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From Fragmented DMD Management Toward Digitally Enabled Circularity: A Conceptual Operations Framework for Durable Medical Devices

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Abstract

Durable medical devices (DMD) are essential healthcare assets, yet their management in public hospitals is constrained by fragmentation, limited traceability, reactive maintenance, and weak lifecycle integration. This study proposes a framework for digitally enabled, sustainable, and circular DMD management. A mixed-methods design integrated a literature review, expert consultation using the Best–Worst Method, weighted technology nominations, and case-based process mapping in Brazilian hospitals. Eleven experts assessed the criteria guiding Industry 4.0 technology selection for DMD management and the technologies best responding to these priorities; nine consistent judgments were aggregated. Patient-Centered Care, Operational Efficiency, and Resource Efficiency and Cost Reduction emerged as the leading influences on technology selection. Big Data and Analytics, Artificial Intelligence, the Internet of Things, Cloud Computing, Cyber-Physical Systems, Smart Sensors, and Machine Learning formed the priority portfolio, accounting for 84% of the weighted score. The cases contextualized these priorities by revealing discontinuous information flows, limited asset visibility, corrective maintenance, fragmented governance, and weak end-of-life practices. By connecting decision priorities and technological capabilities with observed gaps, the TO-BE framework organizes sustainable procurement, traceable use, predictive maintenance, redeployment, refurbishment, and responsible disposal through material and information flows, providing a pathway for digital and circular transformation in resource-constrained healthcare systems.

Keywords: durable medical devices; digital transformation; circular economy

Academic Editor: Fabrizio D’Ascenzo

Received: 25 June 2026

Revised: 27 July 2026

Accepted: 29 July 2026

Published: 4 August 2026

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1. Introduction

Digital transformation has become a central driver of modernization in health systems worldwide, reshaping how institutions organize information, coordinate processes,

and manage resources [1,2]. The World Health Organization (WHO) emphasizes in its Global Strategy on Digital Health 2020–2025 that digitalization strengthens administrative efficiency and sustainability only when supported by coherent policies, interoperable infrastructures, and institutional capacity building [3]. However, despite global advances, progress remains uneven between clinical digitalization and the modernization of managerial and operational practices, particularly in contexts where health systems face chronic limitations in infrastructure and workforce development [4,5].

In Brazil, these asymmetries are evident within the Unified Health System (Sistema Único de Saúde—SUS). While national initiatives such as the SUS Digital Program have expanded digital health tools, persistent fragmentation between clinical, logistical, and asset management systems limits interoperability and reduces the capacity of institutions to plan, monitor, and evaluate key operational processes [6,7]. This gap is especially critical for the management of medical technologies, which depend on coordinated information flows to support procurement, maintenance, utilization, and end-of-life decisions [8,9].

Durable medical devices (DMD) occupy a strategic position within this scenario. Defined by the World Health Organization as equipment with long service life requiring periodic maintenance, these devices are essential for diagnostic, therapeutic, and monitoring activities [10]. Studies show that inadequate DMD governance leads to increased operational costs, premature obsolescence, extended downtime, and risks to patient safety [11–13]. Conversely, digital solutions strengthen lifecycle management by enabling traceability, improving maintenance planning, and supporting environmentally aligned decisions [14–16]. Yet, these advances remain limited in Brazilian public hospitals due to infrastructural heterogeneity, low digital maturity, and dependence on supplier-driven processes [7].

Technologies associated with Industry 4.0 (I4.0), originally applied in the industrial sector, offer promising pathways to overcome these constraints by expanding visibility over device use, predicting failures, and linking clinical and administrative systems in real time [17,18]. However, the literature still lacks integrated models that clarify how hospitals can connect specific operational weaknesses to appropriate technological solutions or transition from fragmented, linear routines to more circular and data-driven management approaches. Existing studies address isolated problems or technologies [14,15], but do not articulate how digital priorities, decision-making criteria, and structural gaps intersect to shape management outcomes [2,19].

Given these gaps, there is a need for structured models that help public hospitals align digital priorities with institutional realities and sustainability goals. While the literature identifies the potential of I4.0 and documents weaknesses in asset governance, it does not offer a framework that integrates these elements into a coherent management approach. Thus, the objective of this study is to propose a conceptual framework for the digital and sustainable management of DMD in Brazilian public hospitals, integrating priority decision-making criteria, relevant I4.0 technologies, and identified operational gaps. This contribution strengthens ongoing national digital-health strategies and supports managers and policymakers in advancing more efficient, traceable, and circular practices in device management.

2. Materials and Methods

This applied research adopted an exploratory-descriptive mixed-methods design integrating expert judgment, multicriteria prioritization, and cross-case empirical grounding. The objective was to identify relevant I4.0 technologies and decision-making criteria for the sustainable management of DMD, and to characterize operational and informational gaps in Brazilian public hospitals through lifecycle mapping.

The methodological structure comprised two sequential stages:

- (i) An expert panel for identifying and prioritizing I4.0 technologies and criteria relevant to DMD management;
- (ii) A qualitative multiple-case study in medium- and high-complexity healthcare units to map current DMD management practices and identify recurrent operational and informational gaps.

2.1. Stage 1: Expert Panel for Technology Identification

The first stage consisted of a structured expert consultation designed to identify and prioritize decision-making criteria and I4.0 technologies relevant for strengthening the sustainable management of DMD.

(a) Selection of criteria and technologies

Prior to the expert consultation, a literature review was conducted in databases such as Scopus, Web of Science, and PubMed (Table A1), focusing on studies addressing digital transformation, healthcare sustainability, and medical device management. From this review, nine decision making criteria commonly used to guide technology adoption in hospitals were identified: (i) interoperability and integration, (ii) data security and privacy, (iii) resource efficiency and cost reduction, (iv) operational efficiency, (v) organizational transformation and workforce training, (vi) environmental sustainability, (vii) implementation feasibility, (viii) adaptability and scalability across hospital sizes, and (ix) patient-centered care [20].

In parallel, the same literature review identified 13 digital technologies associated with the principles of I4.0 and recurrently cited in healthcare contexts. These included Internet of Things (IoT), Big Data and Analytics (BDA), Artificial Intelligence (AI), Smart Sensors (SS) [21,22], Cloud Computing (CC) [2], 3D Printing (3DP) [23], Cyber-Physical Systems (CPS), Blockchain (BC) [24], Collaborative Robotics (CR), Drones (DR), Augmented and Virtual Reality (AR/VR) [18,25], Machine Learning (ML) [26], and Digital Twins (DT) [27].

(b) Expert consultation

Eleven experts participated, selected for their combined experience in healthcare management, digital transformation, and industrial technology. The panel included university professors, clinical engineers, information technology professionals, and process-improvement consultants. A purposive sampling strategy ensured diversity of expertise, institutional affiliation, and regional representation. To preserve confidentiality, participants were identified by an alphanumeric code (R1–R11), as detailed in Table 1.

The consultation followed two main objectives:

- (i) To determine the relative importance of the nine decision-making criteria using the Best–Worst Method (BWM) [28];
- (ii) To identify the I4.0 technologies considered most relevant to each criterion.

The consultation was conducted individually between July/2025 and September/2025 using an electronic questionnaire developed in Google Forms (Google LLC, Mountain View, CA, USA). Each expert completed the assessment independently after receiving standardized instructions on the criteria, technologies, and BWM comparison scale.

The BWM was chosen because it derives priority weights using fewer pairwise comparisons than traditional approaches, such as the Analytic Hierarchy Process (AHP). Each expert identified the best and worst criteria among the nine evaluation criteria and completed two pairwise-comparison vectors using a 1–9 scale: the Best-to-Others vector, $A_{BO} = (aB1, \dots, aBn)$, and the Others-to-Worst vector, $A_{OW} = (a1W, \dots, anW)$. Comparisons of the best criterion with itself and of the worst criterion with itself were fixed at 1.

Individual criterion weights were obtained using the linear BWM model proposed by Rezaei [28], which minimizes the maximum absolute deviation between the weight ratios and the stated pairwise comparisons, subject to nonnegative weights summing to one.

$$\min \xi$$

subject to

$$|w_B - a_{Bj}w_j| \leq \xi, \forall j,$$

$$|w_j - a_{jW}w_W| \leq \xi, \forall j,$$

$$\sum_{j=1}^n w_j = 1, w_j \geq 0.$$

The optimization model was solved separately for each respondent using the Simplex LP method in Microsoft Excel for Microsoft 365, with the Solver add-in (Microsoft Corporation, Redmond, WA, USA).

Judgment consistency was assessed using the input-based consistency ratio (CR^I) proposed by Liang et al. [29]. For each criterion j , the local inconsistency was calculated as $CR_j^I = |a_{Bj}a_{jW} - a_{BW}| / (a_{BW}^2 - a_{BW})$, for $a_{BW} > 1$, where a_{BW} represents the direct comparison of the best criterion with the worst criterion. The respondent-level consistency ratio was calculated as $CR^I = \max_j CR_j^I$. For the nine criteria evaluated on the 1–9 scale, each respondent's CR^I was compared with the associated threshold corresponding to the respective a_{BW} value. A judgment was retained when its input-based CR did not exceed this threshold. The consolidated criterion weights were calculated as the arithmetic means of retained individual weights. The complete Best-to-Others and Others-to-Worst vectors are provided in Table A2.

Technology prioritization was subsequently calculated through weighted nominations. For each criterion j , the technology identified by respondent i as the most relevant was coded as $x_{ijt} = 1$, while all other technologies received $x_{ijt} = 0$. The raw weighted nomination score for technology t was calculated as $Q_t = \sum_{i=1}^R \sum_{j=1}^9 \bar{w}_j x_{ijt}$, where $\bar{w}_j$ is the consolidated BWM weight of criterion j , and R is the number of retained judgments. The normalized technology score was then obtained as $S_t = Q_t / \sum_{t=1}^{13} Q_t$ (Table A3). The thirteen normalized scores sum to one, and the ranking was determined using the unrounded values. For the subsequent analytical synthesis, the smallest leading set of technologies whose cumulative normalized score exceeded 80% was retained (Table A4).

