Analysis and Exploration of a Diversified Collaborative Maintenance Scheme for Medical Equipment in Tertiary Grade A Hospitals Based on the SPO Model

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Abstract: With the continuous expansion of medical equipment assets in large tertiary grade A hospitals, the contradiction between cost, efficiency, and technical depth in the traditional single maintenance mode has become increasingly prominent, necessitating a systematic governance framework to guide the optimal allocation of maintenance resources. Based on Donabedian's "Structure-Process-Outcome" (SPO) three-dimensional quality evaluation model, this study explores the construction of a diversified collaborative maintenance framework for medical equipment applicable to large medical institutions, promoting the transformation of maintenance governance from "single-mode dependence" to "hierarchical and classified collaboration." Through a systematic literature review and international comparative analysis, a multidimensional comparative framework for three mainstream maintenance modes was established; based on longitudinal data from a tertiary grade A hospital from 2023 to 2025, the SPO model was applied for structural diagnosis. The hospital's three-year data showed that the total value of equipment assets increased by 21.3% (2.82 billion yuan→3.42 billion yuan), while the number of engineers increased by only 3 (14→17), with the ratio as low as 1:1123 (international benchmark: 1:250–300); annual maintenance expenditure increased by 8.8% (57.03 million yuan→62.04 million yuan), among which OEM maintenance accounted for continuously >60%, and the book COSR remained at 1.8%–2.0%, but indirect costs such as labor costs were not included. SPO diagnosis revealed progressive deficiencies in the current governance, characterized by "insufficient structural resources—incomplete process development—concentration of outcome modes." This paper proposes a four-level hierarchical governance structure: Level A core assets adopt "OEM primary service + daily in-hospital inspection"; Level B critical equipment adopts "in-hospital preventive maintenance as the main approach + OEM technical support for major failures"; Level C general equipment adopts "in-hospital independent maintenance + audited third-party repair"; Level D low-value equipment adopts "replacement instead of repair." This framework provides a theoretical basis and practical pathway for large medical institutions to overcome dependence on OEMs and build a sustainable maintenance ecosystem.

***Keywords*:** medical equipment maintenance; SPO model; tertiary grade A hospital; diversified collaborative maintenance; OEM maintenance; cost-to-service ratio

1. Introduction

1.1 Research Background

In China's hospital grading management system, tertiary grade A hospitals, as the highest level, have experienced exponential growth in the quantity, variety, and technical complexity of medical equipment. The value of a single high-end imaging system, surgical robot, or life-support device often exceeds several million yuan, and the reliability management of such equipment throughout its entire life cycle is directly related to medical quality and patient safety.

The global medical equipment maintenance market is undergoing rapid expansion. According to Mordor Intelligence's forecast, the global market size will increase from USD 59.29 billion in 2025 to USD 108.17 billion in 2031, with a compound annual growth rate of 10.54% [1]. Multi-vendor service contracts are expanding at a rate of 11.85%, while independent service organizations (ISOs) are eroding OEM market share at a rate of 13.7% [1], and preventive maintenance accounted for 40.56% of revenue in 2025. These trends indicate that the global maintenance market is evolving from an OEM-dominated structure toward an ecosystem characterized by multiple suppliers and collaborative maintenance modes.

However, the maintenance management of many tertiary grade A hospitals in China remains predominantly based on a single mode. The three mainstream modes each have their own advantages and disadvantages: in-hospital teams respond rapidly and are familiar with hospital conditions, but are technically constrained when dealing with sophisticated and high-end equipment; OEM services are authoritative and reliable but costly; third-party services are highly price-competitive and flexible across brands, but concerns remain regarding quality consistency and data security. The core research gap lies in the lack of an integrative theoretical framework to systematically coordinate the aforementioned heterogeneous maintenance

resources [3].

