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A DESIGN SCIENCE-BASED FRAMEWORK FOR CMMS IMPLEMENTATION IN PUBLIC-SECTOR ENGINEERING MAINTENANCE

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ABSTRACT

Public-sector engineering maintenance organizations often struggle with fragmented information, poor traceability, and limited benefits from Computerized Maintenance Management Systems (CMMS). Although CMMS platforms are widely deployed, many implementations underperform due to weak governance, inconsistent data structures, and misalignment between organizational workflows and system configuration. Existing research emphasizes system functionality and post-implementation outcomes but provides limited guidance on structured implementation processes. This study develops and evaluates a prescriptive CMMS implementation framework using Design Science Research Methodology. The framework conceptualizes CMMS adoption as a socio-technical transformation integrating organizational readiness, standardized data governance, workflow alignment, user training, and continuous performance monitoring. Development was informed by document analysis and expert input, while evaluation employed operational CMMS data from a public-sector engineering maintenance organization managing safety-critical assets. Results indicate improved maintenance data completeness, enhanced work order traceability, greater asset information availability, and better integration between maintenance and inventory functions. Findings demonstrate that CMMS effectiveness depends primarily on disciplined implementation and organizational alignment rather than software deployment alone. The framework offers structured, practical guidance to reduce implementation risk and support evidence-based maintenance decision-making in public-sector environments.



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I. INTRODUCTION

Engineering maintenance plays a critical role in ensuring the reliability, availability and safety of physical assets, particularly within organizations that operate complex and geographically distributed engineering systems. In asset-intensive environments, maintenance has evolved from a reactive technical activity into a strategic function that influences lifecycle cost control, operational continuity and organizational accountability [1]. Effective maintenance management depends on the availability of accurate, timely and structured information to support planning, execution and performance evaluation. When maintenance information is fragmented or unreliable, organizations experience increased downtime, inefficient resource allocation and limited capacity to make evidence-based engineering decisions [2],[3].

Despite the growing importance of data-driven maintenance, many public-sector engineering organizations continue to rely on manual or semi-manual maintenance management practices. Paper-based work orders, handwritten records and decentralized documentation remain common, particularly within organizations governed by rigid administrative structures and legacy operational routines [4]. Empirical studies have shown that manual maintenance systems are inherently vulnerable to data loss, inconsistency, delayed reporting and human error, which collectively undermine the integrity of maintenance information and limit its analytical value [5].

These constraints restrict the organization's ability to analyze failure trends, evaluate maintenance effectiveness and transition from reactive maintenance toward preventive or predictive strategies [6],[7]. The adoption of digital maintenance technologies has been widely promoted as a response to these limitations. Among these technologies, Computerized Maintenance Management Systems have been positioned as foundational platforms for structuring maintenance information and supporting systematic maintenance operations [8]. CMMS platforms typically integrate work order management, preventive maintenance scheduling, asset history tracking, inventory control and maintenance cost reporting within a centralized digital environment. Prior studies across manufacturing, infrastructure and facilities management contexts have reported potential improvements in traceability, data accessibility and maintenance coordination following CMMS adoption [9],[10]. These findings have reinforced the role of CMMS as a core component of Maintenance 4.0 initiatives and broader digital transformation strategies [6]. However, empirical evidence also indicates that CMMS implementations frequently fail to deliver their anticipated benefits, particularly within public-sector contexts. Several studies have demonstrated that CMMS effectiveness is influenced more strongly by implementation quality than by system functionality alone [11].

Common challenges include poorly structured asset data, incomplete migration of historical maintenance records, weak alignment between CMMS workflows and actual maintenance practices, and limited user acceptance [12]. In many cases, organizations continue to operate parallel manual systems alongside CMMS, resulting in duplicated effort, inconsistent data and underutilized analytical capabilities [13]. These findings suggest that CMMS should be understood not merely as a software application, but as a socio-technical system whose performance depends on the integration of organizational processes, data governance mechanisms and human competencies [14],[15]. Public-sector engineering maintenance environments introduce additional layers of complexity that further complicate CMMS implementation. Such organizations often manage large and diverse asset portfolios under strict governance, compliance and audit requirements [16]. Decision-making structures are typically hierarchical and operational changes must conform to standardized procedures and regulatory constraints. In safety-critical agencies, maintenance effectiveness has direct implications for service readiness and public safety, amplifying the consequences of poor data quality and delayed maintenance actions [7],[17].