Table 1. Characterization of specialists participating in the study.

Code	Position/Role	Field of Expertise	Years of Experience in the Area	State (Brazil)	Experience or Interaction with the Healthcare Sector
R1	University Professor	Production Engineering	3 to 5 years	Santa Catarina	Conducts research on sustainable hospital management and circular economy in healthcare institutions
R2	University Professor/Entrepreneur	Software Development	More than 10 years	Ceará	Developer of hospital information systems and data integration platforms for healthcare networks
R3	Clinical Engineering Technician	Full Clinical Engineering Technician	5 to 10 years	São Paulo	Direct experience with maintenance and calibration of medical devices in public hospitals
R4	University Professor	Information Science and Management	More than 10 years	Paraná	Participated in digital transformation projects for hospital data systems
R5	University Professor	Production Engineering	More than 10 years	Minas Gerais	Research digitalization and process optimization in hospital logistics
R6	Process Engineering Analyst II	Operational Excellence Consultant	More than 10 years	Ceará	Consultant in process improvement projects involving biomedical equipment management
R7	Technical and University Professor	Information Systems Development	More than 10 years	Rio Grande do Norte	Collaborates in the implementation of IoT-based monitoring systems in healthcare facilities

R8	University Professor	Information Systems Development	3 to 5 years	Rio Grande do Norte	Involved in research on data integration and cybersecurity in health services
R9	Senior Developer	Information Systems Development	More than 10 years	São Paulo	Works with data interoperability projects for public hospitals
R10	Continuous Improvement Analyst	Specialist/experienced in I4.0 technologies	3 to 5 years	Ceará	Supports digital maturity assessments for healthcare organizations
R11	Information Technology Coordinator	IT Professional and MSc in Information Technology	More than 10 years	Rio Grande do Norte	Responsible for IT infrastructure and maintenance management in hospital networks

2.2. Stage 2—Process Mapping and Contextual Grounding

The second stage examined how DMDs were managed throughout their lifecycle and identified recurrent operational, informational, and technological gaps. A multiple-case study was conducted across nine public healthcare organizations, comprising medium- and high-complexity healthcare units and municipal health secretariats with different management structures and levels of operational complexity within SUS (Table 2). The health secretariats were included because they coordinated equipment procurement and maintenance procedures for the units under their jurisdiction. Data were collected through on-site visits, document analysis, and semi-structured interviews addressing acquisition, use, maintenance, disposal, decision-making responsibilities, information flows, supplier interactions, and digital technologies (Appendix A.5).

Seventeen semi-structured interviews were conducted with participants purposively selected according to their involvement in DMD-related decisions. They included institutional managers and professionals responsible for equipment acquisition, inventory and asset control, maintenance coordination, procurement feasibility, and end-of-life procedures. In institutions without dedicated medical-equipment management or clinical engineering personnel, the senior manager responsible for these activities was interviewed. Additional professionals were included when responsibilities were distributed across different organizational functions. Participants were not individually linked to their institutions or specific roles. Before each interview, they were informed of the study objectives, ethical approval, and data-handling procedures and provided written informed consent. Responses were documented through structured field notes organized according to the DMD lifecycle stages.

Field notes, documentary evidence, and process observations were organized in an analytical matrix covering acquisition, use, maintenance, and disposal. A deductive coding structure based on these stages and the interview protocol was initially applied, followed by the identification of recurrent operational and informational gaps. Interview evidence was triangulated with institutional documents and direct observations whenever available.

The findings were modeled using Business Process Model and Notation (BPMN) in Bizagi Modeler, version 4.3.0.008 (Bizagi, Buckinghamshire, UK), to represent activities, actors, decision points, and information flows (Appendix A.6). Cross-case synthesis was used to compare workflows and governance arrangements across the institutions. Recurrent procedures, including procurement authorization, device allocation, maintenance requests, and repair-or-replacement decisions, were integrated into a unified pathway, while relevant context-specific variations were preserved during the analysis. This synthesis resulted in a reference model of the recurrent AS-IS configuration of DMD management, which supported the analysis presented in the Section 3.

Table 2. Structural and functional characterization of the healthcare units analyzed.

Nº	Code	Type of Institution	Location	Level of Care	Average Procedures per Month ¹	Number of Sus Beds ²	Type of Management	Relevance to the Research	Type of Care
1	HM1	Municipal Hospital	Parnamirim/RN	Emergency and Urgent Care	156.136 ³	66	Municipal Management	Provides hospitalizations and medium-complexity procedures for childbirth and care of children up to 2 years old.	Open Access + Referrals
2	HM2	Municipal Hospital	Parnamirim/RN	Emergency and Urgent Care	10.118 ³	18	Municipal Management	Provides hospitalizations and medium- to high-complexity procedures.	Open Access + Referrals
3	HR1	Regional Hospital	Parnamirim/RN	Emergency and Urgent Care	370.396 ³	135	State/Municipal Management	Provides hospitalizations and medium- to high-complexity procedures.	Open Access + Referrals
4	HR2	Regional Hospital	Currais Novos/RN	Medium Complexity Care	123.365 ³	78	State/Municipal Management	Only hospitals in the city offer inpatient care, with their own device management.	Open Access + Referrals
5	HR3	Regional Hospital	Macaíba/RN	Medium Complexity Care	70.843 ³	54	State/Municipal Management	Provides hospitalizations and medium-complexity procedures.	Closed Access
6	UPA1	Emergency Care Unit (ECU)	Parnamirim/RN	Emergency and Urgent Care	24.666 ⁴	8	Municipal Management	Strategic unit for emergency care in the metropolitan region.	Open Access + Referrals
7	UPA2	Emergency Care Unit (ECU)	Macaíba/RN	Emergency and Urgent Care	19.606 ⁴	7	Municipal Management	High patient flow and an essential role in triage and stabilization of patients.	Open Access + Referrals
8	SM1	Municipal Health Secretariat	Macaíba/RN	Public Management	—	—	—	Coordinates centralized purchasing, waste management, and hospital maintenance.	—
9	SM2	Municipal Health Secretariat	Sobral/CE	Public Management	—	—	—	Responsible for planning and standardizing local flows and processes. Coordinates the purchasing/maintenance of units without financial autonomy.	—

¹. Average number of procedures performed between March, April, May, and June 2025; ². Internal report provided by the unit; ³. <http://tabnet.datasus.gov.br/cgi/defctohtm.exe?sih/cnv/sparn.def> (accessed on 17 August 2025); and ⁴. <https://cnes.datasus.gov.br/pages/estabelecimentos/consulta.jsp> (accessed on 13 August 2025).

3. Results

3.1. Industry 4.0 Technologies for DMD Management: Analysis and Prioritization

The first stage of the analysis prioritized the decision-making criteria associated with the adoption of I4.0 technologies for the sustainable management of DMD. Using the BWM, the experts evaluated the relative importance of nine criteria related to operational performance, digital integration, sustainability, organizational capacity, and implementation conditions. Table 3 presents the individual criterion weights, CR values, associated thresholds, consolidated average weights, and resulting ranking.

The consistency assessment showed that the CR values of R4 and R9 exceeded their respective associated thresholds. Therefore, these two judgments were excluded from the aggregation, and the consolidated weights were calculated as the arithmetic mean of the nine retained evaluations, all of which had CR values below their associated thresholds.

Table 3 reveals considerable variation in the individual priorities, reflecting the different professional perspectives represented in the expert panel. Nevertheless, the aggregated results indicate a coherent concentration around three complementary dimensions: Patient-Centered Care (0.1580), Operational Efficiency (0.1445), and Resource Efficiency and Cost Reduction (0.1380). Together, these criteria account for 44.05% of the consolidated weight. Their relatively close values suggest that technology selection should not be guided by a single dominant objective, but by the combined capacity to improve clinical value, operational continuity, and resource utilization.

Implementation Feasibility ranked fourth, indicating that the perceived benefits of an I4.0 technology must also be considered in relation to its practical applicability within hospital settings. Adaptability and Scalability and Interoperability and Integration occupied intermediate positions, reinforcing the importance of solutions that can operate across institutions with different capacities and connect fragmented information environments. Figure 1 synthesizes this ranking in descending order. The lower relative weights assigned to organizational transformation, data security, and environmental sustainability should not be interpreted as evidence of irrelevance; rather, they indicate that these dimensions were comparatively less influential when experts evaluated the immediate priorities for technology selection.

The consolidated criterion weights were subsequently combined with the technologies nominated by the retained respondents. Each nomination was weighted according to the consolidated BWM weight of the corresponding criterion, thereby assigning greater influence on technologies associated with higher-priority decision dimensions. The resulting scores were normalized across the thirteen alternatives. Table 4 presents the weighted technology ranking and the cumulative proportion represented by each successive position.

The prominence of Big Data and Analytics and Artificial Intelligence indicates that the perceived value of digitalization in DMD management lies less in the isolated automation of activities than in the capacity to transform fragmented asset data into actionable knowledge. This result is particularly meaningful when considered alongside the criterion ranking. Patient-Centered Care, Operational Efficiency, and Resource Efficiency and Cost Reduction emerged as the leading decision dimensions, while BDA and AI provide the analytical capabilities required to connect equipment condition, utilization, maintenance history, cost, and clinical demand. Their prioritization therefore suggests that patient-centered care is understood not only through technologies directly used in clinical care, but also through the informational and predictive infrastructure that supports device availability, reliability, and appropriate allocation. This interpretation is consistent with studies positioning data integration and intelligent analytics as central capabilities for improving healthcare performance and decision quality [2,8,24].

Table 3. BWM prioritization matrix: consolidated weights of the evaluation criteria for I4.0 technologies applied to DMD management.

