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Risk-Gated Capital Allocation for Radiological Equipment Replacement Under Safety and Budget Uncertainty

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Abstract

Capital allocation for radiological equipment replacement is not a simple age-ranking problem. Hospitals must decide when continued operation is no longer admissible, which otherwise admissible systems have the strongest replacement case under uncertain technical evidence, and which replacement portfolio should be funded when capital, commissioning capacity, and service continuity are constrained. Existing medical-equipment models commonly aggregate age, reliability, safety, obsolescence, clinical importance, and cost into compensatory scores, whereas radiological renewal guidance emphasizes lifecycle planning, quality assurance, and technological obsolescence. This integrative conceptual review develops Risk-Gated Replacement Allocation (RGRA) for Computed Tomography (CT), fluoroscopy, radiography, and radiotherapy equipment. RGRA separates three decisions that should not be collapsed. First, a non-compensatory radiation-safety and mandatory-compliance gate excludes inadmissible retain-or-defer choices. Second, robust replacement-priority intervals quantify decision stability across plausible criterion-weight and evidence uncertainty. Third, a budget-constrained portfolio model selects replacements by avoided expected lifecycle loss while respecting service-continuity and implementation constraints. An Expected Value of Information (EVI) rule targets additional testing or vendor evidence only when it can change a borderline decision. The synthesis yields seven formal decision rules, six falsifiable propositions, and a prospective validation design. The framework contributes an auditable management architecture in which safety defines feasibility, uncertainty determines confidence, and optimization determines the funded replacement portfolio.

Keywords: Radiological equipment replacement, Capital allocation, Radiation safety, Robust optimization, Multi-criteria decision analysis, Healthcare technology management.

1 | Introduction

Hospitals increasingly manage medical equipment as a lifecycle portfolio rather than as a collection of isolated assets. The World Health Organization (WHO) describes health technology management as a sequence that

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extends from needs assessment and procurement through inspection, inventory, training, maintenance, and decommissioning [1]. Decommissioning guidance likewise frames retirement as a managed decision requiring evidence on why, when, and how a device should leave service [2]. Replacement is therefore a strategic management decision located between continued operation and final retirement: it determines whether limited capital is committed before reliability, safety, supportability, or clinical performance deteriorate further.

The research problem is more specific than general medical-equipment management. When several safety-critical devices compete for a limited replacement budget, managers must distinguish three logically different questions. First, is continued operation an admissible option at all? Second, among admissible devices, which ones have the strongest case for replacement? Third, given unequal acquisition costs and service-continuity requirements, which combination of replacements should actually be funded? Classical replacement work demonstrated the value of structured attributes for service and support, function, cost, and clinical efficacy [3], while later linear and fuzzy models improved discrimination among replacement candidates [4]. Recent studies have developed multi-criteria models for large-equipment replacement [5] and user-centered analyses showing that safety can be particularly salient to medical engineers [6]. Yet these approaches still leave a conceptual gap between ranking and portfolio selection.

The gap matters because weighted ranking is usually compensatory. A device can receive a moderate overall score even if one safety dimension is severe, provided other dimensions are favorable. A 2025 systematic review of medical-device prioritization methods found substantial methodological heterogeneity and widespread use of multi-criteria decision analysis, while also identifying the absence of a generally accepted prioritization approach [7]. Lifecycle optimization studies add another perspective: repair-versus-replace policies can be estimated from maintenance histories and modeled as dynamic decisions [8]. These streams are valuable, but they rarely specify when compensation between criteria should be forbidden, how uncertain criteria should affect rank stability, or how a ranking should be converted into an annual capital plan.

Safety-critical equipment makes these omissions particularly consequential. ISO 14971:2019 formalizes medical-device risk management across the lifecycle [9], and IEC 62353:2014 addresses recurrent testing and testing after repair of medical electrical equipment [10]. For radiological technologies, organizational safety culture and radiation protection introduce additional non-negotiable duties [11], while the International Atomic Energy Agency (IAEA) basic safety standards establish requirements for radiation protection and safety of sources [12]. In such settings, the managerial objective cannot be to maximize an unconstrained average score. It must first exclude decisions that violate a safety or compliance boundary, and only then optimize among feasible alternatives.

1.1 | Motivation and Decision Context

Capital replacement committees operate under a recurring asymmetry. Evidence about acquisition cost is usually precise, whereas evidence about future downtime, failure consequences, vendor support, parts availability, residual life, and clinical substitution can be noisy or partly judgmental. Moreover, the costs of false decisions are asymmetric. Replacing a serviceable device too early wastes scarce capital and may trigger training, integration, and implementation costs. Deferring a genuinely unsafe or unsupported device can expose patients and staff to harm, extend downtime, or force emergency procurement under worse commercial conditions. This asymmetry motivates a decision architecture that is conservative about admissibility but explicit about uncertainty once safety constraints have been satisfied.

The paper focuses only on capital allocation for replacement of high-cost radiological equipment that uses ionizing radiation. It does not attempt to optimize preventive-maintenance frequency, corrective-repair dispatching, radiation-protection operations, procurement negotiation, cybersecurity operations, or the entire technology lifecycle. Those functions supply evidence or constraints to the replacement decision, but they are outside the optimization target. This narrower scope is deliberate: a reviewer should be able to identify the decision variable, the unit of analysis, and the proposed mechanism without treating the framework as a generic checklist for all biomedical engineering activity.

1.2 | Innovation, Contributions, and Main Work

This article develops Risk-Gated Replacement Allocation (RGRA). The innovation is architectural rather than merely additive. RGRA separates three decisions that are often collapsed into one score: 1) safety admissibility, governed by non-compensatory gate conditions, 2) replacement priority, represented as an interval rather than a single deterministic rank, and 3) capital allocation, formulated as a budget-constrained portfolio choice. The separation is designed to make the decision process auditable: a device can be escalated because it fails a gate, prioritized because its robust interval dominates another device, or selected because its avoided expected lifecycle loss justifies scarce capital.