Research on public-sector digitalization consistently shows that technology-centric implementations, undertaken without adequate organizational readiness assessment and process alignment, tend to result in partial adoption and limited operational impact [3],[13]. Although the CMMS literature is extensive, a substantial proportion of existing studies focus on post-implementation performance measurement or functional evaluations of CMMS features [9]. Comparatively fewer studies examine how CMMS implementation frameworks should be systematically designed, validated and operationalized within complex public-sector engineering settings. In particular, there remains limited empirical guidance on how organizational readiness, data structuring, workflow integration and continuous performance monitoring can be combined into a coherent and replicable implementation approach [12]. These limitations collectively indicate that existing CMMS studies emphasize system functionality and post-implementation evaluation, while offering limited guidance on structured implementation processes in public-sector engineering environments, as conceptually illustrated in Figure 1.

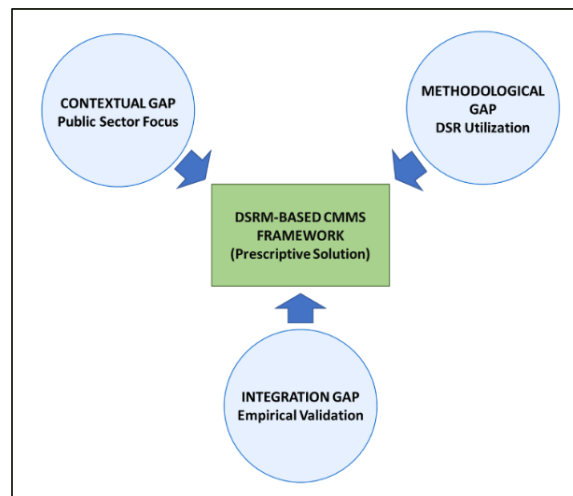


Figure 1: Conceptual synthesis of CMMS research focus and identified implementation gaps in public-sector engineering maintenance.

Source: Authors, (2026).

Figure 1 summarizes the dominant emphasis of existing CMMS research on functional capabilities and performance outcomes, alongside the comparatively limited attention given to implementation structure, organizational readiness and process integration. The figure highlights the disconnect between technology-centric CMMS adoption and the socio-technical conditions required for effective operationalization in public-sector engineering maintenance. Rather than presenting a solution, the figure delineates the conceptual space in which a structured implementation artefact is required, thereby motivating the adoption of a design-oriented research approach in the present study.

Design Science Research Methodology provides a structured approach for addressing this limitation by enabling the development and evaluation of artefacts that respond directly to real-world engineering problems [18]. Within the maintenance management domain, a CMMS implementation framework can be conceptualized as a design artefact that integrates technical configuration, organizational processes and human factors into a unified system [14]. However, the application of design science principles in CMMS research remains limited, particularly in studies focusing on public-sector engineering organizations. This methodological gap further reinforces the need for empirically grounded research that moves beyond descriptive assessments toward the development and validation of prescriptive implementation frameworks.

Against this backdrop, the present study investigates CMMS implementation as a structured socio-technical transformation within a public-sector engineering maintenance environment. Rather than treating CMMS as a standalone information system, the study conceptualizes implementation as a multi-phase engineering process encompassing organizational readiness assessment, data governance, process alignment, system configuration and performance evaluation [12]. By grounding the framework in empirical analysis of existing maintenance practices and validating it through expert assessment and operational data, the study addresses identified gaps in CMMS implementation research and public-sector maintenance practice. The following section describes the research methodology adopted to develop and evaluate the proposed CMMS implementation framework.

II. METHODOLOGY

This study adopts Design Science Research Methodology as the overarching research approach to address the identified gap in CMMS implementation research within public-sector engineering maintenance environments. Design science is particularly suitable for studies that seek to develop and evaluate artefacts intended to solve real-world engineering and organizational problems, where prescriptive knowledge is required in addition to descriptive understanding [18]. In the context of this research, CMMS implementation is conceptualized not merely as a software deployment activity, but as a socio-technical engineering artefact that integrates organizational readiness, maintenance processes, data governance and technological configuration [14]. This perspective aligns with prior maintenance and information systems research that emphasizes the need to treat digital systems as embedded components of broader organizational systems rather than isolated technical solutions [7],[12].