Criteria/ Respondent	Interoperability and Integration	Data Security and Privacy	Resource Efficiency and Cost Reduction	Operational Efficiency	Patient- Centered Care	Organizational Transformation and Workforce Training	Environmental Sustainability	Implementation Feasibility	Adaptability and Scalability Across Hospital Sizes	Input- Based CR	Associated Threshold
R1	0.1038	0.1557	0.1557	0.2513	0.1038	0.0623	0.0273	0.0778	0.0623	0.3095	0.3403
R2	0.1107	0.0664	0.0830	0.2680	0.1107	0.1107	0.0291	0.1107	0.1107	0.1528	0.3662
R3	0.0943	0.0404	0.0943	0.1818	0.0707	0.1414	0.1414	0.0943	0.1414	0.1190	0.3403
R4 *	0.0738	0.0886	0.1107	0.1107	0.0738	0.0886	0.3083	0.0347	0.1107	1.0000	0.3262
R5	0.0540	0.0540	0.0863	0.0863	0.3237	0.0719	0.1439	0.1439	0.0360	0.3036	0.3657
R6	0.1156	0.1392	0.1392	0.1392	0.1392	0.1274	0.0118	0.0495	0.1392	0.3333	0.3403
R7	0.0782	0.0782	0.0329	0.0939	0.3333	0.0939	0.0939	0.0782	0.1174	0.3611	0.3662
R8	0.0879	0.0628	0.3295	0.0732	0.0732	0.0439	0.1464	0.0732	0.1098	0.3333	0.3403
R9 *	0.0873	0.0679	0.0873	0.0764	0.3989	0.0311	0.0873	0.0873	0.0764	1.0000	0.3662
R10	0.0978	0.0978	0.2609	0.0870	0.0870	0.0978	0.0870	0.0870	0.0978	0.3194	0.3662
R11	0.1202	0.0515	0.0601	0.1202	0.1803	0.0231	0.0515	0.2728	0.1202	0.3571	0.3657
Average weights (n = 9)	0.0958	0.0829	0.1380	0.1445	0.1580	0.0858	0.0814	0.1097	0.1039	-	-
Ranking	6	8	3	2	1	7	9	4	5		

Note: Rows marked with an asterisk (*) indicate respondents excluded from the aggregation because their input-based CR exceeded the associated threshold. n = 9 represents the number of expert judgments retained for calculating the average weights.

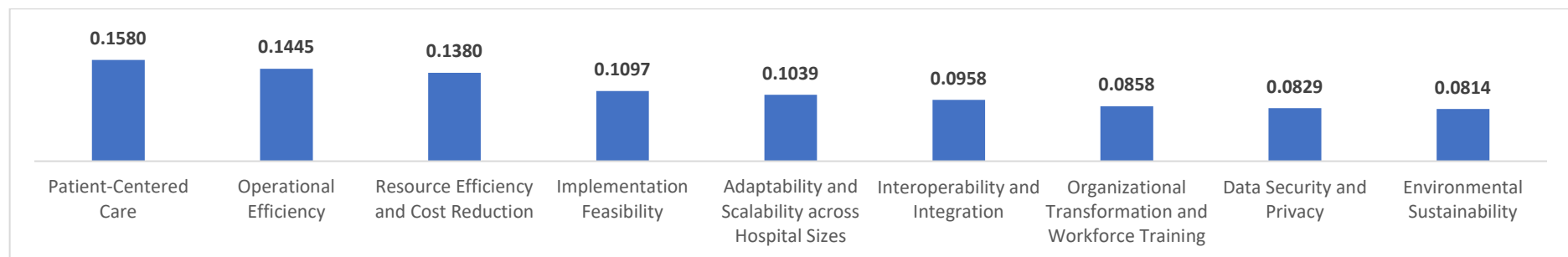
**Figure 1.** Average weights associated with the criteria for selecting I4.0 technologies that can contribute to the sustainable management of DMD.

Table 4. Weighted ranking of I4.0 digital technologies for DMD management.

Ranking	I4.0 Technology	Frequency	Weighted Nomination Score (n = 9)	Cumulative Score
1	BDA	20	0.2351	23.51%
2	AI	16	0.2210	45.61%
3	IoT	8	0.1015	55.76%
4	CC	8	0.0996	65.72%
5	CPS	5	0.0688	72.60%
6	SS	4	0.0649	79.09%
7	ML	5	0.0526	84.35%
8	BC	5	0.0461	88.96%
9	AR/VR	4	0.0455	93.51%
10	3DP	3	0.0271	96.22%
11	DT	2	0.0217	98.39%
12	CR	1	0.0161	100.00%
13	DR	0	0.0000	100.00%

Note: Rankings were determined using unrounded weighted nomination scores. n = 9 represents the number of expert judgments retained for aggregation after the consistency-based exclusion of R4 and R9. Rankings were determined using unrounded weighted nomination scores.

The subsequent positions occupied by IoT, Cloud Computing, CPS, Smart Sensors, and Machine Learning reinforce this interpretation by revealing a coherent digital architecture rather than a collection of independent technological alternatives. These technologies perform interdependent functions across data generation, connectivity, integration, contextualization, and predictive analysis [11,21,30]. In combination, they enable the construction of a digital thread across the DMD lifecycle, linking acquisition and use data to maintenance, redistribution, refurbishment, and end-of-life decisions. The ranking thus converges with research showing that the benefits of I4.0 arise from complementary technological capabilities and their integration into organizational processes, rather than from the adoption of isolated tools [14,17,24–26]. It also explains why technologies with different immediate applications appear within the same priority group: their strategic contribution derives from their position within an interconnected information and decision architecture.

Conversely, the lower positions of technologies such as Blockchain, AR/VR, 3D Printing, Digital Twins, Collaborative Robotics, and Drones should not be interpreted as evidence of limited technological potential. The ranking instead reflects the breadth with which each technology was associated with the decision criteria examined. General-purpose data and connectivity technologies can contribute simultaneously to several managerial needs, whereas more specialized technologies tend to depend on particular applications, lifecycle stages, infrastructure conditions, or levels of organizational readiness. This distinction is consistent with the literature on digital capability development, which suggests that advanced and application-specific solutions generate greater value when supported by consolidated data, integration, and governance capabilities [14,17,25]. Accordingly, the results establish a sequencing logic: foundational capabilities for visibility and analytical intelligence precede, but do not eliminate, more specialized applications.

The seven leading technologies jointly represent 84.35% of the normalized score and constitute the smallest group exceeding the adopted cumulative coverage threshold of 80%. They were therefore retained for the subsequent synthesis connecting the prioritized technologies to the management gaps identified in the case studies. Importantly, their selection should not be interpreted as evidence that digitalization itself produces circularity. Rather, these technologies provide the informational and analytical conditions required

to operationalize circular practices, such as utilization monitoring, preventive maintenance, redistribution, refurbishment, life extension, reverse logistics, and end-of-life management, whose effective implementation still depends on organizational procedures, governance arrangements, and institutional capacity. In this sense, the ranking identifies digital enablers of the proposed TO-BE model, not evidence that circular DMD management has already been achieved.

3.2. Mapping of DMD Operational Flow Management in Public Healthcare Units

The cross-case analysis identified recurrent structural, informational, and operational weaknesses affecting DMD management across municipal hospitals, Emergency Care Units, and regional hospitals. The detailed BPMN representation provided in Appendix A.6 documents the activities, decision points, actors, and process sequences observed in the participating institutions. Figure 2 performs a complementary analytical function by consolidating the recurrent findings into four macro-stages (acquisition, use, maintenance, and disposal). For each stage, the figure summarizes the principal actors, subprocesses, and operational gaps identified across the cases, thereby providing an overview of the fragmented AS-IS management configuration.

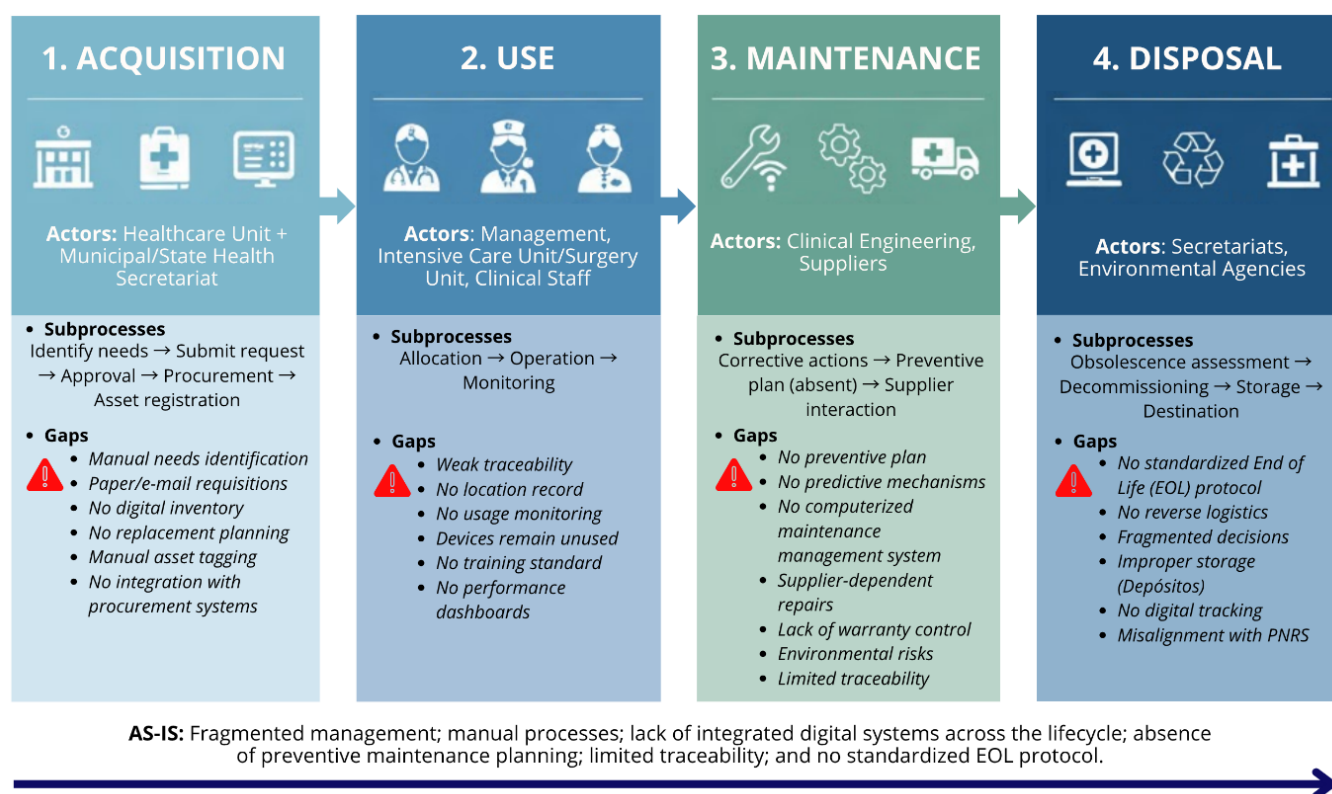


Figure 2. Consolidated AS-IS representation of DMD management in the participating public healthcare units.

