

Optimising Biomedical Equipment Maintenance Management: A Lifecycle Approach

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Background: Biomedical equipment management represents a major financial burden for healthcare institutions, yet many organisations still rely on reactive, corrective maintenance. **Objective:** This review systematically examines the economic and operational benefits of an integrated lifecycle approach to biomedical equipment management. **Methods:** A narrative literature review was conducted using PubMed, IEEE Xplore, and Scopus (2019–2023). Fifteen peer-reviewed studies met inclusion criteria. **Results:** Evidence indicates that proactive lifecycle management can reduce total cost of ownership (TCO) by an estimated 20–30% compared with reactive models, although exact figures vary by equipment type and institutional context. Predictive maintenance strategies are associated with downtime reductions of approximately 25% in selected high-value devices (e.g., medical imagers). However, these benefits require upfront investment in computerised maintenance management systems (CMMS) and staff training. **Conclusion:** Shifting from reactive to strategic lifecycle maintenance is a viable economic optimisation lever, with reported return on investment within three to five years. **Implications:** Hospital managers should integrate TCO analysis from the acquisition phase and adopt risk-based or predictive maintenance for critical assets.

Keywords:

Health Economics;
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Biomedical Equipment;
Total Cost of Ownership (TCO);
Organizational Efficiency.

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1. Introduction

Healthcare institutions face mounting economic pressures from ageing populations, technological innovation, and constrained public budgets, compelling administrators to scrutinise every operational expenditure. Among the largest and most underestimated cost centres is biomedical equipment management, which accounts for up to 15% of a typical hospital's capital budget, though the full cost of ownership extends far beyond the purchase invoice (Wang, Furst, Cohen, Keil, & Ridgway, 2020). For decades, the dominant approach has been reactive maintenance: equipment is operated until it fails, generating unpredictable downtime, expensive emergency repairs, and shortened equipment lifespans. Fennigkoh (2019) estimated that hospitals dependent on corrective maintenance may spend up to 40% more over a complete equipment lifecycle compared with institutions using structured preventive programmes. In response, a paradigm shift toward strategic lifecycle management (LCM) has emerged, aligning technical, clinical, and financial decisions across all asset phases, accelerated by technologies collectively described as "Biomed 4.0" (Hashemian & Bean, 2021). Despite growing advocacy for LCM, a significant gap remains between theoretical frameworks and actionable evidence, with commonly cited quantitative claims, such as "20–30% TCO reduction", often presented without qualification regarding equipment type, institutional context, or baseline maturity. This review therefore addresses the following central research question: What is the documented impact of an integrated lifecycle management approach on total cost of ownership, equipment downtime, and maintenance efficiency in healthcare institutions? Three subsidiary questions guide the analysis: (1) what percentage TCO reduction is associated with proactive management across different settings? (2) which maintenance strategies (preventive, risk-based, or predictive) yield the greatest improvements? and (3) what are the reported

implementation challenges and return on investment timelines? Based on the available literature, we hypothesise that institutions adopting strategic LCM report lower TCO and higher equipment availability than those relying predominantly on corrective maintenance.

2. Methods

This study is designed as a narrative literature review, selected because the research question addresses a broad, multidimensional domain (lifecycle management, maintenance strategies, economic outcomes) encompassing heterogeneous study types including case studies, quasi-experimental comparisons, technical guidelines, and expert consensus documents. Quantitative meta-analysis is infeasible because outcome measures (percentage reductions in TCO, downtime, maintenance labour hours) are reported using different denominators, time horizons, and equipment classifications across studies. Nevertheless, we adopted several features of systematic review methodology to enhance rigour: explicit search strategies, predefined inclusion and exclusion criteria, documented screening, and independent verification of all references. We conducted a comprehensive literature search across PubMed, IEEE Xplore, and Scopus for publications from January 2019 to December 2023, using the search string: ("lifecycle management" OR "life cycle management" OR "LCM" OR "total cost of ownership" OR "TCO") AND ("biomedical equipment" OR "medical device" OR "healthcare technology") AND ("maintenance" OR "predictive maintenance" OR "preventive maintenance" OR "risk-based maintenance"). In PubMed, we also applied the MeSH term "Equipment and Supplies, Hospital" where appropriate.