1.2 Theoretical Framework: SPO Three-Dimensional Quality Evaluation Model

In 1966, Avedis Donabedian proposed the "Structure-Process-Outcome" (SPO) model as a comprehensive paradigm for healthcare quality evaluation [5]. It is operationalized and applied to medical equipment maintenance management as follows:

Structure dimension (Structure): This dimension involves the organizational structure of maintenance (BMET staffing ratio, supplier management functions), resource allocation (budget allocation, spare parts inventory), and institutional standards and regulations (SLA standards, qualification review procedures), answering the question, "What resources do we have?"

Process dimension (Process): This dimension focuses on the standardization of maintenance activities (PM completion rate), timeliness (response time, repair time), and quality control (repeat failure rate), answering the question, "How do we do it?"

Outcome dimension (Outcome): This dimension focuses on equipment operational quality (availability, MTBF), economic benefits (tiered COSR), and patient safety (equipment-related adverse event rate), answering the question, "How well are we doing?"

The core value of the SPO model lies in revealing the causal chain among the three dimensions: structural deficiencies → process barriers → outcome deterioration, thereby providing theoretical support for the transformation of equipment maintenance management from "experience-driven" to "evidence-driven."

1.3 Regulatory Background and International Standards

China's Measures for the Supervision and Administration of the Quality of Medical Device Use (2015) and Measures for the Administration of Clinical Use of Medical Devices (2021) require medical institutions to establish comprehensive maintenance systems while explicitly allowing multi-source maintenance arrangements [7-8]. The ISO 13485 medical device quality management system, the IEC 60601 safety standard for medical electrical equipment, and the European Union Medical Device Regulation (MDR), among other international standards, jointly constitute the compliance framework for global medical equipment maintenance. These standards not only specify technical requirements for maintenance but also emphasize risk-based quality management approaches, providing regulatory support for the international applicability of the framework proposed in this study.

1.4 Research Objectives

This study aims to operationalize the SPO model and, by combining literature research with current status data from a tertiary grade A hospital from 2023 to 2025, explore the design of a multi-mode collaborative maintenance framework and answer the following questions: (1) For which categories of equipment do different maintenance modes have comparative advantages? (2) What structural deficiencies exist in the current maintenance governance of large tertiary grade A hospitals? (3) How can an operation and maintenance framework characterized by "the coexistence of multiple maintenance modes and hierarchical and classified collaborative governance" be established?

2. Multidimensional Comparative Analysis of Three Maintenance Implementation Schemes

Based on international literature and practical experience in the management of tertiary grade A hospitals, this section systematically compares three mainstream maintenance modes across six key dimensions.

2.1 Independent Maintenance by the In-Hospital Medical Equipment Department

The in-hospital maintenance department is composed of biomedical engineering technicians (BMETs). Its greatest advantage lies in geographical proximity, enabling it to respond to clinical calls within minutes. The team is embedded in the hospital's organizational structure and has an in-depth understanding of the equipment inventory and clinical workflows, while closed-loop data management ensures information security. However, when dealing with high-end imaging equipment, the team has insufficient technical expertise, and staffing ratios are constrained by authorized staffing levels. At the process level, the team is proficient in first-level troubleshooting and routine preventive maintenance (PM), but quality is highly dependent on individual experience. At the outcome level, the advantages in response speed and data security are evident, but complex failures may prolong equipment downtime due to repeated trial and error. Economically, international data show that the COSR of in-hospital maintenance is approximately 4%–6% [4].

2.2 Original Equipment Manufacturer (OEM) Maintenance

OEM service providers possess authoritative technical expertise, proprietary diagnostic software, and guaranteed access to original manufacturer parts, and the quality outcomes of complex repairs are generally optimal. However, the structural limitation lies in vendor lock-in: each manufacturer can only service its own brand, and contract management costs increase significantly in multi-brand environments. At the process level, OEM maintenance follows standardized procedures with strict quality control, but scheduling is constrained by the availability of regional technicians, resulting in insufficient response flexibility. At the outcome level, quality is reliable, but the economic outcome is unfavorable, particularly for equipment beyond the warranty period—OEMs still hold a 52.13% share of the international market, while ISOs are rapidly catching up at a growth rate of 13.7% [1]. A longitudinal empirical study by Miguel-Cruz et al. of 590 repair transactions across 20 hospitals in Colombia found that the OEM governance structure performed better in private hospitals than in public institutions, suggesting that resource constraints affect the feasibility of manufacturer-dependent maintenance models [9].