A central weakness was the absence of an integrated traceability structure. None of the nine participating units maintained a digital inventory capable of simultaneously recording device location, operational condition, utilization, and maintenance history. Information was instead distributed among spreadsheets, paper records, isolated systems, and the knowledge retained by individual employees. This fragmentation affects more than inventory accuracy: it limits the ability to associate clinical demand with device availability, identify underutilized assets, anticipate replacement needs, and reconstruct lifecycle histories. The finding is consistent with Hoveling et al. [11] and Rowan [18], who

identify lifecycle information and asset visibility as prerequisites for safer, more efficient, and potentially circular medical-device management.

Maintenance practices reproduced the same informational fragmentation. Corrective intervention predominated, generally occurring after failure or at the end of warranty coverage, while preventive schedules, condition monitoring, and predictive mechanisms were either absent or not systematically institutionalized. Maintenance records were not integrated with procurement, utilization, or replacement decisions, thereby preventing accumulated technical data from informing subsequent interventions. Supplier dependence was therefore not merely a contracting issue but also a consequence of limited internal diagnostic capacity and weak organizational learning. This pattern converges with Tortorella et al. [17] and Toscas et al. [12], who associate reactive maintenance structures with increased downtime, shortened asset lifespans, and reduced capacity for technology management.

Governance arrangements further intensified these discontinuities. In municipal hospitals and Emergency Care Units, procurement, bidding, and end-of-life decisions were largely centralized within municipal health secretariats, producing organizational distance between the units that used the devices and the administrative structures authorized to act on them. Regional hospitals presented comparatively greater decision autonomy, but this difference did not compensate for the absence of integrated inventories, standardized records, and computerized maintenance systems.

Consequently, fragmentation occurred both vertically between healthcare units and central administrative authorities, and horizontally between clinical, technical, procurement, and asset-management functions. These findings reinforce the importance of standardized nomenclatures and integrated registries for traceability, regulatory compliance, and coordinated planning [31–33].

The weaknesses also extended to asset utilization and lifecycle recovery. Obsolete devices were frequently retained in storage while awaiting administrative decisions; functional equipment could remain underutilized because usage information was unavailable; and redistribution was not supported by systematic comparisons between demand and installed capacity. Procurement workflows were lengthy and poorly visible to operational units, while standardized training records and digital guidance for device use were limited. Moreover, the participating institutions did not employ formal criteria for evaluating refurbishment, upgrading, reuse, or replacement. These conditions connect problems that might otherwise appear independent: inadequate records obscure utilization; low visibility inhibits redistribution; delayed decisions prolong storage; and the absence of technical and economic assessment criteria restricts recovery and life-extension alternatives.

End-of-life management represented the point at which these operational and governance limitations became environmental constraints. Devices could remain stored for prolonged periods, and reverse-logistics and recovery pathways were not systematically incorporated into routine decision-making. Although the National Solid Waste Policy provides a formal regulatory basis for environmentally appropriate management, the cases revealed limited operational translation of these requirements into defined responsibilities, information flows, assessment criteria, and documented procedures [34,35]. The evidence therefore points primarily to an implementation gap: existing regulatory guidance was not consistently converted into coordinated organizational practices.

Taken together, the AS-IS findings indicate that fragmentation is not confined to a particular lifecycle stage. It operates as a cross-cutting condition produced by disconnected information, distributed decision authority, reactive routines, and limited integration among clinical, technical, administrative, and environmental responsibilities. The resulting management model reduces asset visibility and decision predictability while reinforcing supplier dependence and constraining maintenance, redistribution,

refurbishment, and end-of-life planning. Figure 2 summarizes how these weaknesses manifest across the four macro-stages of the current DMD management process. The broader cross-case analysis, however, identified additional problems related to storage, redistribution, training, procurement coordination, and refurbishment or replacement decisions. These findings were subsequently consolidated into the ten management problems presented in Table 5.

Table 5. Strategic Alignment of DMD Management Gaps with Digital Enablers.

Identified Problem (AS-IS)	Decision Need	Applicable I4.0 Technology	Technology Output/Contribution to Decision-Making
P1. No traceability of DMD (no location record, no usage data, no maintenance history)	Improve visibility of inventory, usage and status	IoT, SS, CPS, CC	Continuous monitoring, automatic data capture, cyber-physical linkage between device status and information systems, and real-time dashboards
P2. Reactive maintenance and absence of preventive/predictive planning	Anticipate failures and improve reliability	SS, CPS, AI, ML, BDA	Condition monitoring, integration of device-generated data, predictive models, failure forecasting and optimized maintenance scheduling
P3. Fragmented information systems (paper spreadsheets, parallel controls, lack of interoperability)	Integrate administrative, technical and clinical data	CC, BDA, CPS	Centralized databases, interoperable systems, unified access, and continuous information flows across administrative, technical, and clinical functions.
P4. Supplier-dependent repairs and diagnostics	Strengthen internal diagnostic capabilities and decision-making autonomy	SS, CPS, AI, ML	Automated diagnostics, condition-based monitoring, anomaly detection, and greater internal diagnostic autonomy
P5. No standardized end-of-life (EOL) protocol	Ensure compliance with PNRS and structured disposal decisions	CC, BDA, IoT	Tracking of obsolescence triggers, EOL classification, documentation for legal compliance, digital recordkeeping
P6. Improper storage of obsolete devices	Define recovery, reuse or disposal pathways	BDA, CC	Categorization models, feasibility assessment, and lifecycle traceability to support environmentally sound recovery, reuse, or disposal decisions
P7. Underutilized or idle devices (unmonitored usage)	Optimize redistribution and avoid unnecessary purchases	IoT, SS, CPS, BDA	Real-time usage monitoring, device-status integration, performance analysis, and identification of underused assets
P8. Long acquisition cycles and opaque approval workflows	Improve procurement coordination	CC, AI	Workflow integration, automated routing, documentation tracking, transparency
P9. Lack of structured training and digital records in use stage	Standardize operation and reduce misuse	CC, AI	Protocol access, guided instructions, digital checklists, reduction in operational errors
P10. No structured refurbishment or upgrade criteria	Evaluate the feasibility of reuse, refurbishment, upgrading, or replacement	BDA, ML, CPS	Data-driven assessment of performance degradation and lifecycle status, supporting decisions on refurbishment, upgrading, or replacement

Legend: Internet of Things (IoT), Big Data and Analytics (BDA), Artificial Intelligence (AI), Smart Sensors (SS), Cloud Computing (CC), Machine Learning (ML), Cyber-Physical Systems (CPS), and Brazilian National Solid Waste Policy (PNRS).

To translate the cross-case evidence into structured decision needs, the recurrent weaknesses identified in the process mapping were consolidated into ten management problems (P1–P10). Each problem was first associated with the managerial response required to address it and was then linked to technologies drawn from the seven alternatives retained in the weighted ranking. These mappings were not inferred from technological popularity alone. They were developed by combining the empirical characteristics of each gap with the functional capabilities reported in the literature and the priorities established through the expert assessment.

Table 5 shows that the digital response to DMD management gaps cannot be reduced to a one-to-one correspondence between a problem and a technology. Most gaps require complementary capabilities. Traceability, for example, depends on device-level identification and monitoring, but also on interoperable storage and analytical environments capable of converting status data into allocation and replacement decisions. Likewise, predictive maintenance requires sensing and connectivity to capture equipment conditions, analytical models to identify degradation patterns, and organizational processes capable of acting on the resulting information. The mappings therefore represent configurations of enabling capabilities rather than deterministic technological solutions.

The table also reveals that several technologies contribute to problems located at different lifecycle stages. This cross-cutting role is particularly evident for BDA, AI, IoT, Cloud Computing, Smart Sensors, and CPS, whose functions extend from acquisition and utilization monitoring to maintenance, redistribution, and lifecycle assessment. Their recurrence across the mappings is consistent with the technology ranking and supports the interpretation that DMD management depends on an integrated data architecture rather than isolated digital applications. At the same time, the proposed contributions remain conditional on data quality, interoperability, workforce capability, governance, and clearly assigned decision responsibilities. Accordingly, Table 5 provides the analytical bridge between the diagnosed AS-IS configuration and the proposed TO-BE framework, rather than evidence that technology adoption alone will resolve the identified weaknesses.

