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Research on The Schedule and Cost Control of Wind Turbine Blade Product Development based on Earned Value Management

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Abstract

Cost, schedule and quality constitute the core objectives of project management. Accurate cost and schedule control and prediction are critical to the smooth delivery of wind turbine blade R&D projects. As the mainstream tool for integrated project control, the earned value method can identify project deviations and optimize the allocation of duration and cost. Nevertheless, the traditional earned value model ignores quality constraints, scope changes and external market disturbances, and its prediction errors tend to be amplified in long-cycle, high-uncertainty blade R&D scenarios. To address this issue, this paper combines critical path screening and secondary earned value decomposition, incorporates earned schedule dimension, Monte Carlo probabilistic risk correction and agile-predictive hybrid management philosophy, and effectively improves the prediction accuracy and control reliability of schedule and cost for wind turbine blade R&D under frequent technical iterations, material price fluctuations and supply chain disruptions.

Keywords

Wind Turbine Blade; Project Management; Earned Value Management; Cost and Schedule.

1. Introduction

With the global low-carbon energy transition, the wind power industry has maintained steady and orderly development. As the core component of wind turbines, wind turbine blades are undergoing continuous iteration and upgrading, with new models equipped with high-power and super-long blades launched every year. The maximum length of mainstream wind turbine blades has gradually reached 150-180 meters, which puts forward higher requirements for lightweight, high-strength and long-service-life blade products. Wind-turbine blade development belongs to typical high-uncertainty complex R&D activity, which integrates aerodynamic profile design, composite material research, custom mold development and multi-round prototype verification. Distinct from conventional construction projects, blade R&D contains plenty of exploratory iterative design tasks. Raw material price fluctuation, supply chain disruption of non-standard equipment and frequent technical modification bring dual pressure to schedule and cost management. Once schedule delay or cost overrun occurs, it will compress the profit margin of wind-power equipment manufacturers and hinder the overall construction progress of wind-farm projects.

In practical enterprise practice, managers mostly rely on empirical judgment rather than quantitative project management tools. Even if the earned value method is adopted, most enterprises still apply traditional aggregated earned value calculation. Aggregated monetary indicators are liable to conceal deviation risks of critical-path sub-tasks. Good performance from noncritical work packages may offset cost overrun and schedule lag on key links, resulting in overoptimistic project assessment and missing the optimal risk-intervention window [1,14].

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Therefore, project managers are required to accurately evaluate the project development trend, timely identify potential risks and problems in the development process, and implement effective optimization measures, so as to ensure the smooth progress of wind turbine blade development project

In the 1960s, the U.S. Department of Defense and the National Aeronautics and Space Administration (NASA) introduced the Work Breakdown Structure (WBS) and the Cost/Schedule Control Systems Criteria (C/SCSC), the direct forerunner of modern Earned Value Management (EVM), together with a corresponding indicator system. The method was later codified by ANSI/EIA-748 and ISO 21508, and it now supports timely and comprehensive evaluation and control of cost and schedule throughout the entire project life cycle [2,3]. In project management, project cost is measured by budget and project schedule is quantified by time. The earned value method connects the two core elements to form a unified indicator system. By comparing and analyzing cost and schedule data during project implementation, it enables targeted control and response to deviations, timely adjustment of project implementation plans, and restricts adverse schedule and cost deviations within a reasonable and controllable range. Among various project management methods, EVM is a comprehensive control method with remarkable application effects.

Domestic and international scholars have carried out extensive improvement studies on earned value theory. Secondary earned value method realizes hierarchical decomposition calculation for sub-projects and overcomes the coarse-grained evaluation defect of traditional EVM[10]. Critical-path-based earned value distinguishes different impacts brought by critical and non-critical activities on overall duration[10,12]. Earned Schedule theory addresses the defect that monetary weighted SPI cannot truly reflect time-delay risks[15]. Monte-Carlo-based probabilistic prediction introduces uncertainty analysis into EVM, shifting from single-point deterministic forecasting to probability-interval decision-making[27]. Meanwhile, several studies attempt to combine quality gate constraints and agile management thoughts to adapt to R&D oriented projects with massive iterative tasks[21,23,24].

Nevertheless, existing research still has obvious gaps targeting wind turbine blade development scenarios. Most improved EVM models are developed for construction engineering projects. Few studies integrate secondary decomposition, critical path filtering, earned schedule measurement, probabilistic simulation and quality gate constraint into a unified framework for composite blade R&D. In addition, blade development shows hybrid project characteristics: mold manufacturing and trial production belong to predictive waterfall type activities, while aerodynamic structural optimization belongs to agile iterative tasks. Rare literatures discuss the adaptability of improved EVM under such hybrid mode. Current engineering applications mostly stay at simple indicator computation, lacking complete model workflow and practical case verification for hundred-meter-class blade R&D projects[17,19].

On the basis of the traditional earned value method, the project granularity can be refined by dividing interrelated and attribute-consistent work contents into multiple secondary sub-projects under the overall project. In this way, the entire project can be regarded as an overall system composed of several independent sub-projects. The secondary earned value method performs earned value analysis on each secondary sub-project under the overall project to obtain project performance data and complete final evaluation, thus delivering more accurate and objective analysis results.

From the perspective of schedule management, project tasks can be divided into critical path and non-critical path activities. The traditional earned value method ignores the differences in schedule deviation characteristics between critical and non-critical paths, which may cause evaluation results to deviate from the actual situation when large deviations occur on the critical path. Therefore, this paper constructs an improved comprehensive earned-value control model oriented to wind-turbine-blade R&D projects. The proposed model integrates secondary earned-value decomposition, dynamic critical-path identification, earned-schedule time-dimension measurement, quality-gate constraint and Monte-Carlo probabilistic simulation, so as to adapt to the hybrid agile-predictive characteristics of such projects. Taking the development of a hundred-metre-class wind-turbine blade as an

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engineering case, this paper carries out model verification, analyzes deviation formation mechanisms, and puts forward targeted schedule-cost control countermeasures.

2. Overview of Earned Value Management Mode

2.1 Basic Principles of Earned Value Method

The indicator system of the earned value method consists of basic elements, evaluation indicators, and prediction indicators [1,2].

2.1.1 Basic Elements

BCWS (Budgeted Cost for Work Scheduled): It refers to the cumulative budget funds required for scheduled work.