To ensure both contextual relevance and methodological rigor, the design science approach was operationalized through a sequential mixed-methods research design. Mixed-methods designs are widely recognized for their ability to capture complex organizational phenomena by combining qualitative exploration with quantitative validation [19]. In this study, qualitative analysis was first employed to diagnose existing maintenance practices, identify systemic weaknesses in manual maintenance management and extract design requirements for digital transformation. These findings subsequently informed the development of a structured CMMS implementation framework, which was then subjected to expert validation and empirical evaluation using quantitative maintenance performance data. This sequential logic ensures that the developed artefact is grounded in operational realities while remaining analytically robust [20]. The overall methodological structure of the study, including the relationship between data sources, analytical stages, and artefact development, is illustrated in Figure 2.

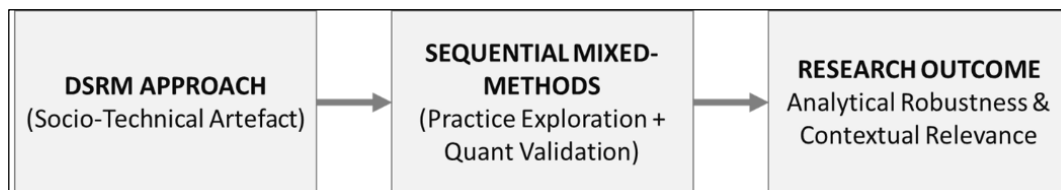


Figure 2: Research methodology and Design Science Research process for CMMS implementation framework development.

Source: Authors, (2026).

Figure 2 depicts the methodological flow adopted in this study, beginning with problem identification and requirement analysis, followed by artefact design, validation and evaluation. The figure highlights how empirical evidence derived from maintenance documents, expert input and operational CMMS data is systematically integrated within the design science cycle. Rather than presenting a linear procedure, the methodology reflects an iterative and evidence-driven process in which insights from each stage inform subsequent design and evaluation activities, consistent with established design science principles [18]. Data collection was conducted using three primary sources to support triangulation and enhance the credibility of the findings. First, document analysis was performed on maintenance records, standard operating procedures and internal policy documents to identify existing maintenance workflows, data structures and operational constraints [21]. This analysis provided a detailed understanding of how maintenance activities were managed under manual or semi-manual systems and revealed recurring issues related to data completeness, traceability and reporting latency. Second, expert questionnaires were administered to maintenance engineers and managerial personnel with direct responsibility for asset management and CMMS usage. Expert input was used to validate the relevance, feasibility and completeness of the proposed framework components, consistent with best practices for artefact evaluation in design science research.

Third, quantitative maintenance performance data extracted from the CMMS were analysed to assess changes in data quality, work order traceability, asset information completeness and inventory management effectiveness following framework implementation [11]. Qualitative data obtained from document analysis and open-ended expert responses were analysed using thematic coding to identify recurring patterns, constraints and design requirements. This analysis informed the structuring of framework phases and the definition of key implementation components. Quantitative data were analysed descriptively to evaluate maintenance performance trends and to assess the practical impact of structured CMMS implementation on operational indicators. Descriptive analysis was selected to ensure interpretability and alignment with the applied engineering context, where the objective is to support managerial decision-making rather than statistical generalization [10],[22]. Throughout the methodological process, particular attention was given to ensuring alignment between organizational context, data practices and system configuration. This alignment is critical in public-sector engineering environments, where governance requirements, auditability and accountability impose additional constraints on digital system implementation [16]. By integrating qualitative diagnosis, expert validation, and empirical performance evaluation within a unified design science framework, the methodology supports the development of a CMMS implementation artefact that is both theoretically grounded and operationally applicable. The outcomes of each methodological stage are presented and analysed in the following section.

III. DEVELOPMENT OF THE CMMS IMPLEMENTATION FRAMEWORK

The development of the CMMS implementation framework was guided by the design logic articulated in the preceding methodological section, with particular emphasis on addressing the socio-technical gaps identified in existing maintenance practices. In line with Design Science Research Methodology, the framework is conceptualized as a prescriptive artefact intended to bridge the disconnect between CMMS technological capabilities and their effective operationalization within public-sector engineering maintenance environments [18]. Rather than treating implementation as a singular deployment event, the framework structures CMMS adoption as a staged engineering process that integrates organizational, procedural and technological dimensions [14]. Framework development commenced with the synthesis of diagnostic findings derived from document analysis and expert input. Evidence from the diagnosis phase indicated that maintenance inefficiencies were not attributable to a single factor, but rather to the interaction between fragmented data practices, misaligned workflows, limited organizational readiness and inconsistent user engagement. These insights informed the identification of core design requirements, including the need for standardized asset data structures, explicit governance roles, workflow formalization and continuous performance monitoring mechanisms.