4. Discussion and Framework Proposal

The cross-case analysis revealed that the weaknesses affecting DMD management are not confined to isolated activities but arise from the interaction among fragmented information, reactive operational routines, limited coordination, and insufficient lifecycle visibility. The absence of reliable records regarding device location, condition, utilization, and maintenance history restricts the capacity of healthcare units to anticipate failures, redistribute underused assets, and make evidence-based decisions. Rowan [18] similarly emphasizes the importance of digitally supported lifecycle information for improving the safety and sustainability of medical devices, while Toscas et al. [12] demonstrate how weaknesses in medical equipment management can compromise availability, maintenance planning, and institutional responsiveness within the Brazilian public health system.

The predominance of corrective maintenance observed in the participating units further illustrates how informational fragmentation becomes an operational constraint. Without integrated inventories, standardized records, or continuous monitoring, maintenance decisions remain dependent on equipment failure, supplier intervention, and locally dispersed knowledge. Tortorella et al. [17] associate Healthcare 4.0 implementation with the ability to strengthen process control and operational performance, whereas Osama et al. [36] identify connectivity, data availability, interoperability, and technical capacity as essential requirements for the effective application of Internet of Medical Things solutions. The findings therefore suggest that maintenance deficiencies are not

exclusively technical. They also reflect limitations in the institutional capacity to generate, integrate, and use information throughout the device lifecycle.

Governance fragmentation reinforces these limitations. The separation among administrative, technical, clinical, procurement, and disposal functions creates discontinuities that prevent information generated in one stage from supporting decisions in subsequent stages. Mishra et al. [8] and Sharma et al. [9] show that the integration of assets, logistics, and information systems is central to improving operational performance in digitally enabled healthcare and supply chains. Freitas et al. [13] further demonstrate that medical device decisions depend on the clarification of stakeholder roles and contributions. In the analyzed institutions, however, responsibilities were distributed among multiple actors without a common informational structure, weakening accountability and reducing the continuity of decisions across acquisition, use, maintenance, and end-of-life management.

The findings also indicate that regulatory provisions alone are insufficient to ensure integrated DMD management. The principal limitation observed was the institutional difficulty of translating requirements into standardized and coordinated routines. Kartavtsev and Slabkiy [31] highlight the importance of structured medical device classification, while Aida Neto [32] and Iadanza et al. [33] emphasize the contribution of standardized records and nomenclature systems to equipment identification, traceability, and regulatory compliance. These elements were only partially present in the participating units. Consequently, compliance, operational performance, and lifecycle planning remained dependent on parallel spreadsheets, paper records, and localized procedures rather than on a shared management infrastructure.

This interpretation is consistent with the barriers identified in broader digital transformation research. The World Health Organization [3] recognizes interoperability, institutional capacity, and information governance as fundamental components of digital health transformation. In the Brazilian context, the SUS Digital Program [6] and the challenges identified by IEPS [7] similarly indicate that digitalization requires more than the acquisition of technological tools. It depends on organizational readiness, workforce capabilities, data governance, and integration among existing systems. Dixit and Dutta [4] also associate limited technical capacity, financial restrictions, and institutional fragmentation with difficulties in adopting circular practices in healthcare. These conditions help explain why the operational gaps persisted across the cases despite the existence of regulatory guidance and national digitalization initiatives.

The BWM results complement this diagnosis by showing that the experts did not prioritize technological adoption solely from an efficiency perspective. Patient-Centered Care received the highest consolidated weight, followed by Operational Efficiency and Resource Efficiency and Cost Reduction. Together, these criteria indicate that the expected contribution of digital technologies is simultaneously clinical, operational, and economic. Patient safety and continuity of care depend on the availability and reliability of devices, while operational stability and resource stewardship determine whether this availability can be sustained. Mariz et al. [19] similarly connect Healthcare 4.0 technologies with patient safety, and Saha and Rathore [15] argue that digital information-processing capabilities can improve healthcare supply chain performance by strengthening coordination and responsiveness.

The proximity among the three leading criterion weights is particularly relevant. Rather than indicating the predominance of a single objective, the results reveal an interdependent set of priorities in which clinical value, operational performance, and efficient resource use must be addressed jointly. Implementation Feasibility and Adaptability and Scalability across Hospital Sizes occupied the following positions, indicating that perceived technological relevance also depends on whether solutions can be implemented

under heterogeneous infrastructural and organizational conditions. This finding is compatible with Tortorella et al. [17], who demonstrate that Healthcare 4.0 priorities vary according to institutional readiness, and with Rossetti et al. [30], who emphasize the organizational and knowledge-related conditions required for I4.0 technologies to generate value.

Conversely, the lower relative weights assigned to Environmental Sustainability, Data Security and Privacy, and Organizational Transformation and Workforce Training should not be interpreted as evidence that these dimensions are unimportant. Their position reflects the relative urgency attributed to immediate clinical and operational problems within the evaluated decision structure. Beltrami et al. [21] and Ghobakhloo et al. [22] caution that the sustainability benefits of I4.0 are contingent on organizational capabilities and cannot be assumed as automatic consequences of digitalization. Likewise, Piscicelli [23] argues that digital technologies can support circularity only when their adoption is accompanied by appropriate governance and value-retention strategies. The lower ranking of these criteria therefore exposes a potential implementation risk, since the technologies prioritized to address urgent operational needs will still require data protection, workforce preparation, and environmental governance.

The technology ranking reinforces this systemic interpretation. Big Data and Analytics and Artificial Intelligence achieved the highest relevance, followed by the Internet of Things, Cloud Computing, Cyber-Physical Systems, Smart Sensors, and Machine Learning. These technologies should not be understood as independent alternatives. Together, they constitute complementary layers of digital architecture. IoT and Smart Sensors enable the capture of device condition, location, and utilization data; CPS connects physical equipment with computational processes; Cloud Computing supports data availability and integration; and BDA, AI, and ML transform these records into analytical and predictive information. Kumar et al. [24] discuss the value of integrating AI, IoT, Big Data, and related digital technologies in healthcare, while Deepa et al. [26] demonstrate how IoT-enabled monitoring and machine-learning algorithms can support real-time analysis. Tao et al. [27] further explain the role of CPS in linking physical assets and digital decision environments.

The prominence of this technological configuration is also consistent with the operational gaps identified in the case studies. Traceability requires continuous data capture and device identification, predictive maintenance requires reliable historical and condition data, and redeployment depends on visibility over location, utilization, and functional status. Liu et al. [14] associate digital capabilities with improved resource coordination and circular supply chain management, while Rowan [18] highlights the contribution of digital technologies to lifecycle monitoring and safer medical device management. Swayamsiddha et al. [37] and Osama et al. [36] likewise demonstrate the relevance of connected monitoring infrastructures for real-time surveillance and decision support. The results therefore suggest that the principal contribution of the seven technologies lies in their integration rather than in the isolated performance of any single tool.

The lower ranking of technologies such as Digital Twins, Augmented and Virtual Reality, 3D Printing, Collaborative Robotics, and Drones does not indicate an absence of potential value. Their application tends to be more specialized, dependent on mature digital infrastructure, or concentrated in specific clinical, manufacturing, training, or logistical functions. Rowan [18], for example, identifies relevant applications of Digital Twins and extended reality in the medical device sector, while Tao et al. [27] demonstrate their relationship with CPS and advanced digital environments. In the context examined here, however, experts assigned greater relevance to technologies capable of addressing foundational problems such as fragmented data, limited traceability, reactive maintenance,

and insufficient interoperability. The ranking thus expresses contextual applicability rather than universal technological superiority.

The convergence among the process mapping, BWM prioritization, and technology ranking provided the basis for the proposed framework presented in Figure 3. The framework does not represent an empirically implemented circular system. Instead, it translates the identified AS-IS gaps into a TO-BE conceptual configuration that connects six lifecycle-oriented stages: sustainable procurement, traceable use, predictive maintenance, device redeployment, refurbishment and upgrading, and responsible disposal. This progression extends the four macro-stages represented in the AS-IS mapping by explicitly incorporating redeployment and refurbishment as value-retention strategies. Hoveling et al. [11] emphasize the importance of reuse, repair, refurbishment, and lifecycle-oriented design for medical device circularity, while Elmassah [34] and Jabbour et al. [35] relate I4.0 capabilities to circular strategies based on resource visibility, coordination, and value recovery.