The paper contributes in four ways. First, it reframes safety as a feasibility condition rather than another weighted criterion. Second, it incorporates uncertainty in weights and evidence through robust priority intervals, reducing false confidence in precise ordinal rankings. Third, it distinguishes rank from allocation by introducing an explicit portfolio capital-allocation model. Fourth, it adds a value-of-information rule for borderline devices, directing measurement effort toward cases where additional evidence can actually change the decision. The main work is conceptual and design-oriented; no empirical performance claims are made without hospital data. Six falsifiable propositions and a prospective validation protocol are provided so that the framework can be tested rather than accepted as a managerial narrative.

The remainder of the article is organized as follows. Section 2 reviews replacement, reliability, maintenance prioritization, safety governance, and decision-analytic methods. Section 3 defines the conceptual design and variables. Section 4 presents the RGRA model and decision rules. Section 5 develops governance, implementation, and testable propositions. Section 6 concludes with limitations and future research.

2 | Literature Review

2.1 | Replacement Models and the Limits of Single-Score Prioritization

Medical-equipment replacement research has long recognized that age alone is an inadequate criterion. Fennigkoh's model [3] used ten attributes spanning service and support, equipment function, cost benefits, and clinical efficacy. The subsequent Galliera Hospital comparison of a linear replacement model with fuzzy logic showed that model form materially affects discrimination among assets [4]. Huang et al. [5] combined multiple-criteria weighting and ranking methods for large-equipment replacement, reinforcing the importance of systematic rather than purely subjective decisions.

Park et al. [6] found occupational differences in replacement priorities and reported that safety was especially important to medical engineers. The implication is not that one set of weights is universally correct; it is that replacement scores encode organizational preferences and professional perspectives that may change across hospitals and device classes.

The broad health-technology-assessment literature reaches a similar conclusion. Pimenta and Vieira [7] reviewed 51 prioritization studies and found that multi-criteria methods were dominant among studies that specified their value-assessment method, but no generally accepted approach existed. This finding exposes a methodological risk for replacement committees: The apparent precision of a final score may be much greater than the precision of the underlying criteria, weights, and stakeholder judgments. A point rank of 1 versus 2 can therefore be unstable even when the reporting format looks definitive.

Lifecycle-data approaches partly address subjectivity by using observed maintenance histories. Liao et al. [8] used a discrete-time Markov chain and Markov decision process to study repair and replacement using 24,516 repair and maintenance records for 5,171 products.

Such models demonstrate the value of transition histories and lifecycle costs, but their objective is different from annual multi-device capital allocation. A hospital still needs a governance rule for combining technical evidence with clinical consequence and for handling devices that present safety conditions before an economic repair-replace comparison is meaningful.

2.2 | Reliability and Maintenance Evidence as Replacement Signals

Replacement decisions depend on evidence generated by maintenance systems, but maintenance prioritization should not be confused with replacement prioritization. Taghipour et al. [13] proposed a structured approach for prioritizing medical equipment for maintenance, establishing the importance of function, risk, and maintenance-related attributes.

Saleh et al. [14] developed a preventive-maintenance prioritization index using quality function deployment, while Jamshidi et al. [15] proposed a fuzzy risk-based framework for prioritizing medical devices. Hernandez-Lopez et al. [16] also developed an index for preventive-maintenance prioritization. These models are operationally valuable, yet their dependent decision is normally which maintenance activity deserves attention, not which capital replacement should be authorized.

Operations-research models further clarify the distinction. Ben Houria et al. [17] developed quantitative techniques for medical-equipment maintenance management, and Hamdi et al. [18] proposed intelligent work-order prioritization. These tools may generate important replacement signals such as repeated corrective work, downtime burden, maintenance complexity, and inability to restore performance.

However, a high maintenance priority need not imply immediate replacement: a newer critical device can require urgent repair yet still have strong supportability and remaining life. Conversely, an apparently functioning asset can merit replacement because of end-of-support, recurrent safety alerts, or inability to meet contemporary clinical requirements.

Reliability evidence has become increasingly data-driven. A systematic review by Zamzam et al. [19] synthesized approaches to medical-equipment reliability assessment. Abd Rahman et al. [20] used machine learning to predict device failure, and Zamzam et al. [21] developed integrated failure-analysis models for maintenance management. Ye et al. [22] reported a 2026 real-hospital deployment of machine-learning-assisted maintenance prioritization across 9,924 devices, demonstrating that predictive systems can be operationally embedded. These advances support better evidence for replacement decisions but do not eliminate the decision problem: a probability of failure must still be translated into consequence, intervention, and capital choices.

Recent replacement-oriented evidence reinforces the relevance of condition and supportability. Amran et al. [23] integrated reliability, replacement priority, and maintenance strategy criteria in Malaysian hospitals, including safety alerts, age, utilization, failure and availability indicators, downtime, alternatives, cost, and support-related factors.

Wang et al. [24] examined patient incidents associated with maintenance omissions, highlighting why missing maintenance actions can carry safety consequences. Evidence-based equipment-management implementations [25] and computerized maintenance systems in hospital settings [26] also show that data quality, inventory completeness, and standardized work-order recording are prerequisites for defensible lifecycle decisions. Accordingly, RGRA treats maintenance and reliability data as evidence inputs, not as substitutes for replacement governance.