BCWP (Budgeted Cost for Work Performed): It represents the budgeted cost of completed work up to a specified time node in accordance with the project plan. Serving as the performance measurement standard for actual project progress, it is also defined as the earned value [3].

ACWP (Actual Cost for Work Performed): It denotes the actual expenditure incurred for completed work tasks.

BCWS(CP)(Budgeted Cost of Work Scheduled Critical Path): Cumulative planned budget only for work packages located on the dynamic critical path.

BCWP(CP) (Budgeted Cost of Work Performed Critical Path): Cumulative earned value only for completed work packages located on the dynamic critical path.

ACWP(CP) (Actual Cost of Work Performed Critical Path): Cumulative actual cost consumed by work packages located on the dynamic critical path.

2.1.2 Evaluation Indicators

Deviation Indicators:

CV (Cost Variance): CV = BCWP - ACWP, i.e. the difference between the budgeted cost of the work actually performed and the actual cost incurred for that work at a specific milestone or inspection point.

SV (Schedule Variance): SV = BCWP - BCWS, i.e. the deviation between the budgeted value of the work actually performed and the budgeted value of the work scheduled at a specific milestone or inspection point.

Performance Indicators:

CPI (Cost Performance Index): It is the ratio of budgeted cost to actual cost of completed work.

SPI (Schedule Performance Index): It is the ratio of budgeted cost for work performed to budgeted cost of work scheduled.

Note: When the critical path shifts during project execution, the set of critical path work packages shall be updated, and all above (CP) indicators shall be recalculated accordingly.

Since SV and SPI are cost-weighted indicators, they may distort true time-delay information[9,15]. Earned schedule introduces ES (earned schedule) and SV(t) (time-based schedule variance): ES is the time point at which the cumulative BCWS equals the cumulative BCWP, SV(t) = ES - AT, where AT is the actual elapsed time, and the time-based schedule performance index is SPI(t) = ES/AT. This realizes direct measurement of schedule deviation in the time dimension rather than in the monetary dimension. Deterministic indicators only give single point estimated values; probabilistic extended indicators combine Monte-Carlo simulation to output confidence intervals of CPI and SPIt, quantifying the uncertainty range of project performance[26,27].

2.1.3 Prediction Indicators

EAC (Estimate At Completion): The estimated total project cost upon completion.

ETC (Estimate To Complete): The predicted remaining work scope, time and cost required for project completion.

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The earned value method can calculate and predict the cost, performance indicators and schedule deviations during project implementation. Adopting project value indicators that reflect project duration, resources, cost and task complexity, it realizes quantitative comparison between actual cost and budgeted cost deviations.Traditional deterministic prediction formulas output only single point results. For R&D projects with multiple risk sources, Monte-Carlo stochastic earned value prediction can generate probability distribution of EAC and project completion date, output P50, P80 and P90 quantile prediction results, which provides probability based decision support rather than a single deterministic value.

2.2 Secondary Earned Value Method

The earned value method relies on real-time process data and realizes quantitative analysis by benchmarking with the project database, enabling project managers to carry out deviation correction and dynamic adjustment according to actual operating conditions [4,6]. As an optimized improvement of the traditional earned value method, the secondary earned value method divides the overall project into multi-level structural sub-projects and implements independent earned value management and calculation for each sub-project[5-11]. The relevant calculation formulas and parameters of the secondary earned value method are described as follows.

Calculation of Basic Parameters:

(1)

$$BCWS(t)_{\text{Project}} = \sum_{i=1}^{n} BCWS_i(t) = \sum_{i=1}^{n}\sum_{0}^{t} PQ \times SC$$

$$ACWP(t)_{Project} = \sum_{i=1}^{n} ACWP_i(t) = \sum_{i=1}^{n}\sum_{0}^{t} AQ \times AC$$

$$BCWP(t)_{\text{Project}} = \sum_{i=1}^{n} BCWP_i(t) = \sum_{i=1}^{n}\sum_{0}^{t} AQ \times AC$$

Calculation Formulas of Cost and Schedule Deviations and Performance Indicators:

(2)

$$CV\ （t）_{Project} = BCWP\ （t）_{Project} - ACWP\ （t）_{Project} = \sum_{i=1}^{n} BCWP\ （t） - \sum_{i=1}^{n} ACWP_i\ （t）$$

$$SV\ （t）_{Project} = BCWP\ （t）_{Project} - BCWS\ （t）_{Project} = \sum_{i=1}^{n} BCWP\ （t） - \sum_{i=1}^{n} BCWS_i\ （t）$$

$$CPI(t)_{\text{Project}} = \frac{\sum_{i=1}^{n} BCWP_i(t)}{\sum_{i=1}^{n} ACWP_i(t)}$$

$$SPI(t)_{Project} = \frac{\sum_{i=1}^{n} BCWP_i(t)}{\sum_{i=1}^{n} BCWS_i(t)}$$

Where:

N - number of secondary sub-projects;

T - inspection time point or final completion time of the project, which is correlated with the time variable t.

The secondary earned value method enables periodic targeted monitoring of each sub-project, allowing timely identification and resolution of problems in the project implementation process. Its performance evaluation system covers not only the overall project but also all secondary sub-projects, yielding multi-level and in-depth analysis conclusions. Moreover, this method adopts a bottom-up calculation logic: it firstly calculates individual performance indicators of each secondary sub-project,

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and then aggregates the sub-project data to obtain the comprehensive indicators of the overall project. This hierarchical calculation mode can effectively detect subtle schedule and cost deviations at the secondary sub-project level that are overlooked by the traditional earned value method.

In practical application, the secondary decomposition granularity should match project management capacity. Excessively fine division will raise data-collection workload and management overhead, while too coarse decomposition loses early-warning capability; for complex R&D projects, three-layer WBS is recommended, and each secondary sub-project should correspond to clear responsible department and person-in-charge to realize traceability of deviation causes[16]. For exploratory iterative sub-tasks in blade design phase which adopt agile development mode, work packages can be decomposed according to sprint iterations; iteration-level BCWS, BCWP and ACWP are calculated, and iteration outputs are constrained by quality gate check results to adapt to hybrid agile-predictive project characteristics[21].

2.3 Critical Path Earned Value Method

The traditional earned value method only focuses on the overall project results and ignores deviations occurring on critical and non-critical paths. It cannot finely distinguish the deviation magnitude of different paths or quantitatively evaluate their impacts on the overall project schedule [10,12]. The critical path earned value method firstly decomposes the overall project into multiple work packages through Work Breakdown Structure (WBS). Based on the duration and logical correlation of each task, the time float of each independent work package is calculated to determine the critical path of the project.