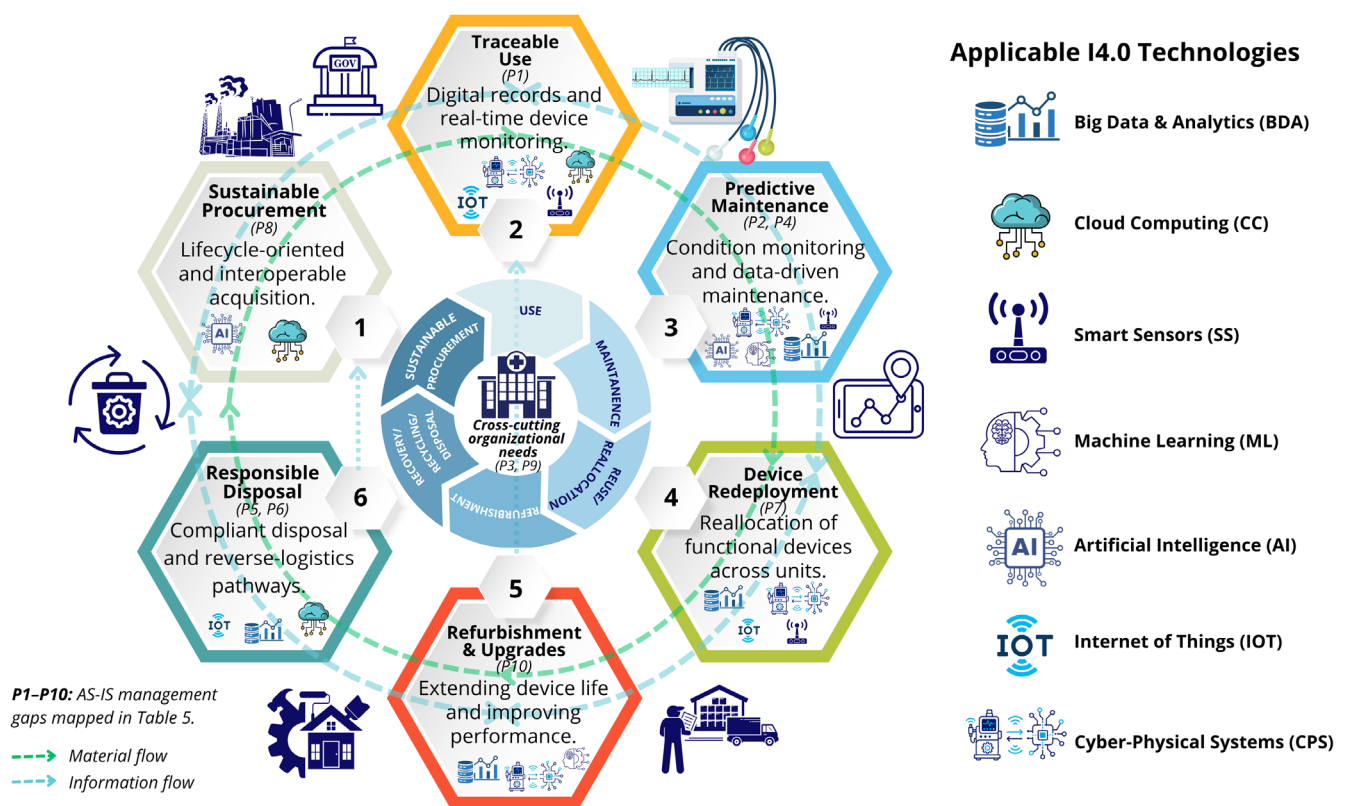


Figure 3. Proposed TO-BE conceptual framework for digitally enabled sustainable and circular DMD management. Numbers 1–6 represent the six management stages: (1) sustainable procurement, (2) traceable use, (3) predictive maintenance, (4) device redeployment, (5) refurbishment and upgrades, and (6) responsible disposal. The different colors visually distinguish these stages and do not represent quantitative values or levels of importance. Green dashed arrows represent material flows, while blue dashed arrows represent information flows.

The framework also distinguishes stage-specific management needs from cross-cutting organizational requirements. Problems related to fragmented information systems and insufficient training and digital records, represented by P3 and P9, are positioned at the center because they affect all six stages rather than a single point in the lifecycle. This central position reflects the argument advanced by the World Health Organization [3] that governance, interoperability, and institutional capacity are transversal conditions for digital transformation. It also responds to the evidence presented by Freitas et al. [13], since

effective DMD management requires the coordination of administrative, clinical, technical, and managerial knowledge.

In Figure 3, material flows represent the movement, retention, redistribution, refurbishment, and final destination of devices, whereas information flows represent the records and decision inputs required to coordinate these movements. Their interaction is essential because circular actions cannot be reliably implemented without information on device identity, location, condition, performance, and maintenance history. Liu et al. [14] and Piscicelli [23] similarly argue that digital capabilities can enable circular strategies by improving visibility and coordination, although these technologies do not guarantee circular outcomes by themselves. Accordingly, the technology icons included in Figure 3 indicate potential enabling capabilities for each stage and should not be interpreted as mandatory, exclusive, or universally applicable technological assignments.

For practical application, the framework can support a four-step decision process. First, institutions should diagnose their current DMD management configuration using the AS-IS mapping and the problems summarized in Table 5. Second, each identified gap should be evaluated against the decision criteria, considering Patient-Centered Care, Operational Efficiency, Resource Efficiency and Cost Reduction, implementation feasibility, scalability, interoperability, organizational capacity, data security, and environmental sustainability. Third, managers should select a compatible technological configuration based on the functional requirements of the problem, existing infrastructure, data availability, workforce capabilities, interoperability, and investment capacity. Finally, implementation should proceed incrementally and be monitored through indicators related to device availability, utilization, downtime, maintenance performance, redeployment, life extension, waste prevention, and end-of-life compliance.

This application logic avoids treating digitalization as an end in itself. Instead, technology selection becomes part of a staged organizational transition in which operational stabilization, information integration, and lifecycle coordination create the conditions for progressively more circular practices. Kraus et al. [1] and Dohan et al. [5] describe healthcare digital transformation as an organizational change in value creation rather than a simple technological substitution. Similarly, Beltrami et al. [21] and Ghobakhloo et al. [22] demonstrate that the relationship between I4.0 and sustainability depends on how technological capabilities are embedded in processes, strategies, and institutional structures. The framework therefore proposes a pathway for connecting technological adoption with clinical, operational, and environmental objectives without assuming that digital maturity or circularity has already been achieved.

The findings should nevertheless be interpreted within the methodological boundaries of the study. The BWM aggregation was based on nine retained evaluations from a purposively selected panel of eleven experts, after two evaluations exceeded their associated consistency thresholds. Although the panel incorporated complementary managerial, technological, and academic perspectives, only a limited number of participants had direct clinical engineering or hands-on DMD management experience. This composition may have influenced the relative priorities obtained and should be considered when interpreting the findings. Accordingly, the resulting weights and technology rankings represent structured expert judgments rather than population-level estimates. In addition, the weighted nomination procedure captures the perceived relevance of technologies in relation to the evaluated criteria but does not compare their technical performance, implementation costs, organizational requirements, or realized sustainability outcomes. The cumulative threshold used to retain the seven priority technologies served as an analytical rule for obtaining a parsimonious set and should not be interpreted as evidence that lower-ranked technologies are ineffective.

The empirical component was limited to nine public healthcare units located in Northeastern Brazil. Although the recurrence of similar weaknesses across different types of institutions supports the analytical relevance of the findings, it does not permit statistical generalization to other Brazilian regions or healthcare systems. Furthermore, the framework was derived from the integration of expert prioritization, cross-case evidence, process mapping, and literature-based technological capabilities, but it was not implemented or longitudinally evaluated in the participating institutions. Accordingly, it should be interpreted as a context-sensitive conceptual proposition rather than as an empirically validated management model.

Within these boundaries, the framework provides a structured conceptual basis for connecting DMD management gaps with decision priorities, lifecycle strategies, and enabling digital capabilities. Its contribution does not lie in prescribing a universal technological configuration, but in demonstrating how healthcare institutions can organize a context-sensitive transition from fragmented and reactive practices toward more traceable, coordinated, resource-efficient, and progressively circular DMD management.

5. Conclusions

This study examined how decision priorities, digital technologies, and operational weaknesses can be integrated to support more sustainable DMD management in public hospitals. The findings indicate that the main challenges are not confined to individual lifecycle stages. They emerge from the combined effects of fragmented governance, discontinuous information flows, limited asset traceability, reactive maintenance, and insufficient coordination among administrative, technical, clinical, and environmental functions.

The multicriteria analysis showed that Patient-Centered Care, Operational Efficiency, and Resource Efficiency and Cost Reduction constitute the leading decision priorities. Their proximity indicates that technological adoption should simultaneously protect clinical value, stabilize operations, and improve the use of constrained resources. The technology ranking complemented this result by identifying BDA, AI, IoT, CC, CPS, SS, and ML as the leading set of digital enablers. Rather than representing isolated alternatives, these technologies form complementary capabilities for data capture, connectivity, integration, monitoring, and predictive analysis throughout the DMD lifecycle.

By combining expert prioritization with cross-case process evidence, the study developed a TO-BE conceptual framework that connects sustainable procurement, traceable use, predictive maintenance, device redeployment, refurbishment and upgrading, and responsible disposal. The framework extends the predominantly linear and fragmented configuration observed in the participating institutions by incorporating value-retention strategies and distinguishing lifecycle stages from cross-cutting organizational needs. Its central contribution is therefore not the prescription of a universal technological solution, but the organization of a decision logic through which hospitals can relate identified management gaps to institutional priorities and compatible digital capabilities.

The proposed framework should be interpreted as a context-sensitive conceptual basis rather than as evidence that digital circularity has already been achieved. Its application will depend on data quality, interoperability, workforce preparation, governance arrangements, financial capacity, and the technological readiness of each institution. Although the recurrence of similar gaps across the analyzed units supports the relevance of the proposed relationships, the purposive expert panel, the regional scope of the cases, and the absence of framework implementation limit statistical generalization and conclusions regarding practical effectiveness.

Future research should therefore evaluate the framework through pilot implementation and longitudinal analysis in different healthcare contexts. Such studies should

examine not only technological adoption but also measurable changes in device availability, utilization, downtime, maintenance performance, redeployment, refurbishment, useful-life extension, waste prevention, and end-of-life compliance. This evaluation would clarify the conditions under which digital capabilities can effectively support the transition from fragmented DMD management toward more coordinated, resource-efficient, and progressively circular practices.

Author Contributions: Conceptualization, E.d.J.L. and M.B.; methodology, E.d.J.L., M.B., P.S.C. and D.C.F.; validation, E.d.J.L., F.H.S., P.S.C., D.C.F. and M.B.; formal analysis, E.d.J.L., M.B. and D.C.F.; investigation, E.d.J.L.; resources, E.d.J.L. and M.B.; data curation, E.d.J.L.; writing—original draft preparation, E.d.J.L.; writing—review and editing, F.H.S., P.S.C., D.C.F. and M.B.; visualization, E.d.J.L., F.H.S. and M.B.; supervision, M.B.; project administration, E.d.J.L. and M.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Research Ethics Committee of the Federal University of Santa Catarina (UFSC), Brazil (CAAE 86351325.8.0000.0121; Approval No. 7.659.567; approved on 23 June 2025).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available from the corresponding author upon reasonable request. The data are not publicly available due to ethical and confidentiality restrictions related to the participating institutions and respondents.