2.3 | Decision Analysis, Non-Compensation, and Robustness

Multi-criteria decision analysis provides formal tools for combining heterogeneous evidence, but different families of methods embody different assumptions. The Analytic Hierarchy Process developed by Saaty [27] structures pairwise judgments and derives relative weights.

Promethee, introduced by Brans and Vincke [28], and ELECTRE-family outranking methods associated with Roy [29] can support preference structures that do not reduce every comparison to a single additive utility. These methods are relevant because replacement choices often involve veto-like conditions: A severe safety or compliance concern should not be neutralized by low acquisition cost or good utilization performance.

A second problem is uncertainty. Replacement scores depend on estimated failure rates, uncertain remaining life, subjective severity assessments, variable vendor support, and weights negotiated by different

stakeholders. Robust optimization offers a disciplined alternative to pretending that uncertain inputs are known exactly. Bertsimas and Sim [30] formalized a tractable approach that controls the conservatism of solutions under data uncertainty, and Bertsimas et al. [31] reviewed the theory and applications of robust optimization. The key managerial idea adopted here is not a particular uncertainty set; it is the principle that a decision should remain defensible over a plausible set of inputs rather than only at one nominal estimate.

The literature therefore suggests a three-part gap. Existing replacement models provide criteria and ranks; reliability models improve evidence; and decision science provides non-compensatory and robust tools. What is missing is a focused hospital replacement architecture that connects them in the correct order: Safety admissibility first, robust priority second, and capital allocation third. *Table 1* summarizes this synthesis.

Table 1. Focused literature synthesis and unresolved decision gap.

Literature Stream	What it Contributes	Remaining Problem for Replacement Governance
Replacement scoring [3-6]	Structured criteria for supportability, clinical value, condition, cost, age, and safety.	Typically returns a score or rank; severe safety conditions may remain compensable.
HTA prioritization [7]	Broad evidence on value attributes, stakeholder involvement, and MCDA prevalence.	No generally accepted prioritization approach; context and weight choices remain material.
Lifecycle repair-replace optimization [8]	Uses observed maintenance histories and transition dynamics to optimize repair or replacement.	Does not by itself solve multi-device annual capital allocation with heterogeneous safety gates.
Maintenance and reliability analytics [13-26]	Failure, downtime, maintenance burden, condition, and predictive evidence.	Predicts or prioritizes maintenance; does not define replacement admissibility and funding.
MCDA and outranking [27-29]	Formal preference, trade-off, and veto structures.	Requires a hospital-specific architecture linking vetoes to later capital selection.
Robust optimization [30], [31]	Decision stability under uncertain parameters.	Rarely integrated with medical-equipment replacement gates and audit trails.

2.4 | Safety and Regulatory Boundaries

The proposed gate is grounded in the distinction between acceptable trade-offs and mandatory risk controls. ISO/TR 24971:2020 provides guidance on applying ISO 14971 risk-management principles [32], while ISO 31000:2018 emphasizes integration of risk management with organizational decision making [33]. Connected medical equipment can also introduce safety, effectiveness, and security dependencies; IEC 80001-1:2021 addresses risk management for networks incorporating medical devices or health software [34]. For ionizing-radiation technologies, IAEA guidance on medical uses of ionizing radiation [35] and diagnostic reference-level principles [36] illustrate that equipment management interacts with protection, quality assurance, and optimization requirements.

These sources do not prescribe a universal replacement score, and RGRA should not be presented as a substitute for law, regulator instructions, manufacturer field-safety notices, or hospital-specific engineering procedures. Their relevance is conceptual: some states change the feasible action set. If a mandatory post-repair safety test is failed, a serious unresolved hazard is documented, or legally required controls cannot be satisfied, 'retain because it is cheap' should not remain an ordinary alternative. The replacement model must therefore begin with an admissibility screen.

Decision scope also matters. A recent hospital framework prioritizes repair of failed devices rather than capital replacement [37], while WHO maintenance guidance defines the evidence and processes needed to keep equipment functioning safely [38]. For radiological capital renewal specifically, the European Society of Radiology argues for forward-looking renewal planning because technical and functional obsolescence can increase failure, workflow, and safety exposure [39].

Recent work on Computed Tomography (CT) estimates technological-obsolescence patterns using scanner performance, detection, and image-resolution characteristics [40]. Radiotherapy presents a parallel capital

problem: contemporary funding analysis emphasizes the dependence of radiotherapy services on expensive equipment renewal and long-horizon capital planning [41]. These radiology-specific sources motivate a narrower replacement architecture rather than a generic hospital-equipment score.

3 | Conceptual Method and Model Design

3.1 | Integrative Design Method

This study is an integrative conceptual review and decision-model design, not an empirical effectiveness study. The evidence base was organized around five streams: medical-equipment replacement, maintenance and reliability, healthcare technology management, medical-device and radiation-safety governance, and decision analysis. The design criterion was explanatory parsimony: every construct included in RGRA must answer one of three decisions, admissibility, priority, or capital selection. Constructs that belong primarily to other managerial problems, such as preventive-maintenance interval optimization or corrective work-order dispatch, enter only as evidence variables.

The model deliberately distinguishes repair from capital renewal. Tarakci et al. [37] address which failed device should be repaired first, whereas RGRA asks which radiological systems should receive scarce replacement capital before or instead of further repair. WHO maintenance guidance [38] is used to define maintenance evidence and safe equipment management; ESR renewal guidance [39], CT obsolescence evidence [40], and radiotherapy capital analysis [41] define the narrower renewal context. Mixing these outcomes would recreate the broad managerial framework this article is designed to avoid.

The conceptual model assumes a hospital has an asset register and a minimum set of device-level evidence. A practical implementation can be built from a computerized maintenance management system, procurement and vendor records, safety-test documentation, incident or alert records, and clinical service information. Where evidence is missing, the model does not silently impute precision; uncertainty is widened and, when potentially decision-changing, a value-of-information review is triggered.