Subsequently, deviation evaluation indicators are formulated and analyzed, and targeted corrections and adjustments are implemented according to whether the deviations of critical and non-critical paths exceed the reasonable threshold. Integrating the advantages of the traditional earned value method and critical path method, the critical path earned value method can accurately track the real-time progress of project implementation, analyze the influencing factors of project deviations, and support timely adoption of effective corrective measures.

3. Construction of Earned Value Model for Wind Turbine Blade Projects

3.1 Characteristics of Wind Turbine Blade Product Project Management

Wind turbine blades are large-scale composite structural components. Their product development involves the design of aerodynamic profiles, structural schemes, manufacturing processes, as well as molds and tooling equipment. Various tests are carried out at key process nodes to verify the rationality and reliability of the whole development process.

In the project management of wind turbine blade development, management elements, inspection standards, impact analysis and other control items can be configured at multi-level management control points covering core management fields such as schedule, cost and human resources. Full-process project control can be realized by standardized management of each hierarchical control node. A large number of technical achievements, practical experience and optimized management methods will be accumulated during project implementation, which can eventually form standardized process knowledge and management criteria for enterprises and even the whole wind power industry.

All work tasks in the development process of wind turbine blade products can be refined and quantified in monetary units. Quantitative statistical analysis of human resource consumption, capital investment and equipment occupancy can be performed at preset inspection nodes to dynamically grasp real-time project schedule and cost status. This management mode can effectively avoid potential project risks and ensure the successful completion of project overall objectives. Nevertheless, different from general engineering construction projects, blade R&D projects contain numerous exploratory technical tasks. Partial work packages face technical uncertainty; rework and design iteration are normal phenomena. Pure budget monetized progress measurement may distort real completion degree; quality gate check results shall be bound to earned-value measurement: work

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packages failing quality acceptance cannot be counted as completed BCWP even if consuming actual cost[21]. Meanwhile, large size blade development is sensitive to composite material market volatility and non-standard equipment supply chain interruption; budget benchmark should reserve material price fluctuation contingency besides technical contingency reserves[18,24]. Project tasks show hybrid characteristics: mold manufacturing, trial production and test tasks belong to deterministic predictive workflow; aerodynamic iteration design and structural optimization belong to agile exploratory workflow, so the control model needs to support hybrid management mode[23].

3.2 Model Construction of Improved Earned Value Method

Project management mainly covers ten core management domains, including project integration, scope, schedule, cost, quality, human resource, communication, procurement, risk, and stakeholder management. According to the actual implementation process and practical pain points of wind turbine blade development projects, schedule delay and cost overrun are identified as the two most prominent problems. Therefore, the improved model is constructed focusing on the two core objectives of schedule control and cost control.

On this basis, this study expands the model boundary, adds probabilistic risk prediction module and hybrid agile-predictive measurement module, and forms an improved integrated model with four layers: baseline establishment layer, multi-dimensional performance measurement layer (secondary earned value + critical-path filtering + earned schedule + quality gate constraint), Monte-Carlo probabilistic forecasting layer, and deviation response & baseline change management layer[22].

Project schedule and cost present a unity of opposites relationship throughout the whole project lifecycle. As shown in Figure 1, the total project cost consists of direct cost and indirect cost. It is essential to determine the optimal equilibrium point between project schedule and total cost to guarantee qualified final project deliverables. The secondary earned value method based on critical path adopts monetary measurement to replace traditional engineering quantity measurement. When calculating and evaluating project progress, it utilizes work achievements converted by capital investment for quantitative assessment, which realizes more comprehensive and effective supervision of the actual project schedule.

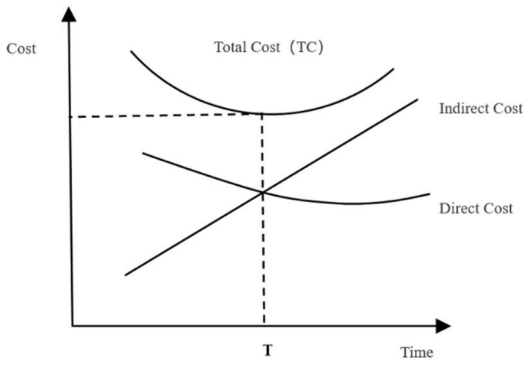


Figure 1. Diagram of project cost and schedule relationship

The implementation procedures of the proposed model are specified as follows.

3.2.1 Work Breakdown Structure (WBS)

According to the attributes of product development, the overall project is decomposed hierarchically into standardized work packages, which clarifies the logical relationships between sub-projects and the interactive relationships between projects and organizational departments. The decomposition hierarchy should be reasonably controlled. Excessively multi-level decomposition will increase workload and management costs, while overly simplistic decomposition will fail to achieve fine-grained overall project monitoring. In practical engineering applications, the WBS hierarchy is generally limited to no more than three levels.

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For wind blade R&D, WBS decomposition should distinguish exploratory design tasks, mold customization tasks, trial-production and test-verification tasks; each work package should define quality acceptance criteria simultaneously with scope and budget, to support quality-bound earned-value calculation[21]. For agile-mode iterative design sub-packages, set sprint cycle boundaries, and each sprint corresponds to measurable deliverables and quality checklists[20,23].

3.2.2 Determination of Overall Project Schedule and Total Budget

The overall project schedule is formulated based on actual project conditions and reliable engineering experience. It comprehensively reflects on-site implementation conditions, fully considers the logical connection and handover of each functional module, highlights key construction nodes, realizes reasonable manpower allocation, and complies with the overall requirements of project contracts.

The total project budget is calculated and summarized layer by layer from subordinate sub-projects to the overall project based on the established WBS framework. Contingency reserves for emergencies and potential project risks are fully incorporated during budget compilation. Meanwhile, the preliminary budget is verified and adjusted against the overall cost control objectives to determine the final authoritative total project budget.

3.2.3 Establishment of Working Network and Confirmation of Critical Path

Based on a hierarchical Work Breakdown Structure (WBS), the Program Evaluation and Review Technique (PERT) and the Critical Path Method (CPM) are combined to construct the project activity network, delineate the main workflow, and identify the initial critical path. Control checkpoints are placed along the critical path to implement target-based management of critical tasks and to enable full process tracking of long cycle, complex activities. A dual inspection mechanism combining periodic reviews and random spot checks is adopted to promptly capture schedule and cost deviations during project execution.

