all equipment is assumed to be λ = 3,000. Calculate the total cost for the two-year cycle.

Solution steps: SubstituteK_0 = 80,000 yuan and λ = 3,000 into formula (1):

Annual average cost of a single device: $C(2) = 80{,}000/2 + 3000 * 2/2 = 43{,}000(yuan)$

Total cost of 100 devices for 2 years: $43{,}000 * 2 * 100 = 8{,}600{,}000$(yuan)

2.2 *THREE LIMITATIONS OF TRADITIONAL METHODS*

First, the assumption of state homogeneity is out of touch with the actual scenario. In reality, the state of equipment is affected by multiple factors and shows differences:

Maintenance level: Equipment may be in the following states: the "excellent state" with the lowest wear and tear (λ_1 = 1,000) shortly after purchase, the "medium state" with general deterioration increment (λ_2 = 3,000), and the "inferior state" (λ_3 = 5,000) of equipment with insufficient maintenance; for example, sudden situations such as overload, impact, and rain may cause damage to the internal structure of the equipment, resulting in a sharp increase in the deterioration value.

The traditional method assumes that all equipment is in the same state (for example, the medium state is defaulted in Example 1). When there is state differentiation in the equipment group, it will inevitably lead to cost prediction deviation. For example, if 20% of the 100 forklifts remain in the excellent state due to good maintenance and 30% enter the inferior state due to harsh working conditions, the traditional method will have a deviation (specific calculations are shown in the later comparison).

In addition, the static model cannot reflect the dynamics of state transitions. The state transition of equipment has "memorylessness", that is, the state at the current moment only depends on the state at the previous moment, and has nothing to do with any state before that, such as the "memoryless" process[1].

Excellent state equipment may still maintain excellence (50%), turn to medium (30%), or directly turn to inferior (20%) in the next year; inferior state equipment will remain in the inferior state forever due to irreversible structural damage after entering this state. The traditional deterioration value method only gets fixed results after the initial value enters, and cannot describe the above state changes, so it can only be applied to the current cost and cannot reflect the long-term costs in the following years.

The last item is the lack of management decision support. Based on past logical deduction, enterprises often have the following situations:

Rigid maintenance strategy: It is unfair to adopt the same maintenance measures for equipment in different states, and good equipment will also suffer; the advance amount of equipment replacement plans is insufficient, and equipment that will deteriorate before deterioration occurs is often invisible, leading to sudden accidents or excessive replacement costs; the budget for equipment expenses is not in place, which will be seriously underestimated when formulating enterprise financial plans, causing cash difficulties for enterprises.

3 THEORETICAL BASIS OF MARKOV CHAIN IN EQUIPMENT STATE MODELING

3.1 *MARKOV PROCESS*

First, define the "Markov process", which is a theory for studying the state of things and their transitions. It determines the change trend of states by studying the initial probabilities of different states and the transition probabilities between states, so as to achieve the purpose of prediction[2].

The first-order Markov chain, which is the simplest and most suitable for embodying the relevant ideas of Markov analysis, satisfies that the current state only depends on the previous state and has nothing to do with earlier states.

3.2 *EXAMPLE*

Example 2: A port purchases 100 new forklifts for the handling of a certain cargo in the next two years. The original value of a single new forklift K_0 = 80,000 yuan. It is assumed that the equipment has three states: "excellent state" (λ_1 = 1,000), "medium state" (λ_2 = 3,000), and "inferior state" (λ_3 = 5,000). Among them, the new equipment is all in the "excellent state" when first put into use. λ is the deterioration increment. According to past experience, the equipment quantity state under daily maintenance obeys a first-order Markov chain, which represents the "excellent state", "medium state", and "inferior state" from left to right and from top to bottom respectively. Based on the example in Traffic System Analysis[3], it is extended to handling equipment. Its state transition matrix is:

$$P = \begin{bmatrix} 0.5 & 0.3 & 0.2 \\ 0 & 0.6 & 0.4 \\ 0 & 0 & 1 \end{bmatrix}$$

Use Markov analysis to predict and calculate the total cost for the two-year cycle.

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3.3 Transition Probability Matrix

Therefore, the following state transition matrix can be constructed according to Example 2:

$$P = \begin{bmatrix} P_{11} & P_{12} & P_{13} \\ P_{21} & P_{22} & P_{23} \\ P_{31} & P_{32} & P_{33} \end{bmatrix}$$

$$P = \begin{bmatrix} P_{11} & P_{12} & P_{13} \\ P_{21} & P_{22} & P_{23} \\ P_{31} & P_{32} & P_{33} \end{bmatrix} = \begin{bmatrix} 0.5 & 0.3 & 0.2 \\ 0 & 0.6 & 0.4 \\ 0 & 0 & 1 \end{bmatrix} \quad (2)$$

In formula (2), P represents the state transition matrix, and P_{ij} represents the probability of transitioning from state i to state j. For example, P_{12} represents that there is a 0.3 probability that the equipment in state 1 ("excellent state") will transition to state 2 ("medium state") in the next year.