Acknowledgments: The authors gratefully acknowledge the healthcare institutions that participated in this study and provided access to information, processes, and operational insights related to the management of durable medical devices. The authors also thank the specialists who contributed to the evaluation of decision-making criteria and the identification of Industry 4.0 technologies with the greatest potential to support sustainable durable medical device management. Their expertise and collaboration were essential to the development and contextual grounding of the proposed framework.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
BDA	Big Data and Analytics
BPMN	Business Process Model and Notation
BWM	Best–Worst Method
CC	Cloud Computing
CPS	Cyber-Physical Systems
CR	Consistency Ratio
DMD	Durable Medical Device
EOL	End-of-Life
I4.0	Industry 4.0
IoT	Internet of Things
ML	Machine Learning
PNRS	Brazilian National Solid Waste Policy
SS	Smart Sensors
SUS	Unified Health System (Sistema Único de Saúde)

Appendix A

Appendix A.1. Literature Review Protocol

Table A1. Search Strategy for Identifying I4.0 Technologies and Decision-Making Criteria for Circular and Sustainable Hospital Resource Management.

Database	<i>Scopus, Web of Science e PubMed</i>		
Database query data:	March 26, updated August 26		
Research question	What are the main Industry 4.0 technologies and decision-making factors reported in literature to support circular and sustainable management of hospital resources?		
Acronym	P—Population	C—Concept	Co—Context
Thematic Axis	Main technologies of Industry 4.0 and decision-making factors	Circular Economy	Management in Hospitals/hospital resources/hospital environment
Keywords	Industry 4.0 Technologies, Digital Technologies, Smart Healthcare Technologies, Internet of Things, IoT, Big Data, Artificial Intelligence, Digital Transformation, Decision-making Factors, Technology Adoption Criteria, Selection Criteria, Decision*Support	Circular Economy, Circular Model, Circular Business, Circular Supply Chain, Closed loop, Circularity	hospital*, healthcare, health system, medical services, hospital supply chain, healthcare supply chain, Hospital Management, Healthcare Practices
Search command	("Circular Economy" OR "Circular Model" OR "Circular Business" OR "Circular Supply Chain" OR "Closed loop" OR Circularity) AND ("Industry 4.0 Technologies" OR "Digital Technologies" OR "Smart Healthcare Technologies" OR "Internet of Things" OR "IoT" OR "Big Data" OR "Artificial Intelligence" OR "Digital Transformation" OR "Decision-making Factors" OR "Technology Adoption *Criteria" OR "Selection*Criteria" OR "Decision*Support") AND (hospital* OR healthcare OR "health system" OR "medical services" OR "hospital supply chain" OR "healthcare supply chain" OR "Hospital Management" OR "Healthcare Practices") AND NOT (hotel OR hospitality)		
Inclusion criteria:	Address studies that: (i) examine Industry 4.0 technologies; (ii) are applied to hospital or secondary/tertiary healthcare settings; (iii) discuss sustainability, circular practices, or efficient resource management (including asset management, device lifecycle processes, or hospital operational flows); and (iv) present decision-making factors or evaluation criteria relevant to the adoption of digital technologies in health services.		
		Selection Procedure	Remaining Articles
		<i>Raw Results</i>	557
<i>Exclusion based on database filters (document type: articles and reviews only; period: 2020–2025; language: Portuguese, English, and Spanish)</i>			272
<i>Exclusion of duplicate results</i>			207
<i>Bibliographic Portfolio extracted from databases</i>			78
<i>Articles with titles aligned with the research topic</i>			33
<i>Articles with abstracts aligned with the research topic</i>			26
<i>Articles available in full and free of charge</i>			26
<i>Articles included from grey literature</i>			3
<i>Articles aligned with the research topic after full reading</i>			29

Note: The asterisk (*) denotes a wildcard/truncation operator used in the database search to retrieve variations of the specified terms (e.g., hospital and hospitals).

Appendix A.2. Detailed Results of the Best–Worst Method Analysis

Table A2. Raw BWM Comparison Vectors, Individual Criterion Weights, Input-Based Consistency Ratios, and Inclusion Decisions.

Respondent	Best	Worst	BO II	BO DSP	BO RECR	BO OE	BO PCC	BO OTCB	BO ES	BO IF	BO ASH	OW II	OW DSP	OW RECR	OW OE	OW PCC	OW OTCB	OW ES	OW IF	OW ASH
R1	OE	ES	3	2	2	1	3	5	7	4	5	5	6	7	8	6	4	1	5	4
R2	OE	ES	3	5	4	1	3	3	9	3	3	4	4	5	7	6	6	1	6	6
R3	OE	RECR	3	7	3	1	4	2	2	3	2	2	1	1	2	3	2	1	1	1
R4	ES	IF	6	5	4	4	6	5	1	5	4	6	5	4	4	5	5	5	1	5
R5	PCC	ASH	8	8	5	5	1	6	3	3	6	3	3	5	5	7	4	7	6	1
R6	OE	ES	1	1	1	1	1	1	7	3	1	9	9	9	9	9	8	1	7	9
R7	PCC	RECR	6	6	9	5	1	5	5	6	4	5	5	1	6	6	6	7	5	6
R8	RECR	OTCB	5	7	1	6	6	5	3	6	4	4	3	6	2	3	1	3	2	5
R9	PCC	OTCB	7	9	7	8	1	6	7	7	8	9	9	7	7	9	1	6	7	7
R10	RECR	ASH	8	8	1	9	9	8	9	9	8	4	4	7	3	2	4	3	3	1
R11	IF	OTCB	3	7	6	3	2	8	7	1	3	9	4	3	7	9	1	4	9	7
Respondent	A BW	Local CR II	Local CR DSP	Local CR RECR	Local CR OE	Local CR PCC	Local CR OTCB	Local CR ES	Local CR IF	Local CR ASH	W II	W DSP	W RECR	W OE	W PCC	W OTCB	W ES	W IF	W ASH	Sum Wi
R1	7	0.1905	0.1190	0.1667	0.0238	0.2619	0.3095	0.0000	0.3095	0.3095	0.1038	0.1557	0.1557	0.2513	0.1038	0.0623	0.0273	0.0778	0.0623	1.0
R2	9	0.0417	0.1528	0.1528	0.0278	0.1250	0.1250	0.0000	0.1250	0.1250	0.1107	0.0664	0.0830	0.2680	0.1107	0.1107	0.0291	0.1107	0.1107	1.0
R3	7	0.0238	0.0000	0.0952	0.1190	0.1190	0.0714	0.1190	0.0952	0.1190	0.0943	0.0404	0.0943	0.1818	0.0707	0.1414	0.1414	0.0943	0.1414	1.0
R4	6	1.0000	0.6333	0.3333	0.3333	0.8000	0.6333	0.0333	0.0333	0.4667	0.0738	0.0886	0.1107	0.1107	0.0738	0.0886	0.3083	0.0347	0.1107	1.0
R5	8	0.2857	0.2857	0.3036	0.3036	0.0179	0.2857	0.2321	0.1786	0.0357	0.0540	0.0540	0.0863	0.0863	0.3237	0.0719	0.1439	0.1439	0.0360	1.0
R6	7	0.0476	0.0476	0.0476	0.0476	0.0476	0.0238	0.0000	0.3333	0.0476	0.1156	0.1392	0.1392	0.1392	0.1392	0.1274	0.0118	0.0495	0.1392	1.0
R7	9	0.2917	0.2917	0.0000	0.2917	0.0417	0.2917	0.3611	0.2917	0.2083	0.0782	0.0782	0.0329	0.0939	0.3333	0.0939	0.0939	0.0782	0.1174	1.0
R8	7	0.3095	0.3333	0.0238	0.1190	0.2619	0.0476	0.0476	0.1190	0.3095	0.0879	0.0628	0.3295	0.0732	0.0732	0.0439	0.1464	0.0732	0.1098	1.0
R9	9	0.7500	1.0000	0.5556	0.6528	0.0000	0.0417	0.4583	0.5556	0.6528	0.0873	0.0679	0.0873	0.0764	0.3989	0.0311	0.0873	0.0873	0.0764	1.0
R10	9	0.3194	0.3194	0.0278	0.2500	0.1250	0.3194	0.2500	0.2500	0.0139	0.0978	0.0978	0.2609	0.0870	0.0870	0.0978	0.0870	0.0870	0.0978	1.0
R11	8	0.3393	0.3571	0.1786	0.2321	0.1786	0.0000	0.3571	0.0179	0.2321	0.1202	0.0515	0.0601	0.1202	0.1803	0.0231	0.0515	0.2728	0.1202	1.0

Respondent	Input-Based CR	Associated Threshold	Decision
R1	0.3095	0.3403	Included
R2	0.1528	0.3662	Included
R3	0.1190	0.3403	Included
R4	1.0000	0.3262	Excluded
R5	0.3036	0.3657	Included
R6	0.3333	0.3403	Included
R7	0.3611	0.3662	Included
R8	0.3333	0.3403	Included
R9	1.0000	0.3662	Excluded
R10	0.3194	0.3662	Included
R11	0.3571	0.3657	Included

Note: Rows highlighted in light red indicate respondents excluded from the final aggregation because their input-based consistency ratios exceeded the corresponding thresholds. Legend: BO = Best-to-Others; WO = Others-to-Worst; a BW = largest value of vector BO; w = weight; CR = Consistency Ratio.

Appendix A.3. Technology Nominations by the Expert Panel

Table A3. Individual Nominations of I4.0 Technologies by Respondent and Decision Criterion, with Consistency-Based Inclusion Decisions.