At each checkpoint, a dynamic reassessment of the critical path is performed: if significant performance deviations emerge in certain work packages, the total float of associated activities will change, introducing the risk of critical-path shifting. In such cases, the critical-path work package set must be updated in real time, and the earned value performance metrics oriented to the critical path must be recalculated[14,16]. Furthermore, Monte Carlo simulation is employed to quantify the probability of each work package becoming critical; work packages with a high criticality probability are prioritized in routine project monitoring to achieve proactive risk control [25].

3.2.4 Analysis of Project Cost and Schedule Trends

In accordance with the formulated overall project plan and hierarchical WBS work packages, the budget quota and scheduled progress baseline for each secondary sub-project are explicitly defined. The total budget of each sub-project is evenly apportioned to each time node according to the planned construction cycle, forming a time-based phased cost baseline that matches the project progress rhythm.

3.2.5 Benchmarking Analysis and Performance Calculation

The model adds earned schedule time dimension indicators at this step. Combined with secondary sub-project decomposition results and critical path filtering, it outputs three layer information: overall project indicators, secondary sub project indicators, and critical path exclusive indicators, avoiding single aggregate indicator misleading judgment[14]. For agile sub-packages, convert sprint completed story points into BCWP values constrained by quality gate check results[23]. After calculation of deterministic indicators is completed, the Monte-Carlo stochastic simulation module is triggered. It takes the current CPI, SPI(t), and risk factor distributions of each work package as inputs, outputs the probability distribution and intervals of EAC and completion time, and provides P50/P80/P90 quantile prediction results.

3.2.6 Schedule and Cost Control

For schedule and cost control, the principle of comprehensive control and overall planning shall be followed. Specific corrective measures are formulated on the basis of schedule performance and cost

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analysis. Once corrective measures are confirmed for implementation, the corresponding project plans shall be revised in a timely manner to carry out overall project management. Continuous monitoring is required, and the trends of CPI and CV shall be reviewed periodically or at predefined inspection nodes. In case of obvious adverse trends, priority shall be given to correcting the worst-case deviations. The corresponding workflow is shown in Figure 2.

When implementing corrective measures, distinguish deviation sources: for critical path task deviation, prioritize resource input compression, parallel process transformation; for non-critical-path deviation, make full use of task float buffer. If scope change occurs, trigger baseline change procedure, update WBS, budget and schedule baseline synchronously, and avoid analyzing deviation against expired baseline[16,20]. According to the probability quantile output by stochastic simulation, multi-level risk warning is triggered: when P80 quantile of forecast overrun exceeds reserve threshold, special risk disposal meeting is required. For agile design modules, adjust sprint backlog, balance resource allocation of iterative tasks[22,23].

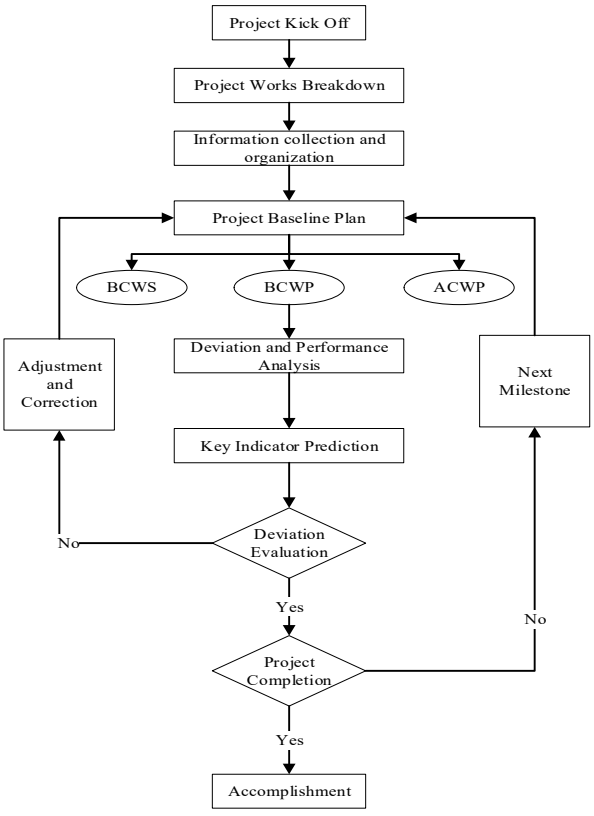


Figure 2. Control flow chart of schedule and cost

4. Case Study of Cost-Schedule Control Using the Improved Earned Value Model in a Wind Turbine Blade Development Project

4.1 Project Overview

This project takes the development of a hundred-meter-class wind turbine blade as a research object. The development of ultra-large wind turbine blades is featured by high technical difficulty and complex manufacturing processes, involving multiple new structures, novel materials, innovative processes and newly-developed molds. The project implementation covers multiple disciplines, including aerodynamics, material science, structural design, manufacturing technology and equipment development. Undertaken by an internal project team, the project sets the following development objectives: a 10-month development cycle, blade weight no more than 45 t, and direct material cost no higher than 1.5 million CNY. Fixed-asset investment is mainly used for molds and supporting tooling equipment.

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4.2 Project Overview

4.2.1 Work Breakdown Structure (WBS)

Project tasks are decomposed at the initial stage. The overall project is divided into five modules, namely five sub-items including aerodynamic design, structural design, manufacturing process, equipment development and trial production, and each sub-item is further subdivided in detail.