3.2 | Decision Set and Core Variables

Let i = 1,...,N index candidate devices or homogeneous asset groups considered in one capital-planning cycle. The binary decision x_i equals 1 when replacement of candidate i is funded in the planning horizon and 0 otherwise. Candidate inclusion is itself governed: only assets meeting the hospital's eligibility rule - for example approaching end of supported life, repeated significant failures, persistent unavailability, material capability deficit, or documented safety concern - enter the replacement review. This prevents annual ranking of every low-risk asset merely because data exist.

For each candidate, the evidence vector z_i contains normalized indicators that are intentionally narrower than a general technology-management score: C_i for clinical consequence if unavailable or malfunctioning; R_i for reliability deterioration and recurrent failure; D_i for downtime and service-continuity exposure; O_i for technological obsolescence and supportability; Q_i for sub-threshold quality-assurance or dose-performance deterioration that has not itself triggered a safety gate; L_i for lifecycle burden of continued retention; and A_i for lack of redundant clinical capacity. These variables need not share identical uncertainty. Age can inform O_i or lifecycle modeling but is not an autonomous replacement objective: two equally old CT scanners can have very different detector performance, support status, failure histories, protocol capability, and service dependencies.

Safety-gate evidence is stored separately as g_im for gate condition m. This separation is essential. If g_im were simply another normalized criterion in z_i, the model would again permit economic or utilization benefits to compensate for a condition that should trigger escalation. The core variables and suggested operational sources are shown in *Table 2*.

Table 2. RGRA variables, interpretations, and candidate data sources.

Construct	Operational Interpretation	Illustrative Evidence Source	Decision Role
Safety gate g_im	Predefined radiation-safety, mandatory-test, or field-action condition that can make ordinary deferral inadmissible.	Radiation QA; safety tests; incident/alert records; regulator or manufacturer instructions.	Admissibility
Clinical consequence C_i	Consequence of losing the imaging or treatment function, including pathway delay and treatment interruption.	Clinical service review; modality dependency; case mix; critical pathway mapping.	Priority
Reliability R_i	Recurrent failure, condition deterioration, or unstable restoration after repair.	CMMS failure history; service logs; repeat-call and component records.	Priority
Downtime D_i	Operational exposure created by outage frequency, repair duration, and external service delay.	Downtime hours; work orders; vendor response and parts lead times.	Priority
Obsolescence O_i	Technological ageing, end-of-support, parts scarcity, software constraints, or capability gap.	Vendor roadmaps; support notices; parts availability; upgrade history.	Priority
QA margin Q_i	Deteriorating image/treatment performance or dose-related QA trend that remains inside the formal gate.	Medical-physics QA; constancy tests; protocol review; performance trending.	Priority
Lifecycle burden L_i	Expected service, component, energy, commissioning, and operational burden of continued retention versus replacement.	Finance; contracts; parts; energy; maintenance and commissioning plans.	Value
Redundancy A_i	Capacity of alternative scanners or treatment units to absorb planned and unplanned downtime.	Utilization; scheduling; installed capacity; referral alternatives.	Constraint
Replacement cost K_i	Full capital requirement including acquisition, installation, acceptance, commissioning, training, and transition.	Procurement quotation; facilities plan; physics/engineering implementation plan.	Capital

3.3 | Uncertainty and Auditability

RGRA does not require one universal uncertainty model. A hospital may use simple scenario bounds, expert-derived intervals, bootstrapped reliability estimates, or statistical prediction intervals. The minimum requirement is that uncertainty be visible. Let W denote a plausible set of criterion weights and Z_i a plausible set of evidence vectors for candidate i. Uncertainty sets can reflect inter-rater disagreement, measurement error, sparse maintenance history, or forecast uncertainty. Their size should be justified and version-controlled, because an arbitrarily wide set can make every decision ambiguous while an unrealistically narrow set reproduces false precision.

Auditability requires recording four elements for each cycle: The evidence snapshot, the gate decision and rationale, the uncertainty assumptions used for robust ranking, and the optimization inputs that produced the funded set. This design allows later post-completion review to distinguish model error from data error, policy override, or new information. It also supports calibration across annual cycles rather than repeatedly rebuilding scores from memory.

3.4 | Artificial Intelligence Assistance

In accordance with the journal's authorship and artificial-intelligence disclosure policy, a large language model was used during manuscript development for structural drafting, language refinement, and organization of the conceptual framework. The author is responsible for verification of references, equations, claims, and final wording; the model is not an author and no empirical results were generated by artificial intelligence. Any future empirical implementation should separately document software, code, data provenance, and model-validation procedures.

4 | Risk-Gated Replacement Allocation for Radiological Equipment

4.1 | Layer 1-Non-Compensatory Safety Gate

The first layer determines whether ordinary retain-versus-replace trade-offs are admissible. Let tau_m denote the escalation threshold for gate condition m. A candidate fails the safety gate when at least one predefined condition crosses its threshold:

$$G_i = \mathbb{1}\{\max_m(g_{im} - \tau_m) \geq 0\}. \quad (1)$$

Here G_i = 1 denotes a gate-triggered case. The gate is not synonymous with automatic purchase. Its function is to remove routine deferral from the compensatory ranking process and trigger a governed response: Restrict or suspend use where required, correct the condition if feasible, escalate to the appropriate engineering/clinical/radiation-safety authority, or pursue replacement/decommissioning. A gate can therefore result in corrective action followed by re-entry into the ranking set if the underlying condition is resolved.