2.3 Maintenance by Third-Party Independent Service Organizations (ISOs)

The core advantages of third-party ISOs lie in cross-brand technical capabilities and competitive pricing (typically 20%–30% lower than OEMs). With the advancement of global "right-to-repair" legislation, ISOs are gaining greater legal support for accessing original manufacturer diagnostic tools. However, structural risks are also significant: technical capabilities vary widely, the sources of parts are uncertain, and vulnerabilities exist in equipment access data security. At the process level, for mature technologies, repair quality can reach levels comparable to that of OEMs, but the degree of standardization varies considerably, requiring rigorous supplier qualification review and performance monitoring. At the outcome level, the cost advantage is prominent, but uncertainty is relatively high.

2.4 Comprehensive Comparison: The Necessity of Collaborative Governance

Table 1 summarizes the above comparative analysis. No single mode is superior across all dimensions. In-hospital maintenance excels in response speed and data security but is limited in technical depth. OEM services ensure quality and technical authority but are costly and reduce institutional autonomy. Third-party providers offer flexibility and cost-effectiveness but introduce quality and security risks.

Table 1. Multidimensional Comparison of Three Medical Equipment Maintenance Modes

Evaluation Dimension	Independent Maintenance by the In-Hospital Medical Equipment Department	Original Equipment Manufacturer (OEM)	Maintenance Third-Party Independent Service Organization (ISO)
Response Efficiency	Excellent; immediate on-site response	Moderate; constrained by regional scheduling	Variable; dependent on service provider network density
Technical Capability	Limited; constrained by training and tools	Excellent; proprietary knowledge and original manufacturer parts	Uneven; requires strict qualification review
Cost Structure	High fixed costs (salaries, training, equipment)	High variable costs (premium service fees)	Moderate variable costs; competitive pricing
Quality Assurance	Unstable; dependent on individual capabilities	High; standardized OEM procedures	Uncertain; requires strong supplier oversight
Data Security	Optimal; closed-loop in-hospital management	Manageable; requires contractual safeguards	Higher risk; requires strict access control
Service Flexibility	High;adaptable to institutional needs	Low; limited by brand boundaries	High; cross-brand service capabilities

This comparative analysis supports the following core proposition: tertiary grade A hospitals need a governance framework that strategically allocates maintenance responsibilities according to different equipment categories rather than relying on any single mode.

3. Construction of a Diversified Collaborative Maintenance Framework Based on the SPO Model

Based on the above analysis, this paper proposes a theoretically robust and operationally feasible framework that integrates the SPO model with multi-mode collaborative maintenance governance, as shown in Figure 1. The framework comprises four interrelated components: hierarchical equipment classification, differentiated governance allocation, integrated process pathways, and outcome-based continuous improvement.