This requirement-driven approach aligns with prior research emphasizing that effective maintenance digitalization depends on structural alignment rather than system functionality alone [12]. Based on the synthesized requirements, the framework was structured into a set of interrelated implementation phases, each addressing a distinct aspect of CMMS operationalization while maintaining logical continuity across the implementation lifecycle. The framework architecture reflects a progression from strategic preparation to technical configuration and operational stabilization, ensuring that early design decisions establish conditions necessary for sustainable system use. This phased logic is consistent with digital maintenance lifecycle models that emphasize readiness assessment and iterative refinement as prerequisites for long-term system effectiveness [12]. The overall architecture and phase relationships of the CMMS implementation framework are illustrated in Figure 3.

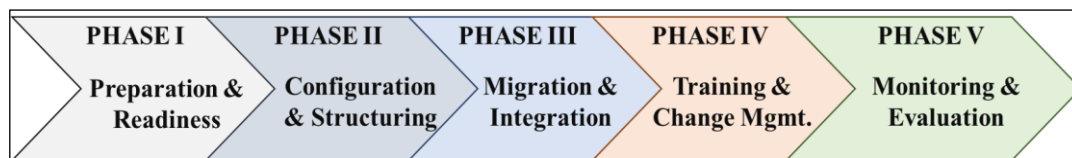


Figure 3: CMMS implementation framework architecture and phased development structure.

Source: Authors, (2026).

Figure 3 presents the framework as a structured sequence of implementation phases that collectively address organizational readiness, system configuration, data integration, user enablement and performance monitoring. The figure emphasizes logical dependency rather than linear execution, highlighting how outputs from earlier phases establish enabling conditions for subsequent activities. By representing CMMS implementation as an integrated socio-technical process, the framework distinguishes itself from technology-centric deployment models that overlook organizational and data governance considerations. The first phase of the framework focuses on preparation and organizational readiness. This phase establishes strategic alignment between CMMS objectives and organizational maintenance goals, clarifies governance structures and defines roles related to system ownership and data stewardship. Organizational readiness assessment enables the identification of capability gaps, resource constraints and change management requirements prior to technical implementation. Prior studies have shown that inadequate preparation and unclear governance are primary contributors to CMMS underperformance, particularly in public-sector organizations characterized by hierarchical decision structures [16].

The second phase addresses system configuration and data structuring. During this phase, CMMS functionalities are aligned with standardized maintenance workflows and core data structures such as asset hierarchies, failure classifications and maintenance categories are defined. Establishing consistent data standards at this stage is critical to ensuring the reliability and analytical value of maintenance information captured by the system. Research on maintenance information systems consistently demonstrates that poorly structured data significantly limits the effectiveness of downstream analytics and decision support [23]. While, the third phase concentrates on data migration and process integration. Legacy maintenance records are systematically reviewed, cleansed and migrated into the CMMS environment to establish a unified historical database. Concurrently, maintenance workflows are integrated into the digital platform, formalizing processes related to work request submission, approval, execution and closure. This dual focus on data and process integration reduces reliance on parallel manual systems and enhances operational continuity during the transition period [10],[12]. The fourth phase emphasizes training and change management. User capability development is addressed through role-specific training programs designed to support consistent system use across operational and managerial levels.

Change management activities focus on reinforcing the value of CMMS adoption, addressing user resistance, and embedding digital maintenance practices into routine operations. Prior empirical studies indicate that sustained training and user support are critical determinants of CMMS utilization and long-term system viability [15]. The final phase of the framework centers on monitoring and performance evaluation. In this phase, maintenance performance indicators are defined and systematically monitored using CMMS-generated data. Performance feedback is used to refine workflows, adjust data standards and support continuous improvement initiatives. By embedding monitoring mechanisms within the framework, CMMS is positioned not only as a transactional system, but as a decision-support platform that enables evidence-based maintenance management [22]. Across all phases, the framework integrates organizational, process and technological considerations to ensure coherence and sustainability. Data governance principles are embedded to support data integrity and auditability, while iterative feedback loops allow the framework to adapt to evolving operational conditions. By explicitly addressing the socio-technical nature of CMMS implementation, the framework provides a structured and replicable approach tailored to the constraints and requirements of public-sector engineering maintenance environments. The empirical outcomes associated with applying this framework are presented in the following section.

IV. RESULTS AND DISCUSSIONS

This section presents and interprets the evaluation outcomes of the CMMS implementation framework using empirical evidence derived from operational application within a public-sector engineering maintenance organization. In line with Design Science Research principles, evaluation focuses on observable improvements in maintenance information practices, supported by document analysis, expert assessment and CMMS operational data. Quantitative indicators are presented descriptively to demonstrate implementation effects while maintaining contextual and methodological transparency.