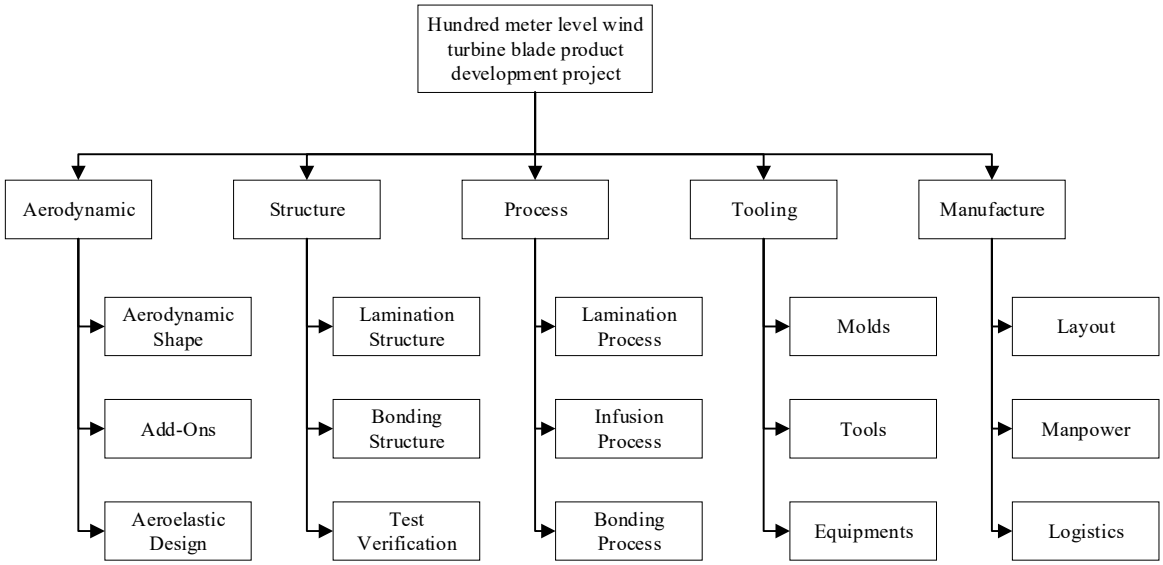


Figure 3. Diagram of project break down structure

The five modules are further decomposed into twelve level-2 work packages (Figure 3), and each work package is assigned a unique WBS code, a responsible department, a budget quota and an explicit acceptance criterion. This coding scheme is what later allows every deviation to be traced back to a single owner rather than to an aggregated sub-project.

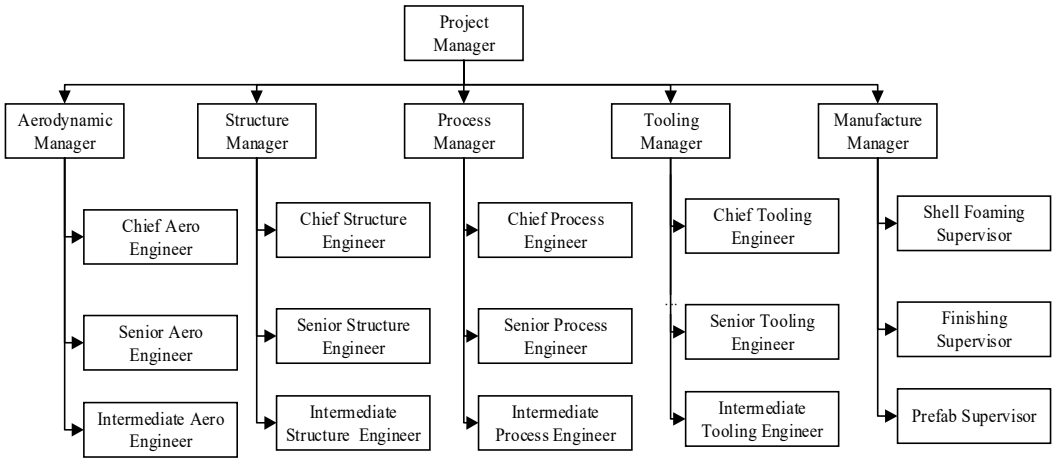


Figure 4. Diagram of project organization

4.2.2 Overall Schedule Plan and Total Budget

According to the delivery timeline required by the customer, the project implementation period is 10 months. A mandatory Finish-to-Start (FS) logical relationship is defined between aerodynamic design and mold development, whereas other tasks can be arranged in serial or parallel modes for work optimization. Therefore, aerodynamic development is carried out first, followed by structural development. The process design, equipment development and trial production are implemented in parallel to shorten the construction cycle and satisfy customer requirements. Based on the work

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schedule and the precedence relationships among various tasks, the Gantt chart and working network diagram of the project are obtained.

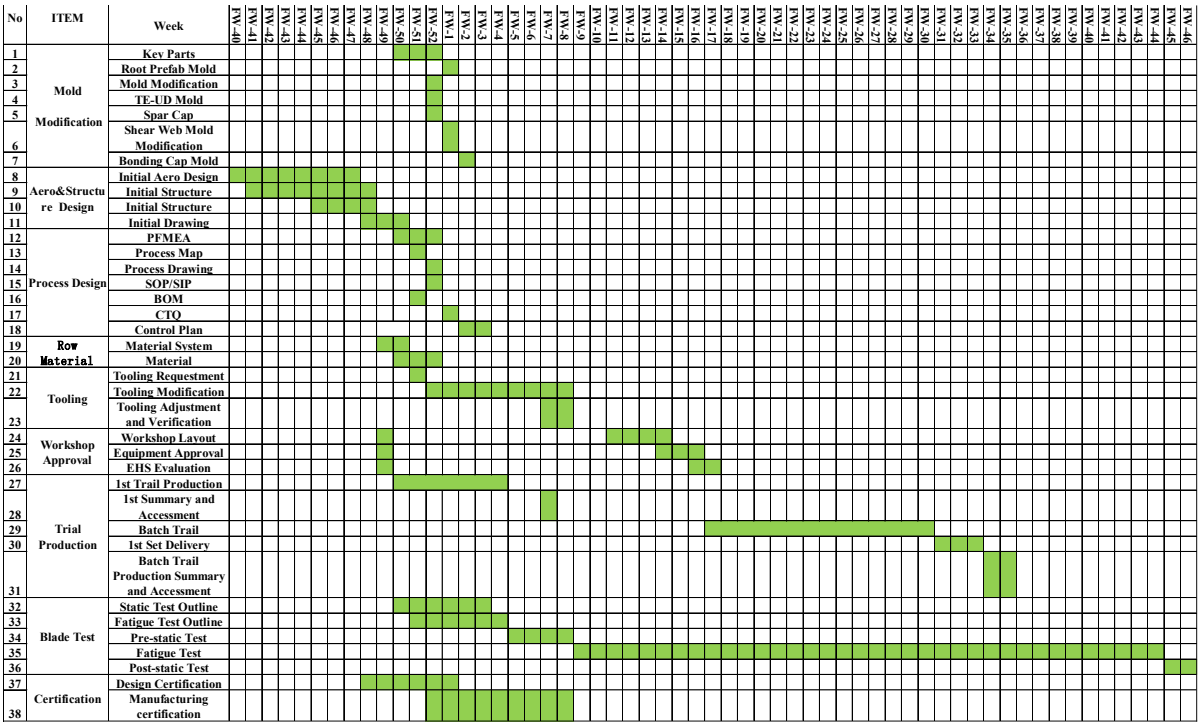


Figure 5. Project schedule network diagram

Project costs are calculated item-by-item for each work package derived from the Work Breakdown Structure (WBS), and then aggregated to obtain the total project budget. The costs of molds and tooling-related equipment are determined through market inquiry, in which transportation and installation expenses are converted according to corresponding percentage ratios.