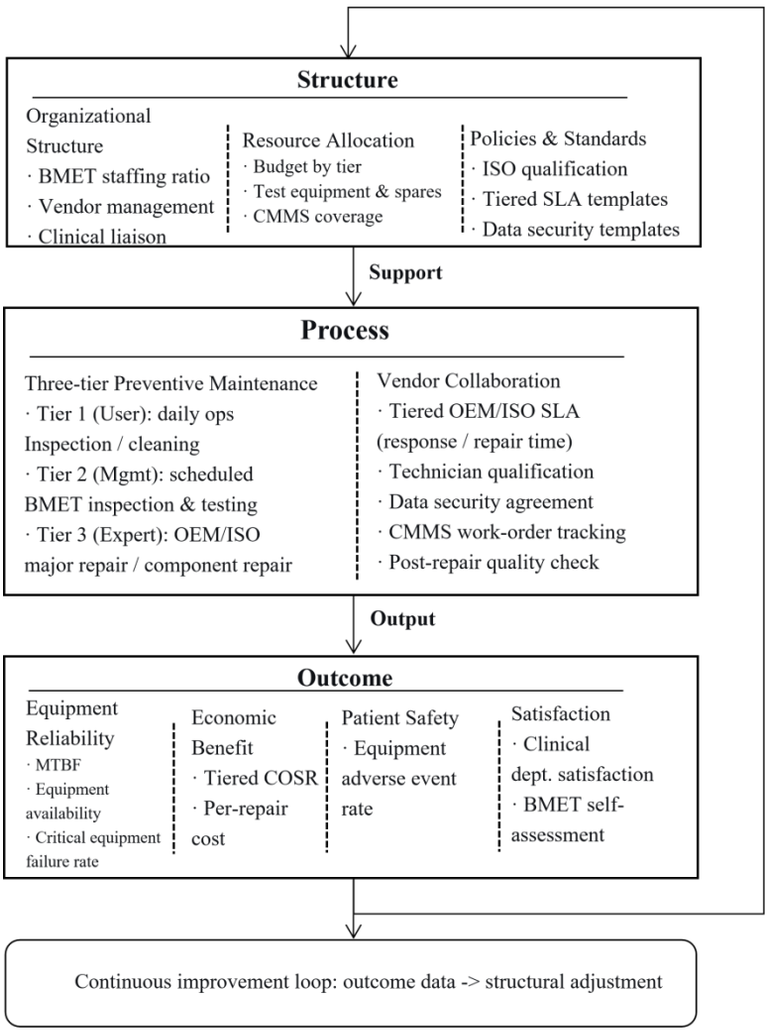

Figure 1. Application Framework of SPO Model in Equipment Maintenance Governance

3.1 Structural Component: Hierarchical Equipment Classification and Governance Allocation

The framework classifies medical equipment into four levels based on two axes (Figure 2), namely technical complexity and clinical criticality, and matches different equipment categories with optimal maintenance providers to avoid the "one-size-fits-all" governance dilemma.

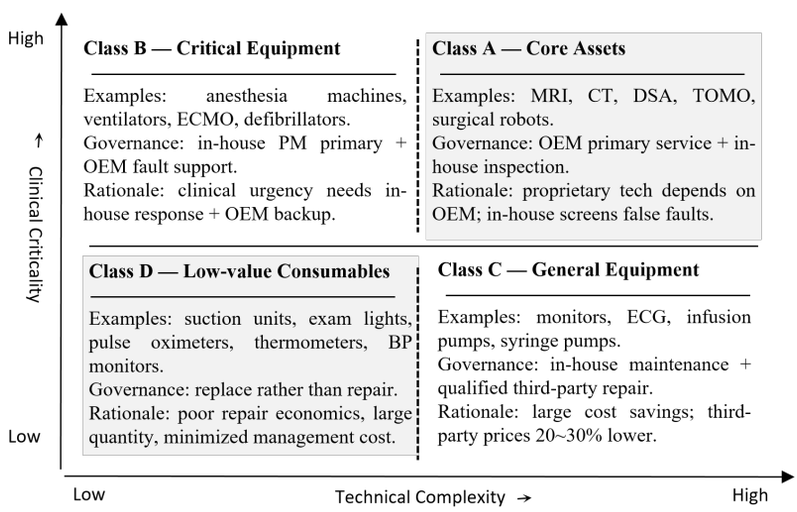

Figure 2. Hierarchical equipment classification and governance allocation matrix

The specific classification and governance strategies for each level are as follows:

Level A — Core Assets (High Complexity + High Criticality): Examples include MRI, CT, DSA, TOMO, linear accelerators, and surgical robots. The governance mode is OEM primary service + daily in-hospital inspection and first-level troubleshooting. Rationale: proprietary technologies require manufacturer expertise; the presence of in-hospital personnel ensures rapid triage and initial isolation, reducing unnecessary OEM on-site visits.

Level B — Critical Equipment (Moderate Complexity + High Criticality): Examples include anesthesia machines, ventilators, ECMO machines, cardiopulmonary bypass machines, and defibrillators. The governance mode is in-hospital preventive maintenance as the main approach + OEM technical support for major failures. Rationale: clinical urgency requires rapid response; mature technologies make in-hospital capabilities feasible; OEM services are retained for software upgrades, replacement of core components, and complex circuit board repairs.