That is: Transition of excellent state equipment in the next year: 50% probability to maintain excellence, 30% to transition to medium, and 20% to transition to inferior; Transition of medium state equipment in the next year: 0% to transition to excellent (maintenance cannot restore to excellent state), 60% to maintain medium, and 40% to transition to inferior due to natural deterioration; Transition of inferior state equipment in the next year: 0% reversal, 100% to remain inferior (i.e., irreversible failure).

3.4 State Vector Evolution

Let the state vector at time t be:

$$p_t = [n_1(t), n_2(t), n_3(t)] \quad (3)$$

In formula (3), t represents time (years), and $n(t)$ represents the number of equipment in each state, where 1, 2, and 3 correspond to the "excellent state", "medium state", and "inferior state" respectively. Then the state transition satisfies:

$$p_t = p_{t-1} * P \quad (4)$$

In formula (4), $p_{t\text{-}1}$ represents the state matrix of the previous year. In the initial state (t=0), all equipment is in the excellent state. In the question, 100 equipment are purchased. According to formula (3), $p_0 = [100,0,0]$.

2.5 Cost Calculation Module

Purchase cost: $K_0 * N = 80{,}000 * 100 = 8{,}000{,}000(元)$ yuan (N is the number of equipment);

Deterioration cost: Calculated according to the state distribution of each year. The cost in year t is:

$$C_t = n_1(t) * \lambda_1 + n_2(t) * \lambda_2 + n_3(t) * \lambda_3 \quad (5)$$

Total cost: The sum of the purchase cost and the deterioration costs of each year, that is:

$$C_{all} = K_0 N + \sum_{t=1}^{T} C_t \quad (6)$$

4 Calculation Process Of Example 2

4.1 State Transition And Cost Calculation In The First Year

Construct the initial vector $p_0 = [100,0,0]$. After the first year of transition, according to formula (4):

Number of excellent: $100 * 0.5 + 0 + 0 = 50$ units

Number of medium: $100 * 0.3 + 0 + 0 = 30$ units

Number of inferior: $100 * 0.2 + 0 + 0 = 20$ units

That is, $p_1 = [50,30,20]$.

According to formula (5), the deterioration cost is: $C_1 = 50 * 1000 + 30 * 3000 + 20 * 5000 = 240{,}000(yuan)$.

4.2 State Transition And Cost Calculation In The Second Year

Similarly, according to formula (4), it can be calculated that:

Number of excellent: 25 units

Number of medium: 33 units

Number of inferior: 42 units

Similarly, according to formula (5), the deterioration cost is: $C_2 = 334000(yuan)$

4.3 Calculation Of Total Equipment Cost

According to formula (6), we get: $C_{all} =$ 8,000,000+240,000+334,000=8,574,000(yuan)

4.4 Comparison Between Model Total Cost And Traditional Method

Note: Difference amount = Traditional method - Markov; Difference rate = Difference amount / Traditional method

Table 1 Comparison Of Costs Between The Two Methods

type	Traditional method	Markov	Difference amount	Difference rate
buy	8,000,000	8,000,000	0	0%
1styear	300,000	240,000	60,000	20%
2ndyear	300,000	334,000	-34,000	-11.3%
cost	8,600,000	8,574,000	26,000	3.02%

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5 Advantage Analysis Of Markov Chain Model

5.1 Theoretical Level: Breaking Through Three Traditional Assumptions

State heterogeneity modeling: Replace the single-state assumption with multi-state division (excellent/medium/inferior), allowing different equipment to have differentiated deterioration parameters;

Dynamic transition description: Use transition matrices to describe the laws of state evolution and capture the sudden impact of accidental events (such as faults) on the deterioration process;

Probabilistic prediction: Output the probability distribution of the number of equipment in each state instead of deterministic results, which is more in line with the uncertainty characteristics of equipment operation.

5.2 Application Level: Dual Core Values

Improvement of cost prediction accuracy: Taking the second case as an example, the traditional method assumes that all are in the medium state, but in reality, 20% of the equipment is already in the inferior state (deterioration value of 5000 yuan), and inferior equipment will be added every year thereafter. If the state transition is ignored, it will cause an underestimation of the deterioration cost in the first year - the result is that assuming all are in the medium state (3000 yuan/unit), but the actual deterioration cost is as high as 240,000 yuan, which is 20% less calculated. At the same time, it will also cause an overestimation of the deterioration cost in the second year - the traditional method still estimates according to 3000 yuan/unit, then the total cost will increase to 334,000 yuan after 20 units are all deteriorated, which is 11.3% more than the assumed value.