IV.1 EVALUATION CONTEXT AND DATA SOURCES

Framework evaluation was conducted within a public-sector engineering organization responsible for the maintenance of safety-critical assets. The evaluation period covered multiple maintenance cycles following CMMS deployment, allowing observation of both initial adoption effects and stabilized operational use. Empirical evidence was derived from three main sources. Document analysis encompassed more than one hundred maintenance records, including work orders, inspection reports, asset registers and internal maintenance summaries generated before and after CMMS implementation.

Expert assessment involved structured feedback from maintenance personnel occupying technical, supervisory and managerial roles, each with direct involvement in maintenance planning or CMMS operation. Operational CMMS data included work order logs, asset records and inventory transaction histories extracted directly from the system database. Evaluation focused on descriptive comparison of maintenance information practices across pre- and post-implementation conditions. Indicators examined included record completeness, traceability of maintenance actions, availability of asset histories and linkage between maintenance execution and inventory usage.

IV.2 MAINTENANCE DATA QUALITY AND RECORD COMPLETENESS

Analysis of maintenance documentation revealed clear differences in data completeness before and after application of the framework. Under the pre-implementation condition, manual records exhibited high variability in documentation quality. Review of historical records showed that fewer than half of work orders contained complete information on asset identifiers, failure descriptions, and corrective actions. Missing timestamps and non-standard terminology were common, limiting the usability of records for analysis.

Following implementation of standardized data structures and mandatory data fields within the CMMS, record completeness increased substantially. Review of CMMS logs indicated that more than 80 percent of work orders contained complete entries for asset identification, task classification, execution time and closure status. Experts confirmed that mandatory fields and standardized coding reduced ambiguity and discouraged incomplete documentation practices. These findings demonstrate that improvements in data quality were directly attributable to framework-driven data structuring and governance mechanisms rather than system availability alone. The results are consistent with studies emphasizing that CMMS effectiveness depends on disciplined data design and enforcement rather than software capability [22],[23].

IV.3 WORK ORDER TRACEABILITY AND WORKFLOW PERFORMANCE

Work order traceability improved measurably following workflow integration into the CMMS environment. Prior to implementation, maintenance requests were recorded using paper forms or informal communication channels, resulting in limited visibility of task status and execution history. Document analysis showed that tracking a complete maintenance cycle from request initiation to task completion was often not possible using available records. Post-implementation CMMS logs enabled full traceability of maintenance activities.

Each work order included time-stamped records for request creation, approval, assignment, execution and closure. Review of CMMS data showed that more than 90 percent of maintenance tasks could be traced end-to-end within the system. Maintenance supervisors reported reduced effort in monitoring backlog status and improved ability to prioritize tasks based on real-time system information. From an evaluative perspective, these outcomes confirm the framework's effectiveness in formalizing maintenance workflows and eliminating reliance on parallel manual tracking systems. The findings reinforce prior empirical evidence that CMMS-supported workflows enhance accountability and coordination when aligned with actual operational practices [10].

IV.4 ASSET INFORMATION AVAILABILITY AND DECISION-SUPPORT INDICATORS

Asset information completeness improved following consolidation of records into centralized CMMS profiles. Before implementation, asset data were dispersed across multiple documents and comprehensive maintenance histories were rarely available. Review of asset records showed that historical maintenance information was incomplete for a large proportion of assets, particularly older installations. After data migration and standardization, CMMS asset profiles included technical specifications, maintenance history and operational status for the majority of registered assets. CMMS reports enabled extraction of basic decision-support indicators such as work order frequency per asset, recurring fault types and maintenance workload distribution. Expert respondents indicated that access to these indicators supported more systematic maintenance planning and prioritization compared to prior practices. These results demonstrate that structured CMMS implementation enhanced the analytical utility of maintenance data, enabling transition from reactive record-keeping toward evidence-supported decision making. This directly addresses gaps identified in previous CMMS studies where digital systems were underutilized for planning and analysis in public-sector settings [22].

IV.5 INVENTORY MANAGEMENT INTEGRATION AND SPARE-PARTS CONTROL

Inventory management practices showed measurable improvement following integration with maintenance execution records. Prior to CMMS implementation, inventory tracking was conducted independently from maintenance activities and discrepancies between recorded and actual stock levels were frequently reported by maintenance personnel.