The screening process proceeded in three stages. Initial searches yielded 187 records; after duplicate removal, 133 unique records remained. Two authors independently screened titles and abstracts against inclusion criteria (peer-reviewed, English or French, hospital-based biomedical equipment, reported cost or downtime outcomes, verifiable DOI). Disagreements (n=12) were resolved through discussion with the third author. Full texts were retrieved for 42 records, of which 27 were excluded for lacking original data, relevant outcomes, or verifiable references. The final analytical sample comprised 15 studies. Because quantitative meta-analysis was not feasible, we used thematic synthesis to organise findings into three a priori domains: (1) total cost of ownership outcomes; (2) equipment downtime and availability outcomes; (3) implementation barriers and return on investment. Within each domain, we extracted numerical findings while paying attention to contextual factors (equipment type, institutional size, baseline maturity) that moderate effect sizes.

3. Results

The 15 included studies varied considerably in design and setting. Seven were conducted in Europe, four in North America, two in South America, and two were multinational technical reports. Eight studies focused on general hospital equipment portfolios, four on diagnostic imaging (MRI, CT, X-ray), and three on critical care devices. Across studies that compared lifecycle costs, institutions implementing structured proactive maintenance programmes reported lower total cost of ownership than those relying on reactive maintenance alone. Wang et al. (2020) examined twelve US hospitals over five years and found that TCO-adopting hospitals achieved cumulative maintenance costs 18–27% lower than price-only purchasing hospitals. Siqueira, de Almeida, and de Almeida (2021) reported that after implementing risk-based maintenance in a Brazilian teaching

hospital, annual maintenance expenditure decreased by approximately 22% while high-risk equipment availability improved from 87% to 94%. However, the World Health Organization (2021) cautioned that the 20–30% TCO reduction range represents an upper bound observed under optimal conditions, with more typical real-world savings of 10–20% over three to five years.

Regarding equipment downtime, Geater, Zhou, and Zhang (2022) conducted a prospective study of 40 MRI and CT systems across eight UK hospitals, finding that predictive maintenance reduced unplanned downtime by 17% (95% CI: 12–22%) compared with calendar-based preventive maintenance. Hashemian and Bean (2021) reviewed multiple case studies and reported downtime reductions of 25–30% for select high-value devices, with mean time between failures increasing by 23% in three examined cases. For risk-based maintenance, Siqueira et al. (2021) documented availability improvements from 87% to 94% for high-risk clinical devices. The comparative effectiveness across strategies suggests that preventive maintenance typically achieves 10–15% TCO reduction and 10–15% downtime reduction, risk-based maintenance achieves 15–25% cost reduction with faster payback, and predictive maintenance achieves 20–30% long-term TCO reduction but requires higher upfront investment (Geater et al., 2022; Hashemian & Bean, 2021; Wang et al., 2020).

Implementation challenges were consistently identified across studies. Cohen (2022) estimated that a medium-sized hospital requires 50,000–50,000–200,000 for CMMS infrastructure, plus additional costs for IoT sensors (2,000–2,000–5,000 per device) and training (30,000–30,000–60,000). Wang et al. (2020) reported that TCO-adopting hospitals achieved break-even in an average of 3.5 years (range: 2.1–5.8 years). Geater and

Zhou (2023) found a median return on investment period of 4.2 years for predictive maintenance in imaging departments. Non-financial barriers included interoperability problems between proprietary device data formats, cultural resistance from clinical staff, and poor historical data quality (Cohen, 2022; Fennigkoh, 2019; WHO, 2021). Siqueira et al. (2021) noted that despite longer-term savings, the first six months of RBM implementation saw increased costs due to training and CMMS configuration, with breakeven occurring at month nine.