Level C — General Equipment (Low Complexity + Moderate Criticality): Examples include patient monitors, electrocardiographs, infusion pumps, syringe pumps, and portable ultrasound systems. The governance mode is independent in-hospital maintenance + qualification-reviewed third-party repair. Rationale: competitive third-party procurement achieves cost-effectiveness without sacrificing basic reliability; the in-hospital team is responsible for preventive maintenance and simple fault repairs.

Level D — Low-Value Consumable Equipment (Low Complexity + Low Criticality): Examples include suction devices, examination lights, pulse oximeters, thermometers, and sphygmomanometers. The governance mode is replacement instead of repair. Rationale: minimizing management costs; repairs are often economically unjustifiable.

3.2 Process Component: Integrated Maintenance Pathways

3.2.1 Three-Level Preventive Maintenance Pathway

The framework establishes a three-level preventive maintenance system: (1) Level 1 (User Level)—clinical personnel perform daily operational checks, cleaning, and basic functional verification; (2) Level 2 (Management Level)—in-hospital BMETs perform regular inspections, safety testing, and consumable replacement; (3) Level 3 (Expert Level)—OEMs or qualified third-party experts perform major overhauls, software upgrades, and component-level repairs [12]. Each level has clearly defined procedures, documentation requirements, and escalation triggers.

Based on the three-level PM system, the framework further specifies a tiered response mechanism: Level 1 failures are resolved by clinical departments through telephone guidance or remote assistance; Level 2 failures are handled on site by in-hospital BMETs within 24 hours; Level 3 failures trigger the involvement of senior OEM or ISO engineers, with a response within 4 hours and on-site arrival within 24 hours. The tiered response mechanism is bidirectionally mapped to the A/B/C/D hierarchical equipment classification: Level 3 failures of Level A equipment require OEM intervention, while Level 3 failures of Level C equipment can be handled by ISOs.

3.2.2 Intelligent Maintenance Information System

The framework advocates the use of a computerized maintenance management system (CMMS) to achieve centralized management and dynamic updating of data on equipment inventories, repair records, maintenance schedules, failure analysis, and cost accounting. The system should have the following functions: full-process tracking of maintenance work orders; intelligent alerts for spare parts inventory; accumulation of a failure knowledge base; and automatic collection, comparison, and analysis of the costs of the three maintenance modes [13].

3.2.3 Supplier Coordination and Quality Assurance Procedures

For OEM and third-party cooperation, the framework specifies mandatory requirements: definition of SLAs for response times and resolution targets; verification of technician qualifications (original manufacturer training certificates or equivalent credentials); data security and patient confidentiality agreements; documentation of parts sources (the use of non-original refurbished parts for Level B and above equipment is prohibited); and post-repair quality verification by in-hospital engineers. All external maintenance activities must be entered into the CMMS to enable performance tracking.

3.3 Outcome Component: Quantitative Evaluation and Continuous Improvement

The outcome dimension establishes a balanced scorecard indicator system aligned with the SPO framework (Table 2).

Table 2. Equipment Maintenance Outcome Evaluation Indicator System Aligned with SPO Dimensions

SPO Dimension	Indicator Category	Specific Indicators
Structure	Organizational Capacity	BMET-to-equipment ratio; training hours per capita; spare parts inventory turnover rate;supplier contract coverage rate
	Resource Adequacy	Budget allocation for equipment at each level; availability of testing equipment; CMMS implementation coverage
Process	Preventive Maintenance	PM plan completion rate; ratio of PM to corrective maintenance; condition monitoring coverage
	Response Capability	Average response time; mean time to repair (MTTR); emergency call resolution rate
	Quality Control	Repeat failure rate within 30 days; post-repair verification pass rate; documentation completeness rate
Outcome	Equipment Reliability	Equipment availability/uptime; mean time between failures (MTBF); critical equipment failure rate
	Economic Benefits	Total maintenance cost for equipment at each level; cost per repair; maintenance cost as a proportion of equipment asset value (COSR)
	Stakeholder Satisfaction	Clinical department satisfaction score; BMET self-assessment of competence; supplier performance rating
	Patient Safety	Equipment-related adverse event rate; patient safety incidents attributable to equipment failures