Maintenance strategy optimization support: For normal state machines, the overhaul cycle can be extended (such as changing quarterly overhauls to semi-annual overhauls) to save overhaul costs. For good state machines, the detection frequency can be delayed (from once every two months to once every three months). For medium state machines, the detection frequency should be increased (vibration detection should be carried out monthly). For inferior state equipment, the replacement time should be arranged in advance (such as replacing 42 inferior state equipment in the third year) to prevent losses caused by their failure shutdown.

6 Systematic Comparison Between The Two Methods

6.1 Core Parameter Comparison

Table 2 Core Parameter Comparison

Dimension	Traditional Deterioration Numerical Method	Markov Chain Model
State	Single State	Multiple States
Deterioration	Linear Uniform	Probabilistic State Transition
Input	K_0, λ, T	K_0, λ, T, P, p_0
Output	Deterministic Cost	Dynamic Cost Sequence

6.2 Applicable Scenario Analysis

Applicable scenarios of traditional methods: Mainly include scenarios with single equipment type, unified maintenance strategy, stable operating environment, no significant state differentiation, and short-term cost calculation. In this case, the operating state of the equipment is basically unchanged, and the impact of state transition can be ignored.

Applicable scenarios of Markov model: Applicable to situations where equipment status is affected by multiple factors, the planning time scale is large, the cumulative effect of state transitions needs to be considered, and equipment group management is required, and its state distribution has statistical laws.

6.3 Limitation Comparison

Traditional methods: Difficult to handle sudden state changes, and long-term prediction errors increase with the increase of service life; ignoring equipment individual differences and analyzing according to certain constants leads to "one-size-fits-all" errors.

Markov model: More dependent on accurate transition probabilities; currently only considering first-order transitions, without involving multi-order correlations or hidden states (such as early fault hazards).

As can be seen from the above calculation analysis, this method is more practical than the traditional equipment cost calculation method (i.e., the deterioration value method). However, compared with the Hidden Markov Model (HMM) that considers unobservable states (such as early fault hazards) or complex Markov models combined with Monte Carlo simulation of multi-factor interference, the model given in Example 2 (first-order Markov chain, that is, satisfying that the current state only depends on the previous state and has nothing to do with earlier states) is relatively simple and difficult to reflect the equipment state transitions in complex environments.

7 Research Conclusions And

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INDUSTRY INSIGHTS

7.1 THEORETICAL FRAMEWORK INNOVATION

The traditional deterioration value method is usually based on the assumption of "single state-linear deterioration", which is a deterministic and static model and is difficult to cope with the complex situations that occur in the actual operation of port handling equipment. Port equipment is usually in high-load, high-corrosion (such as salt spray environment), and high-frequency start-stop conditions. The deterioration process of equipment will be affected by many factors such as operation intensity (such as fluctuations in container throughput), maintenance timeliness (such as night repair efficiency), and environmental erosion (such as sea breeze humidity >80%), resulting in sudden non-linear deterioration of equipment, such as "equipment that was originally running well suddenly enters the fault state due to overload". Therefore, this study proposes a new method by introducing Markov chains to divide the state space of equipment (for example: excellent: normal state; medium: slight wear; inferior: serious fault shutdown) and establish a probability transition mechanism, regarding port equipment as a dynamically changing "state system", thus promoting the practice of transforming from "regular maintenance" to "predictive maintenance".

7.2 INDUSTRY UNIVERSAL INSIGHTS

From the existing research results, the application of Markov analysis and cost calculation is not only limited to port handling equipment, but can also be applied to the management of other port facilities (such as conveyor belts, storage shelves) and waterway navigation equipment (such as buoys, gates) and other transportation fixed assets. Use the Markov chain model to carry out predictive analysis on the metal structure deterioration of port machinery and equipment quay cranes and optimize the non-destructive testing cycle; for the multi-state transitions in automated equipment groups, such as battery decay and sensor failures of AGVs (automated guided vehicles), carry out comprehensive optimization of equipment energy consumption and maintenance costs to help develop green ports.

8 CONCLUSION

The Markov model can give full play to the advantages of Markov chains; the prediction of the operation status of handling equipment management systems plays an important role in the equipment management of port enterprises[4].

Therefore, this paper establishes a dynamic cost calculation model for handling equipment based on Markov chains according to the deterioration characteristics of port handling equipment, and provides port enterprises with cost control means close to the actual production situation based on this model, realizing the cross-disciplinary research of "transportation system engineering + transportation enterprise management". On this basis, it can further use digital twin technology to carry out three-dimensional visual prediction of equipment status and promote the improvement from "cost center" to "efficiency improvement center", which will also provide strong support for the maintenance of new infrastructure in the construction of a transportation power in the future.

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