Table 1. Cost estimates of the project sub-items

Numble	Expense Item	Amount (10 000 CNY)
1	Equipment cost	580
2	Mould cost	620
3	Material cost	75
4	Testing cost	180
5	Processing cost	15
6	Travel expense	20
7	Certification fee	115
8	Personnel cost	70
9	Others (depreciation, amortization, etc.)	25
10	Technical contingency reserve	85
11	Price contingency reserve	65
	Total	1850

4.2.3 Project Inspection Baseline

Product trial production involves mold procurement and installation, tooling commissioning and prototype manufacturing, featuring multi-threaded tasks and a tight development schedule. Reasonable inspection points should therefore be established in this phase. The inspection points

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consist of periodic checkpoints at predefined key nodes and random sampling checkpoints. Periodic inspections are performed once every month from project initiation to completion, with a total of ten inspection points set for the whole project.

The total duration and total budget cost after this phase are determined, and the budget cost is allocated evenly over time by dividing the total budget by the total project duration. The budget at each inspection point is calculated as the product of the unit-time budget and the corresponding time of the inspection point.

Taking the trial-production phase of this project as an example, the BCWS of prototype manufacturing is calculated. The budgeted cost of the trial-production scope is 14.15 million CNY, and the prototype-manufacturing phase has a 19-week baseline duration. The project was launched in September 2025 and is scheduled on the basis of 30 working days per month. By the 2026/5/30 inspection point, three weeks of the 19-week prototype-manufacturing phase had been completed.

Completion ratio at the 2026/5/30 checkpoint: $3 \div 19 = 15.79\ \%$

BCWS of prototype manufacturing at this checkpoint: $15.79\ \% \times 14.15$ million CNY = 2.2343 million CNY

At each monthly inspection point, this case additionally executes dynamic critical-path re-identification, separately calculates BCWS(CP), BCWP(CP), ACWP(CP) for criticalpath work packages, and introduces earned schedule indicators ES、SPI(t) to make up for the defect that SPI based on monetary weight may underestimate time delay risk[15]. For work packages with quality gate pending, partial BCWP will be deducted even if physical work is finished, to avoid overestimation of real progress[21]. For agile aerodynamic design sprint packages, sprint review is carried out synchronously at monthly inspection nodes, and the completed story points of each sprint are converted into BCWP after passing quality acceptance[23]. Meanwhile, Monte-Carlo stochastic simulation is triggered at each inspection node to update the probability distribution of EAC and completion time[26].

Table 2. Cost estimates of the project sub-items

NO.	Inspection Node	Actual Monthly Cost (10 000 CNY)	Planned Monthly Cost (10 000 CNY)	BCWP (10 000 CNY)	ES(weeks)	SPIt	P50EAC(10 000 CNY)	P80EAC(10 000 CNY)
1	2025/9/30	73.33	75.63	74.12	4.1	1.02	1842	1886
2	2025/10/30	138.90	137.93	136.41	7.8	0.97	1856	1912
3	2025/11/30	185.30	133.66	142.08	9.2	0.84	1894	1975
4	2025/12/30	123.80	158.76	147.24	10.4	0.87	1901	1988
5	2026/1/30	100.11	88.79	84.35	11.1	0.79	1933	2034
6	2026/2/28	203.70	193.01	176.20	12.3	0.72	1967	2086
7	2026/3/30	115.30	111.23	102.13	13.1	0.68	1992	2127
8	2026/4/30	210.80	187.99	167.31	13.7	0.72	2028	2173
9	2026/5/30	259.77	221.85	221.97	14.2	0.75	2064	2221
10	2026/6/30	87.40	106.15	94.23	24.7	1.03	1812	1847

The 2026/5/30 checkpoint shows that the monetary-dimension SPI is 1.007 (Table 3), while the time-dimension SPI(t) is 0.75 (Table 2), which reveals a substantial actual schedule delay hidden behind a superficially favourable cost-weighted progress performance. The gap between the two indicators verifies the systematic bias of the traditional cost-weighted SPI: a monetary-based SPI may mask real-world time-delay risk. At the same time, stochastic simulation yields a P80-EAC of 22.21 million CNY at this node, i.e. 20.1 % above the 18.50 million CNY budget at completion, which indicates

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that under the 80 % confidence level the project faces a significant cost-overrun risk if no corrective intervention is implemented [27].

4.3 Project Performance Analysis

The completed workload and planned budget (assigned budget cost) serve as the basic earned value parameters. Project managers collect statistical data of completed tasks at each inspection point. Data are recorded on a daily basis and summarized at the end of each month to obtain authentic and representative earned value results.

The earned value of each work package is calculated as the product of the completed workload and its corresponding budget divided by inspection nodes. The overall earned value at a given inspection point can be acquired by summing up the earned value results of all individual work packages. The actual project cost is obtained by summarizing financial expenditure records and onsite implementation logs.

In this case, work packages failing test and quality acceptance are not counted into BCWP even if finished physically; rework consumption is separately counted in corresponding secondary sub-project actual cost statistics, avoiding over evaluating real project progress by invalid completed workload[21]. For agile sprint packages of aerodynamic design, BCWP is only accumulated after sprint deliverables pass quality gate check; unaccepted iterative outputs are not incorporated into earned value statistics[23].

4.3.1 Monthly Cost and Schedule Deviation at May-30 Checkpoint

According to the level-2 earned-value statistics of Table 3 for May, the aggregated indicators of the trial-production scope are:

Cost deviation: CV = BCWP - ACWP = 15×10^4 CNY = 150,000 CNY

Cost performance index: CPI = BCWP/ACWP = 1.01. CV > 0 and CPI > 1, which means that the trial-production scope is marginally under budget as measured by aggregate monetary indicators.