The most important design rule is that gate definitions must be local, explicit, and linked to authoritative requirements. Examples include a failed mandatory electrical-safety or post-repair test, an unresolved serious field-safety action, inability to maintain required safety performance, or a radiological quality-assurance condition that makes continued clinical use unacceptable. The gate should not include every undesirable attribute; high maintenance cost or low utilization, for example, belong in the priority model rather than the admissibility layer.

Table 3. Illustrative safety-gate logic and managerial response.

Gate Condition	Non-Compensation Rationale	Immediate Response	Re-Entry Condition
Radiation QA or protection condition makes clinical use unacceptable	Dose, output, geometry, or protection requirements cannot be offset by lower cost or high utilization.	Restrict affected use; medical-physics and radiation-safety escalation.	Condition corrected, verified, and formally released.
Mandatory recurrent or post-repair safety test is failed	An unresolved mandatory test failure changes the feasible action set.	Restrict use as required; investigate, correct, and retest.	Documented pass or approved disposition.
Serious field-safety action remains unresolved	External safety information can invalidate ordinary retain/defer choices.	Apply manufacturer/regulatory action; quarantine, correct, or replace.	Field action closed and residual risk accepted.
Required performance cannot be sustained	Persistent inability to maintain essential performance is not an economic trade-off.	Engineering, clinical, and physics review; consider withdrawal or replacement.	Verified restoration of required performance.
Critical support loss creates unacceptable residual risk	End-of-support becomes a gate only when safe operation cannot be assured with validated controls.	Escalate supportability; impose interim controls; accelerate replacement.	Validated support/control restored or asset replaced.

Fig. 1 shows the complete RGRA architecture for radiological equipment. The principal distinction is the branch after the safety-admissibility stage: a gate-fail case is escalated before ordinary economic ranking, so a severe radiological or mandatory condition cannot disappear inside a weighted average.

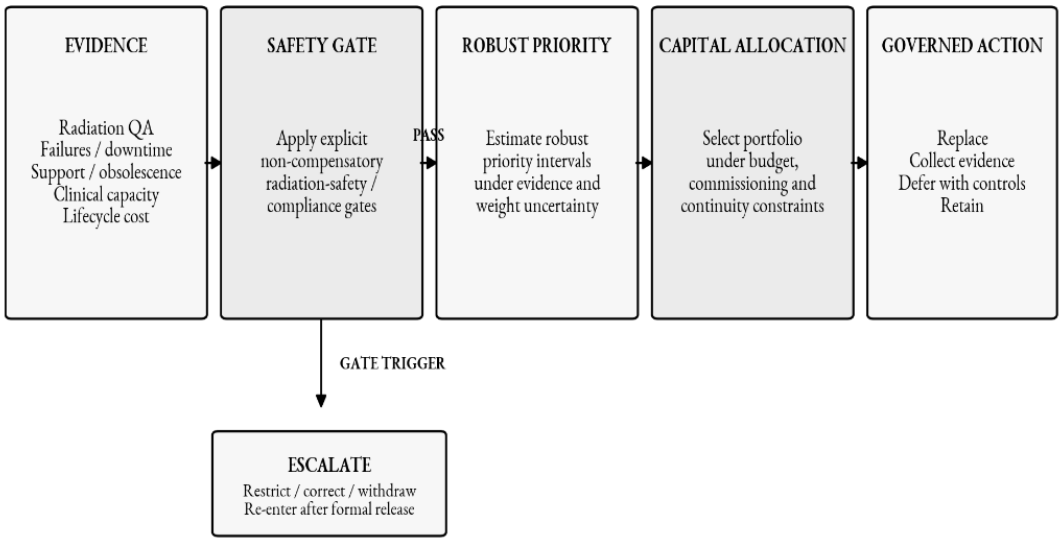

Fig. 1. RGRA architecture for radiological equipment, separating safety admissibility, robust priority, and capital allocation.

4.2 | Layer 2-Robust Replacement Priority

Candidates that pass the gate are evaluated using a transparent replacement-priority function. A simple additive form is useful as a baseline because it is interpretable and easy to audit:

$$P_i(w, z_i) = \Sigma_{k=1}{}^{K} w_k z_{ik}, \quad w_k \geq 0, \quad \Sigma_k w_k = 1. \tag{2}$$

The additive form is not claimed to be uniquely correct. Hospitals may use a validated MCDA or outranking approach. What RGRA requires is that the resulting priority be stress-tested under plausible uncertainty. For an additive implementation, define lower and upper robust priority bounds:

$$P_i^- = \min_{w \in W,\, z_i \in Z_i} P_i(w, z_i), \quad P_i^+ = \max_{w \in W,\, z_i \in Z_i} P_i(w, z_i). \tag{3}$$

The interval [P_i^-, P_i^+] communicates two pieces of information that a point rank hides: The strength of a candidate's case and the stability of its ordering. If the interval for one device lies entirely above another device, the preference is robust to the modeled uncertainty. If intervals overlap materially, the rank should be treated as unstable rather than reported with false precision.

A planning threshold can also be expressed as an interval decision: devices whose lower bound exceeds a threshold have a strong replacement case; those whose upper bound remains below it have a weak case; and threshold-crossing candidates are natural targets for further evidence collection.

Fig. 2 is deliberately illustrative rather than empirical. It shows how robust intervals change managerial interpretation across radiological candidates.

CT-1 is clearly above the planning threshold; Radiography-1 is clearly below it; and Fluoroscopy-1 straddles the threshold. A point ranking would hide that distinction in confidence.