4. Analysis and Observation of the Current Status (2023–2025)

This section relies on the asset and maintenance data of a tertiary grade A hospital in Shanghai, with 2,005 approved beds, from 2023 to 2025, and applies the SPO model to diagnose the current status, reveal structural problems in the current maintenance governance, and demonstrate the practical necessity of the diversified collaborative maintenance framework.

4.1 Changes in Equipment Asset Scale

Over the past three years, the total number of medical equipment in use at the hospital increased from 17,757 units in 2023 to 19,104 units in 2025, an increase of 7.6%; the total asset value increased from RMB 2.82 billion to RMB 3.42 billion, an increase of 21.3%; among these, the number of large medical equipment valued at ≥RMB 1 million increased from 475 units to 553 units, an increase of 16.4% (Table 3). The rapid increase in large equipment indicates a simultaneous rise in the technical threshold and potential risks of maintenance.

4.2 Analysis of Maintenance Expenditure Structure

With the expansion of the asset scale, the hospital's annual total maintenance expenditure increased from RMB 57.03 million in 2023 to RMB 62.04 million in 2025, an increase of 8.8%, which was lower than the growth rate of asset value. The hospital implements OEM services for large medical equipment, supplemented by daily in-hospital inspections. The in-hospital engineering team focuses on the independent repair of equipment such as infusion pumps, syringe pumps, patient monitors, and defibrillators, independently repairing approximately 970 units per year on average. In terms of expenditure structure, OEM maintenance expenditure consistently accounted for more than 60% (Table 3), indicating that the current maintenance mode remains dominated by OEM services. COSR decreased from 2.0% in 2023 to 1.8% in 2025, remaining at a relatively low level. However, it should be clarified that the statistical scope of maintenance expenditure here mainly covers external service fees and direct spare parts consumption, while indirect costs such as labor costs of in-hospital medical equipment engineers, training expenses, and fixed asset depreciation have not yet been fully allocated. If full-cost accounting is conducted according to internationally accepted practices, the actual COSR will increase significantly. Nevertheless, the absolute dominance of OEM maintenance clearly reveals the core problem of the current governance structure: in-hospital independent maintenance and third-party maintenance have not yet formed independent, quantifiable cost centers, and a diversified collaborative maintenance system has not yet been established.

Table 3. Changes in Medical Equipment Assets and Maintenance Expenditure Structure of a Tertiary Grade A Hospital, 2023–2025

Indicator	2023	2024	2025
Total medical equipment in use (units)	17757	19038	19104
Total value of medical equipment assets (RMB 100 million)	28.2	31.9	34.2
Large equipment valued at ≥RMB 1 million (units)	475	495	553
Medical equipment engineers (persons)	14	15	17
Annual total maintenance expenditure (RMB 10,000)	5703	5987	6204
Proportion of OEM maintenance expenditure	61.4%	63.5%	61.3%
Maintenance cost as a proportion of equipment asset value (COSR)	2.0%	1.9%	1.8%

4.3 Current Status of Personnel Allocation and Capabilities

From the structural dimension, the BMET-to-equipment ratio at the hospital is approximately 1:1123 (2025), far higher than the internationally accepted recommended standard of 1:250–300 [4]. This structural gap directly constrains the breadth of coverage and depth of in-hospital independent maintenance, forcing a large amount of medium- and low-complexity repair work that could otherwise be undertaken by the in-hospital team to rely on OEM support, thereby creating a vicious cycle of "OEM dependence → rising maintenance costs → constrained budgetary space → insufficient investment in in-hospital maintenance capabilities," fundamentally weakening the hospital's autonomy and sustainable development capacity in equipment maintenance.