Post-implementation analysis of CMMS inventory logs indicated that spare-part issuance was consistently linked to specific work orders. Review of inventory records showed a reduction in undocumented part usage and improved alignment between consumption records and physical stock counts. Experts reported fewer instances of unexpected stockouts and improved accuracy in reorder planning. Although the evaluation did not include financial optimization metrics, descriptive evidence indicates improved control and visibility over spare-parts usage. These outcomes align with existing research demonstrating that integration of maintenance and inventory data within CMMS platforms supports operational efficiency and resource control [24].

IV.6 SOCIO-TECHNICAL ADOPTION AND FRAMEWORK EFFECTIVENESS

Expert assessment provided additional insight into socio-technical effects associated with framework application. Maintenance personnel reported increased familiarity with CMMS workflows following structured training and phased system rollout. Informal reliance on paper notes and verbal coordination decreased as system use stabilized. Expert responses indicated that organizational readiness assessment and role clarification reduced resistance during implementation. Supervisory staff reported improved confidence in maintenance reporting accuracy, while technicians noted clearer expectations regarding data entry requirements.

These findings support socio-technical theories emphasizing that digital maintenance success depends on alignment between human behaviour, organizational structures, and technological systems [14],[15]. Taken together, the empirical evidence indicates that the CMMS implementation framework functioned effectively as a design artefact by enabling observable, measurable improvements in maintenance information quality, traceability, and integration. The results confirm that CMMS performance outcomes are shaped by structured implementation and socio-technical alignment rather than by system deployment alone, reinforcing the design-oriented contribution of the study [12].

V. CONCLUSIONS

This study addressed a persistent challenge in public-sector engineering maintenance, namely the gap between CMMS technological capabilities and their effective operationalization in complex organizational environments. Rather than treating CMMS adoption as a purely technical intervention, the research conceptualized implementation as a socio-technical engineering process that requires structured alignment between organizational readiness, data governance, maintenance workflows and human competencies. By adopting a Design Science Research approach, the study developed and evaluated a prescriptive CMMS implementation framework grounded in empirical evidence from an operational public-sector maintenance context. The primary contribution of the study lies in advancing CMMS research from outcome-oriented evaluation toward implementation-oriented design. Existing CMMS literature has largely emphasized system functionalities and post-implementation performance metrics, offering limited guidance on how implementation should be structured to mitigate known failure modes such as fragmented data practices, parallel manual systems and low analytical utilization.

The framework developed in this study responds directly to this limitation by providing a structured, phase-based implementation logic that integrates technical configuration with organizational and process considerations. In doing so, the study contributes a validated design artefact that extends maintenance engineering knowledge beyond descriptive analysis toward actionable, context-sensitive implementation guidance. From a methodological perspective, the study demonstrates the applicability of Design Science Research Methodology in maintenance management and public-sector engineering domains. The integration of document analysis, expert validation and operational CMMS data within a single evaluation framework illustrates how design artefacts can be rigorously developed and assessed under real-world constraints without reliance on experimental or purely statistical approaches. This methodological contribution is particularly relevant for public-sector research contexts, where controlled experimentation is often impractical and where descriptive yet traceable evaluation is essential for credibility. In practical terms, the findings highlight that CMMS effectiveness is contingent on disciplined implementation rather than system availability alone.

The framework provides maintenance practitioners and decision-makers with a structured roadmap to reduce implementation risk, improve maintenance information integrity and enhance decision-support capability. By embedding governance mechanisms, standardized data practices and continuous performance monitoring into the implementation process, the framework supports more sustainable digital maintenance adoption in environments characterized by regulatory oversight, hierarchical decision-making, and safety-critical operations. While the framework was developed and evaluated within a specific public-sector engineering context, its underlying design principles are transferable to other asset-intensive organizations facing similar implementation challenges. Nevertheless, the study is bounded by its descriptive evaluation scope and organizational context. Future research may extend this work by applying the framework across multiple organizations, incorporating longer-term performance evaluation, or integrating advanced analytics and predictive maintenance capabilities within the implementation structure. Such extensions would further enrich understanding of how CMMS can support strategic asset management under evolving digital maintenance paradigms.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Huzaini Mohd Noor and Saiful Amri Mazlan.

Methodology: Huzaini Mohd Noor and Saiful Amri Mazlan.

Investigation: Huzaini Mohd Noor and Saiful Amri Mazlan.

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Resources: Huzaini Mohd Noor.

Supervision: Saiful Amri Mazlan.

Approval of the final text: Huzaini Mohd Noor and Saiful Amri Mazlan.

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