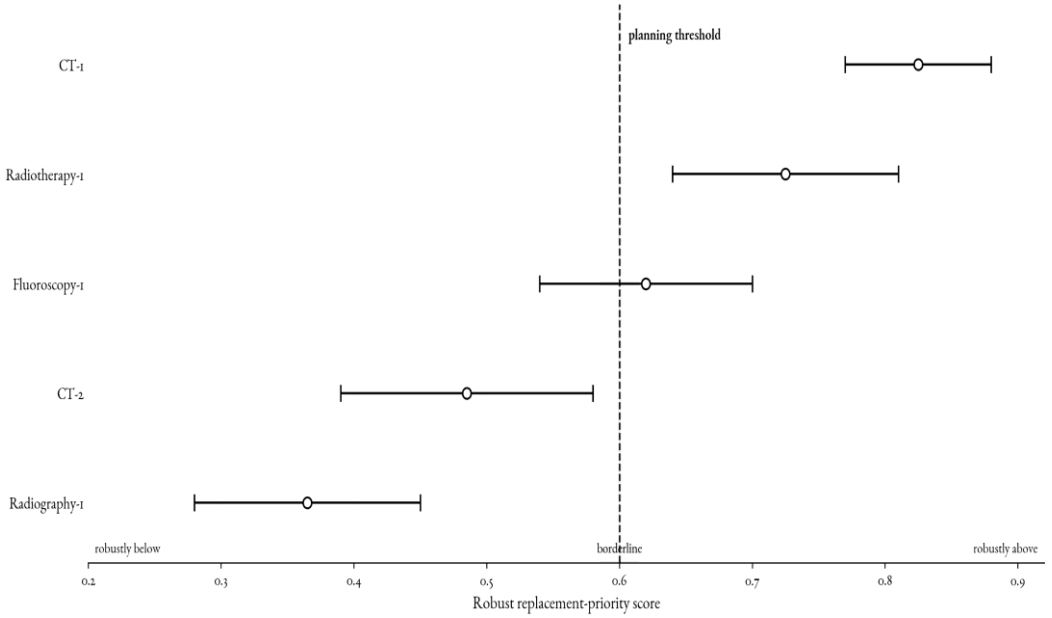

Fig. 2. Illustrative robust replacement-priority intervals for radiological equipment; open circles show nominal scores, horizontal bars show robust intervals, and the shaded band marks the borderline planning threshold.

4.3 | Layer 3-Budget-Constrained Capital Allocation

A ranking still does not solve the budget problem. Suppose a high-priority linear accelerator or CT system costs several times more than a high-priority radiography unit. Selecting the top N ranks ignores acquisition cost, installation cost, capacity constraints, and the total risk reduction that can be achieved by different combinations. RGRA therefore converts replacement priority into a value model. Let V_i denote the expected lifecycle loss avoided by replacing rather than retaining candidate i over the planning horizon:

$$V_i = E(L_i \mid \text{retain}) - E(L_i \mid \text{replace}). \quad \textbf{(3)}$$

Loss can include expected failure and downtime consequences, maintenance and service burden, emergency procurement exposure, and other locally approved components. Clinical harm should be monetized only where the hospital has a defensible framework; otherwise consequence terms can remain in a multi-objective or constrained formulation. The essential point is that V_i represents the decision-relevant advantage of replacement, not merely a rank score. The funded replacement set is then selected under a capital budget B:

$$\max_x \Sigma_i x_i V_i \quad \text{subject to} \quad \Sigma_i x_i K_i \leq B, \quad x_i \in \{0,1\}. \quad \textbf{(5)}$$

Additional constraints can represent service continuity, medical-physics commissioning capacity, installation dependencies, or minimum modality coverage. For example, a hospital can prohibit overlapping replacement outages when the remaining CT or treatment capacity would fall below a prespecified service floor. When avoided-loss values vary materially across plausible scenarios s in S, a conservative capital plan can maximize the worst-case portfolio value:

$$\max_x \min_{s\in S} \Sigma_i x_i V_i^s \quad \text{subject to} \quad \Sigma_i x_i K_i^s \leq B, \quad x_i \in \{0,1\}. \quad \textbf{(3)}$$

Eq. (6) is not mandatory for every hospital; it is a robust counterpart for settings in which lifecycle value or implementation cost is sufficiently uncertain that a nominal knapsack can be unstable. RGRA therefore separates the ordinal question 'which device has the stronger replacement case?' from the allocation question 'which combination remains defensible within the actual capital plan across credible scenarios?'.

Fig. 3 provides a schematic capital-risk frontier at the portfolio level. Open circles on the dashed curve represent efficient feasible portfolios, grey circles represent dominated feasible alternatives, and the black circle marks the illustrative portfolio selected at the capital ceiling. The frontier

emphasizes that a higher-capital portfolio is justified only when the associated reduction in residual lifecycle loss is sufficient; the vertical line is an illustrative budget boundary rather than empirical hospital data.