4.4 Approach to Constructing a Diversified Collaborative Maintenance Structure

Based on the above analysis of the current status, the hospital's current maintenance governance is characterized by "three highs and three lows": high OEM dependence, rapid asset value growth, and high equipment technical complexity; low proportion of in-hospital independent maintenance, low participation of third-party maintenance, and low level of systematization of preventive maintenance. Based on the diagnosis using the SPO model, this paper proposes the following reform pathways: (1) At the structural level: gradually expand the in-hospital BMET team, establish third-party supplier management positions, and establish a multi-source maintenance budget allocation mechanism; (2) At the process level: deploy a CMMS to achieve full life-cycle data management, establish hierarchical and classified PM procedures, and formulate differentiated SLAs for OEMs and ISOs; (3) At the outcome level: establish a KPI system aligned with the SPO dimensions and incorporate COSR, equipment availability, clinical satisfaction, and other indicators into annual performance assessment.

5. Discussion

5.1 Interpretation of the Current Status and Theoretical Validation

The data from this hospital reveal the typical predicament of large tertiary grade A hospitals in China. Against the background of a 21.3% increase in total asset value, annual maintenance costs increased by only 8.8%, while COSR remained at the low level of 1.8%–2.0%, seemingly reflecting effective cost control. However, an in-depth analysis shows that OEM maintenance remains dominant, while in-hospital independent maintenance and third-party repair are almost absent from economic accounting. The essence of this "low-cost–high-dependence" model is the transfer of maintenance risks and technical autonomy to OEM suppliers, which may lead to the loss of bargaining power and the hollowing out of technical capabilities in the long term.

From the perspective of SPO theory, the hospital currently has obvious resource deficiencies at the structural level: insufficient personnel allocation, a single budget structure, and a lack of third-party management functions in the organizational structure; at the process level, there are problems such as insufficient systematization of preventive maintenance, incomplete CMMS coverage, and weak supplier performance supervision; at the outcome level, although the equipment availability rate is acceptable, such availability is achieved at the cost of high OEM expenditure rather than through sustainable performance resulting from optimized governance structures.

The global medical equipment maintenance market is undergoing a structural transformation from OEM dominance toward a multi-vendor ecosystem. Multi-vendor contracts are expanding at a compound annual growth rate of 11.85%, while ISOs are eroding OEM market share at a compound annual growth rate of 13.7% [1]. Hybrid collaboration models between in-house HTM teams and ISOs have been validated as effective strategies by multiple healthcare institutions [10-11]. The hospital's current single OEM-dependent model stands in sharp contrast to this global trend.

5.2 In-Depth Interpretation of the Concept of "Multiple Modes Coexisting"

The core theoretical contribution of this study lies in supporting a refined hierarchical governance structure, recognizing the heterogeneity of medical equipment portfolios and the impossibility of optimal maintenance through a single source in complex tertiary grade A hospitals.

For Level A core assets, OEM primary service remains irreplaceable. Cryogenic management of MRI, tube replacement of CT, and software upgrades of surgical robots all require proprietary technologies from manufacturers. However, daily inspections and first-level troubleshooting by in-hospital teams can significantly reduce unnecessary OEM on-site visits and decrease "false failure" calls. This "in-hospital front end, expert back end" model both ensures technical authority and improves response efficiency.

For Level B critical equipment, the model of in-hospital preventive maintenance as the main approach + OEM technical support for major failures achieves a balance between "clinical urgency" and "cost controllability." Failures of ventilators, defibrillators, ECMO machines, and other equipment directly affect patient safety, and the immediate response capability of

in-hospital teams is unmatched by OEMs.

For Level C general equipment, the model of in-hospital independent maintenance + third-party repair provides the greatest scope for cost optimization. International data show that ISOs have achieved service quality comparable to that of OEMs in areas such as patient monitoring and dialysis equipment, while costs are 20%–30% lower [14]. The hospital currently independently repairs approximately 970 units per year on average, demonstrating that the in-hospital team has the capability to handle Level C equipment. The introduction of qualified third-party ISOs can release out-of-warranty Level C equipment from OEM contracts, with the expected cost per repair reduced by 30%–45%.