Respondent	Decision	II	DSP	RECR	OE	PCC	OTCB	ES	IF	ASH
R1	Included	AI	BC	AI	AI	CPS	AI	3DP	AI	CPS
R2	Included	BDA	CC	CC	CC	SS	AI	CC	CC	AI
R3	Included	AI	BDA	AI	BDA	AI	CC	ML	SS	ML
R4	Excluded	CR	CPS	CR	ML	AI	CR	CPS	AR/VR	AI
R5	Included	IoT	BC	AI	BDA	IoT	BDA	3DP	IoT	BDA
R6	Included	IoT	BC	AR/VR	CR	AI	AR/VR	AR/VR	DT	AR/VR
R7	Included	ML	ML	BDA	BDA	SS	BDA	BDA	BDA	IoT
R8	Included	BDA	BC	AI	BDA	CPS	BDA	BDA	CC	BDA
R9	Excluded	CC	BDA	CC	CC	BDA	CC	IoT	CC	CC
R10	Included	IoT	BDA	BDA	IoT	AI	DT	BDA	IoT	CPS
R11	Included	CPS	BC	AI	CC	SS	BDA	3DP	ML	AI

Note: Nominations from R4 and R9 were excluded from the weighted aggregation because their CR values exceeded the respective associated thresholds. Technology abbreviations are defined in Table A4; Rows highlighted in light red indicate respondents excluded from the final aggregation because their input-based consistency ratios exceeded the corresponding thresholds.

Appendix A.4. Consolidated Technology Prioritization Results

Table A4. Consolidated Weighted Nomination Scores and Ranking of I4.0 Technologies for DMD Management.

Technology	Full Name	Nomination Count	Raw Weighted Score (Q _t)	Normalized Score (S _t)	Ranking	Cumulative Score
BDA	Big Data and Analytics	20	2.1163	0.2351	1	23.51%
AI	Artificial Intelligence	16	1.9892	0.2210	2	45.61%
IoT	Internet of Things	8	0.9132	0.1015	3	55.76%
CC	Cloud Computing	8	0.8965	0.0996	4	65.72%
CPS	Cyber-Physical Systems	5	0.6196	0.0688	5	72.60%
SS	Smart Sensors	4	0.5837	0.0649	6	79.09%
ML	Machine Learning	5	0.4737	0.0526	7	84.35%
BC	Blockchain	5	0.4145	0.0461	8	88.96%
AR/VR	Augmented/Virtual Reality	4	0.4091	0.0455	9	93.51%
3DP	3D Printing/Additive Manufacturing	3	0.2442	0.0271	10	96.22%
DT	Digital Twins	2	0.1955	0.0217	11	98.39%
CR	Collaborative Robotics	1	0.1445	0.0161	12	100.00%
DR	Drones	0	0.0000	0.0000	13	100.00%
-	Total	81	9.0000	1.0000	-	-

Note: Rankings and cumulative scores were calculated using unrounded normalized values. Nomination counts and weighted scores include only the nine retained respondents.

Appendix A.5. Interview Script for Process Mapping of Durable Medical Devices (DMD)

Part 1—General characterization

1. What is your position or role within the institution?
2. How long have you been working in this position or related area?
3. How many durable medical devices (DMD) are currently in use at this unit?
4. Does your unit have a specific sector or professional responsible for managing medical equipment? If so, which one?

Part 2—Acquisition process

5. How are the needs for new medical devices identified within the unit?
6. Who is responsible for requesting the acquisition of new devices?
7. When a new device is needed, what steps are taken to initiate the acquisition process?
8. Does the hospital have financial autonomy to purchase equipment, or are acquisitions centralized at the Municipal or State Health Secretariat?
9. Is there a standardized system (digital or manual) for submitting requisitions or tracking the acquisition process?
10. Are acquisitions linked to a specific plan or equipment replacement program?
11. Upon receiving the equipment, is there an official process for registering and asset-tagging it (tombamento)? If yes, how is this done?
12. Are there any digital systems used to manage acquisition records or equipment inventory?

Part 3—Use and operation

13. How is the equipment distributed and allocated among departments or professionals?
14. Is there a record of which devices are currently in use and where they are located?
15. Do users receive any form of training before operating new equipment?
16. Are there operational manuals or technical guidelines available for users?

17. Are any digital systems used to monitor usage frequency, operational hours, or performance indicators of the equipment?
18. Have you experienced cases where equipment remained unused for long periods? What were the reasons?

Part 4—Maintenance and control

19. How is maintenance of the medical devices organized in your unit?
20. Is there a preventive maintenance plan in place? If so, how is it managed and monitored?
21. When an equipment failure occurs, how is the repair required (via system, memo, email, or phone contact)?
22. Who performs maintenance—internal staff, external companies, or through public procurement?
23. Is there any digitalized record or tracking of maintenance requests, schedules, and completions?
24. How do you control warranty periods and maintenance contracts?
25. Are there indicators used to evaluate the performance or reliability of the equipment?
26. Are maintenance reports integrated into any hospital information systems?

Part 5—Digitalization and use of Industry 4.0 technologies

27. Are any technologies currently used to support the management of medical devices (for example, asset management systems, dashboards, or databases)?
28. Are any Industry 4.0 technologies applied in these processes, such as:
 - (a) Internet of Things (IoT) for equipment connectivity.
 - (b) Artificial Intelligence or Machine Learning for predictive maintenance.
 - (c) Big Data and Analytics for performance analysis.
 - (d) Cloud computing for data storage; or
 - (e) Blockchain for tracking and security?
 - (f) Other?
29. If none are used, what are the main barriers to adopting such technologies (financial, structural, training-related, or regulatory)?

Part 6—End-of-life and disposal

30. How is the end of the equipment's useful life determined?
31. What procedures are followed when a device is no longer functional or repairable?
32. Are there specific policies for reallocation, donation, or recycling of devices?
33. When equipment is discarded, where is it stored or sent?
34. Is there a formal process of reverse logistics with suppliers or authorized collectors?
35. Are there any digital tools used to register or monitor the disposal process?

Part 7—Governance, sustainability, and challenges

36. In your opinion, what are the main challenges in managing DMD in this unit?
37. What improvements or technological solutions do you consider necessary to enhance efficiency and sustainability?
38. How could digitalization contribute to optimizing the management of medical devices in public hospitals?
39. What support would be needed (training, funding, infrastructure) to enable this digital transformation?
40. Would you like to add any additional comments or suggestions regarding DMD management?

Appendix A.6. Detailed BPMN Representation of the AS-IS DMD Management Process

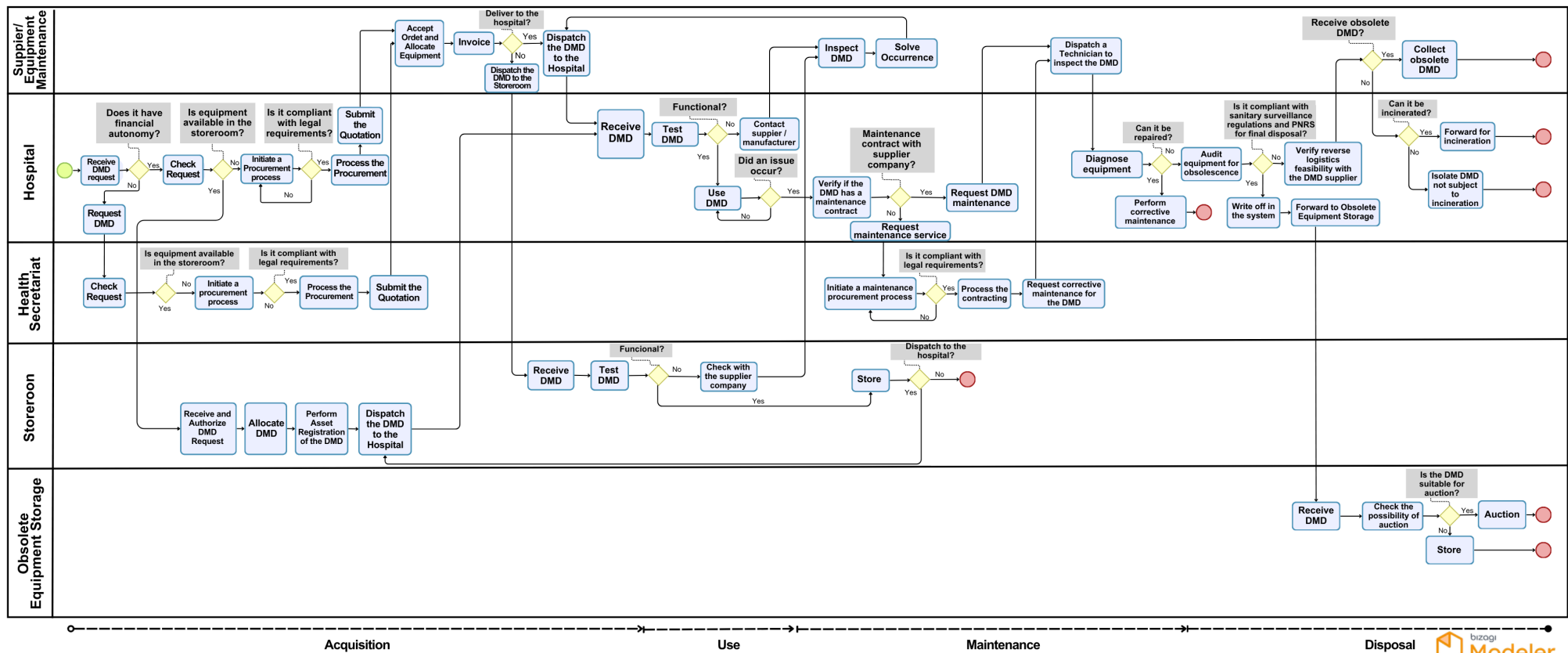


Figure A1. Detailed BPMN representation of the AS-IS DMD management process across the acquisition, use, maintenance, and disposal stages. Blue rounded rectangles represent activities, yellow diamonds represent decision gateways, the green circle represents the start event, and red circles represent end events. Solid arrows indicate sequence flows, horizontal lanes distinguish the actors responsible for each activity, and the dashed arrow at the bottom indicates progression across the DMD lifecycle stages.

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