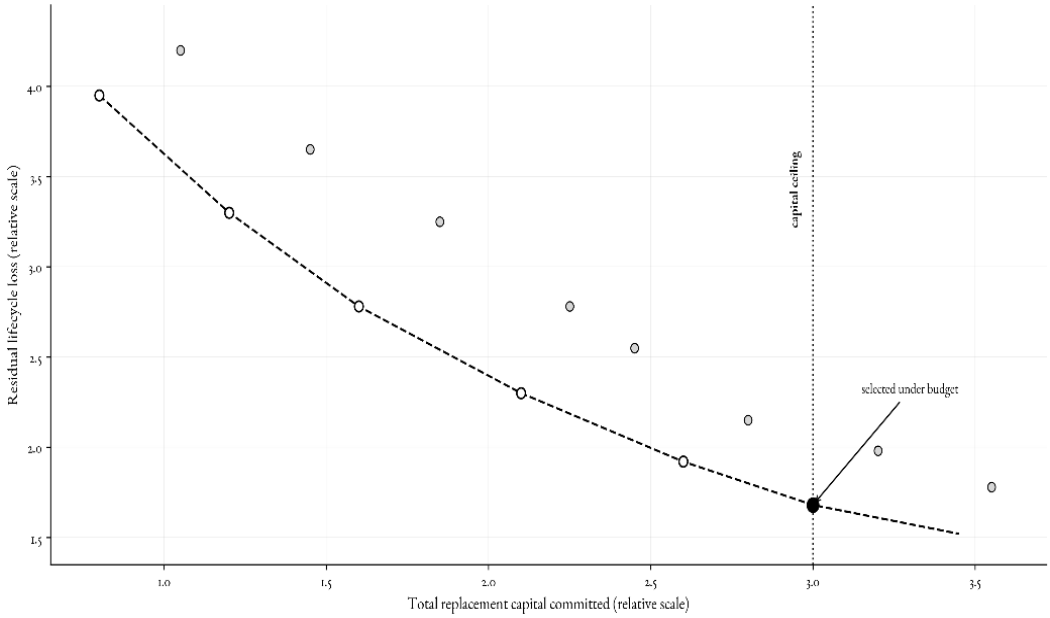

Fig. 3. Schematic capital-allocation frontier for radiological replacement portfolios; the dashed curve is the efficient frontier, gray circles are dominated feasible portfolios, and the black circle is the selected portfolio under the illustrative capital ceiling.

4.4 | Value of Information for Borderline Decisions

Uncertainty should sometimes trigger measurement rather than immediate replacement or deferral. Define a decision-relevant information set q for a borderline device, for example a detailed vendor support confirmation, calibrated performance test, clinical redundancy audit, or component-condition assessment. The Expected Value of Information (EVI) can be written conceptually as the expected improvement in the best attainable decision after information is obtained, net of the cost of acquiring that information. RGRA uses this principle selectively: Evidence collection is prioritized when it has a realistic probability of changing the gate status, interval classification, or funded portfolio.

$$\mathrm{EVI}(q) = \mathrm{E}\_q[\max_a \mathrm{U}(a \mid q)] - \max_a \mathrm{E}[\mathrm{U}(a)] - \mathrm{Cost}(q). \quad (7)$$

The value-of-information layer prevents two opposite errors. Without it, committees may repeatedly request more analysis even when the choice is already robust, delaying necessary replacement. Alternatively, they may commit capital to a borderline device because existing records are incomplete when one targeted inspection or vendor confirmation could resolve the uncertainty. Operationally, the rule is simple: collect more evidence when the expected decision benefit exceeds its cost and delay burden.

5 | Managerial Implementation and Research Propositions

5.1 | Data Architecture and Governance

Implementation should begin with a narrow candidate register, not an enterprise-wide attempt to score every device. Each candidate record should contain an asset identifier, device class, clinical service, gate evidence, failure and downtime history, supportability status, replacement-cost estimate, redundancy information, and the version of the criteria and weights used. Data from a computerized maintenance management system should be joined to safety-test records, procurement/vendor data, and clinical-capacity information using controlled identifiers. Free-text service records can be reviewed, but high-stakes gate decisions should not depend solely on an opaque text classifier.

Decision rights should also be separated. Biomedical or clinical engineering validates technical and maintenance evidence; clinical service owners validate consequence and redundancy; procurement/finance validate replacement cost and implementation burden; medical physics or radiation-safety functions validate applicable radiological conditions; and the capital committee approves the final funded set. A model owner maintains criteria, uncertainty rules, and audit logs, but should not have unilateral authority to override a gate. Overrides, when legally and clinically permissible, should be explicitly documented with accountable approval.

This governance structure directly addresses a common failure mode of decision-support systems: The score becomes the decision. In RGRA, the model is a structured argument. It shows what evidence triggered a gate, what uncertainty drives the priority interval, and why the optimization selected one combination over another. Human judgment remains necessary, but it becomes reviewable rather than hidden in an unexplained final ranking.

5.2|Testable Propositions

Because RGRA is conceptual, its contribution depends on whether its mechanisms can be falsified. The following propositions are therefore stated in comparative terms against realistic baselines such as age-only replacement, deterministic weighted scoring, or rank-first capital selection.

Proposition 1 (safety protection). A non-compensatory safety gate will reduce the rate at which devices with unresolved high-consequence safety conditions are retained or deferred relative to a purely additive replacement score, holding candidate information constant.

Proposition 2 (rank stability). Robust priority intervals will produce fewer decision reversals under plausible perturbations of criterion weights and measurement inputs than a single nominal weighted-score ranking.

Proposition 3 (capital efficiency). A budget-constrained portfolio selection based on replacement value will achieve greater avoided expected lifecycle loss per unit of capital than selecting candidates solely by descending priority rank, when replacement costs are heterogeneous.

Proposition 4 (supportability interaction). The effect of obsolescence and supportability on replacement priority will be stronger when clinical redundancy is low and consequence of unavailability is high than when substitutes are readily available.

Proposition 5 (information targeting). Value-of-information-guided evidence collection will reduce unnecessary immediate replacement or unstructured deferral among threshold-crossing candidates compared with uniform additional review of all candidates.

Proposition 6 (closed-loop calibration). Updating uncertainty sets, thresholds, and evidence mappings using realized post-decision downtime, maintenance cost, service disruption, and safety outcomes will improve out-of-sample decision calibration relative to static age- or score-based rules.

Table 4. Empirical validation design for the RGRA propositions.