For Level D low-value consumable equipment, replacement instead of repair is the most economical option. Such equipment is present in large quantities (accounting for more than 50% of the 19,104 units of equipment), and if maintenance resources are invested, the cost often exceeds the value of the equipment itself.

5.3 Conditions for the Generalizability of the Framework

Although the four-level hierarchical governance framework proposed in this study was developed based on case data, its application to other settings requires three prerequisites:

(1) Basic data for equipment classification: Medical institutions need to have complete equipment inventories (including brand, model, year of acquisition, and maintenance history) in order to implement the A/B/C/D four-level classification. (2) Maturity of the third-party ISO service market: The cost optimization of Level C equipment in the framework depends on qualified and reliable third-party service providers. In regions where the ISO market is underdeveloped, "enhancement of in-hospital team capabilities" may first be adopted as an alternative to "third-party introduction." (3) Baseline requirements for in-hospital BMET capabilities: The framework presupposes that the in-hospital team has the capability to independently repair Level C equipment. For institutions without such capabilities, it is recommended that Level C equipment be temporarily managed under the Level D mode while launching a specialized BMET training program.

The degree to which these conditions are differentially satisfied determines the specific implementation pathway of the framework, but does not affect the applicability of the framework itself as a "governance direction."

5.4 Limitations and Future Research Directions

The limitations of this study include: the data were obtained from a single institution, with no control group design; the calculation methodology for COSR differs from international standards; and the applicability of the framework to smaller hospitals or healthcare systems outside China requires further validation. Future research should prioritize: ① conducting controlled multicenter studies to establish causal efficacy; ② applying the Delphi method to refine indicator weights; ③ exploring the integration of predictive maintenance for highly critical equipment categories, using Internet of Things sensors and artificial intelligence algorithms to achieve early warnings 2–4 weeks before failures [15-16]; ④ conducting cost-effectiveness analyses to directly link maintenance investment with patient outcomes.

6. Conclusion

The maintenance of medical equipment in tertiary grade A hospitals has reached a turning point: the complexity of equipment portfolios, the sophistication of maintenance technologies, and the stringent regulatory requirements have rendered a single-mode maintenance governance approach insufficient. The structural transformation of the global maintenance market toward a multi-vendor ecosystem has further reinforced the necessity of diversified collaborative maintenance. Based on Donabedian's SPO quality paradigm, and combining literature research with data on the current status of a tertiary grade A hospital from 2023 to 2025, this study explored and proposed a multi-mode collaborative maintenance framework. The core innovation of the framework lies in its hierarchical governance structure, which strategically allocates maintenance responsibilities among in-hospital medical equipment engineers, OEM service organizations, and qualified third-party ISOs based on equipment technical complexity and clinical criticality.

Analysis of the hospital's current status showed that the total value of equipment assets was RMB 3.42 billion, with 19,104 medical equipment units in use, 17 medical equipment engineers (ratio of 1:1123), annual maintenance expenditure of RMB 62.04 million, an OEM expenditure proportion of 61.3%, and a COSR of 1.8%. These data reveal the typical predicament of large tertiary grade A hospitals, characterized by excessive dependence on OEMs, insufficient in-hospital independent maintenance capabilities, and inadequate participation of third-party repair providers. Based on the above diagnosis, this study advocates the formation of a diversified collaborative maintenance structure of "OEM primary service for core assets + daily in-hospital inspection and first-level troubleshooting; in-hospital preventive maintenance as the primary approach for critical equipment + OEM technical support for major failures; independent in-hospital maintenance for general equipment + third-party repair; replacement instead of repair for low-value consumable equipment."

The theoretical contribution of this study lies in using the SPO model as an analytical lens to demonstrate the rationality of hierarchical governance, that is, the selection of maintenance modes should be determined by equipment heterogeneity rather than by a single preference of managers. The future of medical equipment maintenance management does not lie in selecting a single optimal mode, but in constructing a collaborative governance ecosystem capable of dynamically adapting to equipment heterogeneity, technological evolution, and regulatory changes.

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