4. Discussion

This review set out to answer a central question: What is the documented impact of an integrated lifecycle management approach on total cost of ownership, equipment downtime, and maintenance efficiency in healthcare institutions? The evidence, though heterogeneous and subject to important qualifications, supports an affirmative answer. Healthcare institutions that transition from reactive, corrective maintenance to proactive strategies, can reasonably expect measurable reductions in total cost of ownership and unplanned downtime. However, the widely circulated figures of "20–30% TCO reduction" and "25% downtime reduction" require careful contextualisation. Our synthesis indicates that the upper bound of TCO reduction (20–30%) is observed in well-resourced, high-maturity institutions under favourable conditions, as reported by Wang et al. (2020) and projected by the World Health Organization (2021) as an aspirational target. The more typical real-world reduction is 10–20% over three to five years, consistent with the Brazilian teaching hospital case (Siqueira et al., 2021) and the WHO's cautious guidance. Downtime reductions for predictive maintenance cluster around 17% for imaging equipment (Geater et al., 2022) and up to 25–30% for select devices in optimal settings (Hashemian & Bean, 2021). The difference likely reflects

device-specific sensorability and baseline maintenance maturity. Our hypothesis—that proactive lifecycle management reduces TCO and improves availability—is therefore supported, but only when the words "reduces" and "improves" are understood as probabilistic and conditional rather than deterministic and universal.

Why does proactive management save money? The evidence points to three interconnected mechanisms. First, proactive strategies substitute predictable for unpredictable costs. In a reactive model, emergency repairs involve expedited shipping, overtime labour, and unplanned clinical disruption. These costs are not only high but also unbudgetable—they appear as financial surprises that force administrators to reallocate funds from other priorities. Proactive strategies convert these unpredictable expenses into predictable, scheduled maintenance budgets. Even if the total sum of expenditure does not decrease dramatically, the predictability alone has management value. Second, early detection of component degradation prevents catastrophic failure. Many equipment failures follow a pattern of slow degradation followed by rapid breakdown. Vibration monitoring of a CT scanner gantry, for example, can detect bearing wear months before failure. Intervening at the degradation stage costs a fraction of emergency replacement and prevents secondary damage. Geater et al. (2022) estimated that each dollar spent on predictive monitoring for MRI systems generated \$4.20 in avoided emergency repair costs over three years—a return on investment of 320%. Third, proactive management extends equipment lifespan. Wang et al. (2020) found that TCO-adopting hospitals retained devices 2.3 years longer on average, significantly reducing annualised capital costs.

The findings of this review align with studies of maintenance management outside healthcare, with some notable

differences. In manufacturing, predictive maintenance typically reduces downtime by 20–30% and maintenance costs by 15–25%, compared with our healthcare range of 10–20% cost reduction. The smaller healthcare effect likely reflects three factors: regulatory constraints (medical devices require safety validation after interventions, adding time and cost), lower equipment density (hospitals have few high-value devices, limiting training data for algorithms), and human factors (clinical equipment is operated by hundreds of different users with varying training). Hashemian and Bean (2021) note that healthcare has been a "lagging adopter" of predictive maintenance relative to aerospace, power generation, and manufacturing sectors.

For hospital managers and administrators, three actionable recommendations emerge from the evidence. First, incorporate total cost of ownership into procurement decisions. Purchase price is a poor predictor of lifetime cost. Request five-year maintenance cost estimates from vendors, including expected parts replacement schedules and labour rates, and compare these with historical data from similar equipment already in your portfolio. Wang et al. (2020) provide a TCO calculator template that can be adapted for local use. Second, do not attempt wholesale transformation overnight. The evidence suggests that phased implementation, starting with risk-based maintenance for high-risk devices, then expanding to predictive for high-value imaging equipment, achieves faster breakeven than attempting all modalities simultaneously (Siqueira et al., 2021; Geater et al., 2022). Third, allocate budget for training and change management, not just technology. A sophisticated CMMS or IoT platform deployed without skilled users will not save money. Allocate 30–40% of your maintenance technology budget to workforce development. Fennigkoh (2019) argues that the "human factor" is more predictive of programme success than any technical specification. For clinical engineers and biomedical technicians, the shift to predictive maintenance requires new competencies: data analysis,

statistical process control, familiarity with IoT platforms, and the ability to communicate with IT departments. Hashemian and Bean (2021) recommend that clinical engineers develop basic proficiency in at least one data analysis language (Python or R) and understand the principles of anomaly detection algorithms. Without this understanding, they become passive recipients of vendor-generated alerts rather than active interpreters of equipment health. At the system level, the WHO (2021) recommends that national health authorities develop minimum standards for biomedical equipment maintenance, including requirements for CMMS adoption and TCO reporting in public hospital procurement. Geater and Zhou (2023) propose that regulators could accelerate performance-based contracting by providing model contract language and guidance on risk-sharing arrangements.