Schedule deviation: SV = BCWP - BCWS = 10×10^4 CNY = 100,000 CNY

Schedule performance index: SPI = BCWP/BCWS = 1.007. SV > 0 and SPI > 1, showing that the aggregated monetary whole-project performance is marginally ahead of baseline plan.

Nevertheless, critical-path exclusive indicators reveal hidden risks behind favorable aggregated metrics:

BCWS(CP) = 10.42 million CNY, BCWP(CP) = 9.40 million CNY, ACWP(CP) = 9.45 million CNY, CPI(CP) = 0.995, SPI(CP) = 0.902.

Although the aggregated SPI is close to unity, SPI(CP) = 0.902 < 1 indicates an obvious schedule lag on the critical path. The delay originates mainly from the online resin infusion equipment procurement and several mould design work packages, both of which sit on the critical path [14]. Non-critical-path work packages' good performance masks this critical-path delay risk.

The earned-schedule calculation is performed on the time base of the trial-production phase, whose baseline duration is 19 weeks: at the May inspection node AT = 19 weeks and ES = 14.2 weeks, hence SPI(t) = ES/AT = 0.747, i.e. about 4.8 weeks of earned schedule are missing relative to the elapsed time. The time-dimension indicator shows a far more severe schedule-delay risk than the monetary-weighted aggregate SPI, which reminds managers not to underestimate time pressure on the strength of aggregate monetary indicators alone [15]. Monte-Carlo simulation at this node shows that the probability of completing within the original 10-month baseline is only 11.3 %, which triggers a level-one risk warning [26].

Note that a deterministic EAC computed with the aggregate CPI would give EAC = ACWP + (BAC - BCWP)/CPI = 1410 + (1850 - 1425)/1.01 = 18.31 million CNY, i.e. a forecast below the 18.50 million CNY baseline. This apparently on-budget outlook is precisely the illusion that the improved model is designed to eliminate: the aggregate CPI is inflated by cost savings on mould work packages (CPI = 1.05-1.17), whereas the remaining scope is concentrated on critical-path procurement and trial

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production, where CPI(CP) = 0.995 and unresolved material-price risk dominates. Once these factors are propagated through Monte-Carlo simulation, the P80-EAC rises to 22.21 million CNY, which is the value used in the forecasts below.

4.3.2 Calculation of Forecasting Indicators

Estimated at completion (EAC):

EAC = ACWP + (BAC - BCWP)/CPI, where BAC (Budget at Completion) denotes the total project budget and CPI is the cumulative cost performance index [13].

Empirical time prediction formula adopted in this case:

EAC(t) = AT + (OD - ES)/SPI(t). Here, EAC(t) is the forecast project duration, AT (Actual Time) is the actual elapsed duration, OD (Original Duration) is the planned duration, and ES and SPI(t) are the earned schedule and its index defined in Section 1.1.

Considering the characteristics of R&D projects with rework risk, this case adopts a three-scheme prediction:

Scheme 1 (deterministic, no corrective action, current performance maintained): forecast duration +21 days and additional budget 3.71 million CNY, which coincides with the P80-EAC of 22.21 million CNY.

Scheme 2 (deterministic, corrective measures implemented, with the cost index benchmarked against a similar historical project, CPIref = 0.97): forecast duration +7 days and additional budget 1.126 million CNY.

Scheme 3 (stochastic Monte-Carlo simulation, corrective-measure scenario): the P50 and P80 forecasts of the additional budget are 0.68 and 1.36 million CNY respectively, which provides a probability-based reference for decision making [26,27].

Substituting the measured data of May into the above formulas, the forecast project duration is 21 days longer than the baseline schedule and an additional budget of 3.71 million CNY is required if no intervention is made. Accordingly, root causes were identified and targeted corrective measures were implemented, as described in Sections 3.4 and 3.5.

4.4 Deviation Cause Analysis

Table 3. Level-2 earned value of the project in May

No.	Project Phase	Subitem	BCWS	BCWP	ACWP	CV	SV	CPI	SPI
1	Mold Design	Root Prefab Mold	30	30	30	0	0	1	1
2	Mold Design	Main Mold	420	420	400	20	0	1.05	1
3	Mold Design	TE-UD Mold	52	50	45	5	-2	1.11	0.96
4	Mold Design	Spar Cap Mold	67	67	60	7	0	1.12	1.00
5	Mold Design	Web Mold	36	35	30	5	-1	1.17	0.97
6	Mold Design	Bonding cap Mold	15	10	5	5	-5	2.00	0.67
7	Tooling Procurement	Online Resin Infusion Equipment Procurement	388	385	419	-34	-3	0.92	0.99
8	Tooling Procurement	Adhesive Mixing Machine Procurement	192	192	192	0	0	1.00	1.00
9	Material Preparation	Material Cost	75	75	89	-14	0	0.84	1.00
10	Product Prototyping	First Blade	10	13	10	3	3	1.30	1.30
11	Product Prototyping	First Set	30	38	30	8	8	1.27	1.27
12	Product Prototyping	Small Batch	100	110	100	10	10	1.10	1.10
13	Total	/	1415	1425	1410	15	10	1.01	1.01

With the adoption of the secondary earned value method, the cost-schedule deviations and performance indicators of each subtask on the critical path are calculated. Abnormal subitems during

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project implementation can be identified, so that precise problem spotting and targeted project management can be realized for cost saving.

To explore the root causes of cost overrun and schedule delay in May, the secondary earned value method is applied to analyze each work package. Specific events that may affect project cost and schedule are identified, and corresponding adjustments are carried out.

The earned-value analysis table indicates that the online infusion equipment suffers from cost overrun and schedule lag, leading to unsatisfactory task progress. Although the main mould achieves cost saving, its schedule falls behind the baseline. Overall, the whole project is delayed. According to the analysis of tasks on the critical path using the secondary earned value method, the project will face total duration extension and monthly cost overrun without proper adjustment and intervention.

The cost-schedule deviation causes of the non-standard and standard equipment work packages, which suffer from severe cost overrun and poor performance, are analysed below, and the main reasons are summarised as follows:

(1) Seasonal price increase occurred for raw materials consumed in the project due to the long development cycle.

(2) Labor shortage took place. Additional wages had to be offered to attract more operators during product manufacturing.