Proposition	Comparator	Primary Outcome	Suggested Design
P1 safety protection	Additive score with safety as an ordinary criterion.	False-retention / false-deferral rate for expert-adjudicated gate cases.	Retrospective blinded re-ranking plus prospective gate review.
P2 rank stability	Nominal fixed-weight ranking.	Rank reversals; top-k overlap; threshold classification stability.	Bootstrap/scenario perturbation of evidence and stakeholder weights.
P3 capital efficiency	Replace top ranks until budget is exhausted.	Avoided lifecycle loss per capital unit; service interruption avoided.	Historical replay or prospective parallel capital-planning simulation.
P4 supportability interaction	Additive main-effects-only score.	Marginal priority effect across redundancy/consequence strata.	Regression or hierarchical model with prespecified interaction terms.

Table 4. Continued.

Proposition	Comparator	Primary Outcome	Suggested Design
P5 information targeting	Uniform extra review or immediate point-score decision.	Decision changes per review cost; avoidable delay; unnecessary replacement.	Prospective randomized or stepped-wedge review workflow where feasible.
P6 Closed-loop calibration	Static criteria/thresholds.	Calibration of predicted loss and decision outcomes across cycles.	Rolling-origin annual evaluation with locked rules per cycle.

5.3 | Empirical Validation and Performance Criteria

A credible validation should use historical replacement candidates and subsequent outcomes without leaking future information into the original decision date. At each historical planning cycle, the model should be reconstructed from records available at that time, then compared with actual committee decisions and alternative baselines. Candidate-level outcomes can include emergency replacement, high-severity failure, unplanned downtime, corrective-maintenance burden, and documented safety escalation. Portfolio-level outcomes can include capital used, planned-versus-emergency procurement, aggregate downtime, and concentration of risk across clinical services.

The strongest validation would be prospective. RGRA recommendations could initially run in shadow mode while the hospital retains its existing process. Disagreements between RGRA and the committee would be adjudicated without forcing action, generating a structured error taxonomy. After calibration, a phased or stepped implementation could compare services or planning cycles while preserving safety oversight. Statistical evaluation should report uncertainty around outcome differences rather than relying on a single success rate. Sensitivity to weight sets, missing data, and alternative loss definitions should be prespecified.

The model should also be evaluated for burden and interpretability. A replacement framework that requires months of manual data collection for every device may be academically elegant but operationally unusable. Metrics should therefore include analyst time per candidate, proportion of evidence automatically available, number of committee overrides, reason for override, and time from candidate nomination to decision. These implementation outcomes matter because the practical value of decision support is partly determined by whether it improves decision quality without creating an unsustainable administrative process.

5.4 | Boundary Conditions and Failure Modes

RGRA is not appropriate for every equipment decision. When a regulator, manufacturer, or governing safety authority mandates withdrawal, replacement, or corrective action, optimization is secondary to compliance. When only one candidate exists and its replacement is mandatory, portfolio optimization adds no value. Conversely, for low-risk commodity equipment with abundant substitutes, a simplified lifecycle-cost rule may be sufficient. The framework is most useful when multiple clinically important candidates compete for scarce capital and evidence contains both hard constraints and uncertain trade-offs.

Several failure modes require monitoring. First, poorly designed gates can become so broad that every aging device escalates, defeating prioritization. Second, narrow uncertainty sets can make robust intervals cosmetically precise; excessively broad sets can make them uninformative. Third, estimates of avoided lifecycle loss can embed double counting if failure, downtime, and maintenance cost are not carefully separated. Fourth, stakeholder weights can drift toward political bargaining if elicitation is not governed.

Finally, missing CMMS data can systematically disadvantage departments with weaker documentation. Governance should therefore treat data completeness and model calibration as quality indicators rather than hidden technical details.

6 | Conclusion

This article narrows healthcare technology management to one capital-allocation problem: how to fund replacement of high-cost radiological equipment when safety evidence, technical condition, service continuity,

and budget constraints interact. Prior research provides valuable replacement scores, reliability models, maintenance priorities, and multi-criteria methods, but these tools often blur three different tasks. RGRA addresses that gap by ordering the tasks explicitly. Safety admissibility is evaluated first through non-compensatory gates; replacement priority is then expressed robustly under uncertain weights and evidence; and the final funded set is selected under capital and continuity constraints. The result is not another universal score but an auditable decision architecture.

For managers, the key implication is that 'priority' and 'selection' should not be treated as synonyms. A device can have a strong replacement case yet be deferred because another combination creates more defensible value under the current budget, provided safety constraints remain satisfied. Conversely, a device with a moderate economic score may require immediate escalation because it fails a safety gate. This distinction protects patient and staff safety while preserving capital discipline. It also creates clearer accountability: the committee can identify whether a decision follows from safety evidence, uncertainty, lifecycle value, or a documented governance override.

The framework has important limitations. It is conceptual and has not yet been validated on a hospital replacement dataset; gate thresholds, criterion definitions, uncertainty sets, lifecycle-loss components, and decision rights require local calibration and legal/regulatory review. Robustness does not remove model risk, and value estimates can be biased by incomplete maintenance records or uncertain clinical consequences.

Future work should therefore build a multi-year dataset linking candidate nomination, maintenance history, safety evidence, replacement costs, committee decisions, and post-decision outcomes; compare RGRA against age-based and conventional multi-criteria baselines; test the six propositions prospectively; and evaluate whether the architecture remains stable across radiological modalities such as CT, fluoroscopy, radiography, and linear accelerators.

A successful empirical extension should be judged not by whether it produces a sophisticated score, but by whether it makes replacement decisions safer, more stable under uncertainty, and more efficient under real capital constraints.

Statements and Declarations

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Author Contributions

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Data Availability

No new datasets were generated or analyzed in this conceptual review. All sources used to develop the framework are cited in the manuscript.

Conflicts of Interest

The author declares no conflict of interest.

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