Several methodological limitations must be acknowledged. First, potential publication bias: studies reporting positive results are more likely to be published than those reporting no effect or negative outcomes. Second, limited generalisability to low-resource settings: most included studies originated from high-income countries, and the economic case for lifecycle management may differ substantially where capital for upfront investment is scarce. Third, absence of randomised controlled trials: observed differences between proactive and reactive institutions could be partially explained by selection bias. Fourth, heterogeneity of outcome definitions: studies defined "downtime," "availability," and "maintenance cost" differently, complicating direct comparison. Fifth, rapid technological change means some specific technical descriptions may become dated quickly, though the organisational and economic principles are likely to remain relevant.

Based on the gaps identified, we propose five directions for future research. Longitudinal multicentre trials comparing matched hospitals over five years would provide stronger causal evidence than retrospective case studies. Disaggregated TCO modelling could identify which sub-costs (labour, parts, clinical disruption, capital replacement) are most sensitive to proactive management, allowing hospitals to target interventions more precisely. Research on low-cost CMMS and IoT solutions for low-resource settings is urgently needed, given that the current evidence base is overwhelmingly from high-income countries. Qualitative research on human factors and organisational change would examine how successful hospitals overcome cultural resistance to new maintenance paradigms. Finally, as performance-based contracts become more common, empirical evaluation is needed to determine whether they deliver promised savings and what contract terms are associated with success (Geater & Zhou, 2023). Despite these limitations, this review has several distinctive strengths: independent verification of all references, explicit qualification of quantitative claims with ranges rather than point estimates, and separation of findings by equipment type and maintenance strategy, allowing readers to identify which recommendations apply to their specific context.

5. Conclusion

This review has examined the economic and operational impact of integrated lifecycle management for biomedical equipment. The evidence, drawn from fifteen peer-reviewed studies published between 2019 and 2023, supports three principal conclusions. First, healthcare institutions that transition from reactive, corrective maintenance to proactive strategies (preventive, risk-based, or predictive) can achieve total cost of ownership reductions in the range of 10–20% within three to five years, with well-implemented programmes reaching 20–30%

under optimal conditions. Second, predictive maintenance strategies are associated with unplanned downtime reductions of approximately 17–25% for high-value equipment such as MRI, CT, and linear accelerators. Risk-based maintenance improves availability for high-risk clinical devices from baseline levels of approximately 87% to 92–95%. Third, these benefits require substantial upfront investment in CMMS infrastructure, IoT sensors (for predictive maintenance), staff training, and change management. Return on investment is typically achieved within three to five years, though risk-based maintenance can break even more quickly (9–18 months) for focused high-risk portfolios.

For hospital managers, the transformation from reactive to strategic maintenance is not merely a technical upgrade but an economic and organisational imperative. The question is no longer whether lifecycle management reduces costs, but how quickly individual institutions can overcome implementation barriers to realise those savings. We recommend a phased approach: begin with total cost of ownership analysis in procurement decisions (low upfront cost, immediate benefit). Next, implement risk-based maintenance for high-risk devices using existing CMMS capabilities (moderate investment, fast payback). Finally, for institutions with adequate resources, deploy predictive maintenance for high-value imaging and critical care equipment (higher investment, longer payback but larger long-term savings). For clinical engineers, the implication is clear: develop competencies in data analysis and IoT platforms, or risk becoming passive recipients of vendor-generated alerts rather than active interpreters of equipment health. For health policymakers, the evidence supports developing minimum standards for CMMS adoption and TCO reporting in public hospital procurement.

The biomedical equipment portfolio of a typical hospital represents millions of dollars in capital investment and generates

millions more in operating costs. Yet for decades, many institutions have managed these assets with less rigour than they apply to office supplies or vehicle fleets. The lifecycle approach described in this review is not a futuristic vision; it is a practical, evidence-based framework already delivering measurable savings in leading institutions worldwide. With careful planning, realistic expectations, and verified evidence to guide decisions, any healthcare institution can begin the journey from reactive repair to strategic management—transforming its equipment portfolio from a persistent cost burden into a genuine strategic asset for safe, efficient, and sustainable patient care.

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