(3) Rework and repair were required for trial-produced components. For instance, secondary dimension adjustment of the shear web not only delayed the progress but also raised costs. Secondary procurement of raw materials was required, which further increased rework expenses.

(4) The delivery of non-standard equipment to the factory was delayed due to transportation issues. Some equipment was supplied later than the scheduled delivery date, resulting in idle waiting of on-site teams.

(5) Processes including component fabrication, skin manufacturing, post-treatment, mould assembly, commissioning and modification should have been arranged in a staggered manner to make full use of time windows. Nevertheless, poor coordination and communication from the trialproduction side led to discontinuous connection between working procedures and subsequent schedule delay. In addition, high turnover of temporary workers from subcontractors adversely affected normal project execution.

4.5 Control Measures and Effect Verification

To ensure that the overall project schedule and cost are consistent with the baseline plan, the secondary earned value method is adopted to analyze project cost and schedule deviations, identify the root causes of cost overrun and schedule delay, and formulate the following targeted control measures.

(1) Organizational management measures: During resource allocation, the project team strictly reviews the material requisition plan and equipment plan submitted by section foremen, and verifies material consumption onsite. Communication with the supply chain and customers is strengthened. Special docking communication is arranged for materials procured by customers, and dedicated personnel are assigned for followup, so as to prevent schedule delays caused by late material delivery.

(2) Technical management measures: The project team optimizes process routes and carries out parallel operations. Clear standards for material acceptance, quality acceptance and production process are formulated. Unqualified materials are prohibited from being put into use, and unqualified construction shall be reworked or repaired in a timely manner. The technical team provides fulltime onsite guidance during trial production to handle deviations as soon as they occur.

(3) Cost management measures: Budget overrun in the construction process is controlled promptly once budget deviations are identified. Nodes with severe budget overrun are analyzed emphatically, and resources on non-critical paths are balanced to remedy budget deviations. Appropriate

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adjustments are made for key budgets and large-scale equipment prices, and the rental period is confirmed in a timely manner.

(4) Team management measures: Incentive contracts concerning quality and schedule are signed with production teams to improve their sense of responsibility and initiative. Reasonable human-oriented care is provided for staff during summer production, including heatstroke prevention and cooling arrangements, so as to boost staff motivation and working efficiency.

With the above analysis and reasonable control measures, the trial-production task proceeded as scheduled. The actual project duration was ultimately 11 working days shorter than the baseline schedule, and a cost saving of 590,000 CNY was achieved, i.e. a final project cost of 17.91 million CNY against the 18.50 million CNY baseline. The application of the improved earned value model therefore exerted a clearly beneficial effect on schedule and cost control throughout the trial-production process.

4.6 Model Validation and Discussion

The contribution of the proposed model lies not in producing more indicators, but in producing earlier and less biased warnings. Three observations from the case support this claim.

First, the critical-path filter located the source of the delay correctly. At the May checkpoint the aggregated indicators (CPI = 1.01, SPI = 1.007) suggested that the project was essentially on track, whereas the layered indicators pointed to the online resin infusion equipment procurement (CPI = 0.92, ACWP 0.34 million CNY above BCWP) and several mould design packages (SPI = 0.96-0.97). These are exactly the work packages that later required expediting and rework, as documented in Section 3.4. The layered decomposition therefore removed the masking effect that the aggregate indicators would otherwise have produced.

Second, the earned-schedule and probabilistic layers converted a qualitative concern into a quantified decision threshold. A deterministic EAC computed with the aggregate CPI (18.31 million CNY) would have suggested a comfortable position, whereas the risk-adjusted P80-EAC (22.21 million CNY), together with an 11.3 % on-time probability, defined a reserve requirement of 3.71 million CNY and triggered the level-one warning well before the delivery milestone. The corrective measures described in Section 3.5 were authorised on this basis.

Third, the realised outcome is consistent with the direction of the intervention. After the measures were implemented the project closed 11 working days ahead of the baseline at 17.91 million CNY, i.e. 0.59 million CNY below the budget at completion. This outcome lies below the P50 of Scheme 3 (0.68 million CNY of additional budget), which should not be read as evidence that the simulation was pessimistic: the simulation was conditioned on the performance distribution observed before intervention, and the purpose of the intervention was precisely to shift that distribution. The gap between the two is therefore a measure of the management effect rather than of forecast error.

Two limitations must nevertheless be acknowledged. First, the validation is based on a single hundred-metre-class blade project, so the improvement in forecast accuracy cannot yet be generalised; a multi-project database is required before statistically robust conclusions can be drawn. Second, the quality-gate deduction applied to BCWP still relies on expert judgement rather than on a formal quality index, and the Monte-Carlo input distributions were estimated from a limited number of historical work packages [17,19].

5. Conclusion

In the development process of wind turbine blade products, the earned value method can be adopted to analyze and control project cost and schedule, enabling quantitative evaluation at each project milestone. In this paper, a comprehensive schedule and cost control model is established for wind turbine blade development projects to obtain the overall optimal control results. The adopted critical path planning and secondary earned value analysis are more consistent with actual engineering conditions and deliver superior control performance.

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Based on the earned value management theory, this study explores refined project management strategies. Meanwhile, the case study elaborates the critical path arrangement and integrated cost-schedule control scheme, enabling project managers to analyze and resolve engineering problems in a more targeted and scientific manner during product development. Effective project management achieves dual benefits of cost saving and schedule shortening. This research lays a solid foundation for improving blade product quality, realizing rapid and qualified product delivery, and optimizing the manufacturing efficiency of wind turbine blades.

Quantitatively, at the May checkpoint the aggregate indicators (CPI = 1.01, SPI = 1.007) suggested that the project was on schedule and slightly under budget, whereas the critical-path index SPI(CP) = 0.902, the earned-schedule index SPI(t) = 0.747 and a P80-EAC of 22.21 million CNY (20.1 % above the budget at completion) revealed an exposure that the traditional aggregated model could not detect. The corrective measures derived from this diagnosis allowed the project to close 11 working days ahead of the baseline with a cost saving of 0.59 million CNY, which confirms that the value of the model lies in advancing the intervention window rather than in adding indicators.

The main limitation of this study is its reliance on a single case, which restricts the generalisation of the accuracy improvement, and the quality deduction applied to BCWP is still judgement-based rather than index-based. Future work will extend the model to a multi-project blade database and replace the expert judgement with a quantitative quality index, so that the earned-value baseline and the quality baseline can be integrated more rigorously.

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