A Conceptual Decision-Support Framework for Digitalization in Orthotic and Prosthetic Business Processes

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DOI: https://doi.org/10.47772/IJRISS.2026.100300339

Received: 17 March 2026; Accepted: 22 March 2026; Published: 08 April 2026

ABSTRACT

Digitalization holds significant potential for transforming business processes, yet organizations frequently face challenges in identifying optimal areas for technological implementation. This study responds to this critical need by developing and validating a structured decision-support framework designed to systematically evaluate and prioritize digitalization opportunities, with specific application to the orthotic and prosthetic (O&P) industry. Grounded in Business Process Reengineering (BPR) principles, the proposed framework comprises three integrated components: (1) Diagnostic Assessment of current operations, (2) Multi-Criteria Evaluation Matrix for scoring digital intervention opportunities, and (3) Strategic Decision Pathway that recommends manual, hybrid, or full digital adoption strategies.

The framework incorporates a comprehensive evaluation system examining three critical dimensions: (1) quality outcomes, (2) time efficiency, and (3) cost-effectiveness, enabling organizations to assess their digital readiness and prioritize workflow transformations. A distinctive feature of this approach is its practical decision tree model and weighted scoring system, which facilitate customized strategy development ranging from manual process optimization to full digital workflow adoption.

Through a rigorous mixed-methods methodology incorporating literature synthesis, expert consultations, and case study validation in Malaysian O&P clinics, this research makes significant contributions to both theory and practice. The study delivers an evidence-based decision-making tool that effectively bridges the gap between theoretical digitalization models and real-world healthcare manufacturing implementation. By aligning technology adoption with organizational capabilities and strategic objectives, this framework empowers small and medium enterprises to make informed investment decisions, effectively manage transition risks, and optimize the impact of their digitalization initiatives.

Keywords: Digital transformation, orthotics and prosthetics, decision tool, business process reengineering, additive manufacturing, framework model

INTRODUCTION

Digital technologies such as 3D scanning, CAD-based rectification, and additive manufacturing have revolutionized production processes across industries, including healthcare. However, the Orthotics and Prosthetics (O&P) industry characterized by craft-based, labor-intensive workflows, faces challenges in adopting digital solutions systematically. Strategic decision-making is required to determine when and where digitalization yields the highest value. This study addresses this gap by developing a decision-support framework aligned with Business Process Reengineering (BPR) principles to guide digital transformation within the Malaysian O&P sector.

The orthotics and prosthetics (O&P) industry faces increasing pressure to adopt digital technologies while maintaining quality standards and cost-effectiveness. Despite growing evidence of digital technologies' potential benefits including 3D scanning, CAD modeling, and additive manufacturing many O&P providers lack structured methodologies to identify optimal areas for digitalization within their business processes.

This study addresses three critical gaps in current research and practice:

1. The absence of systematic decision-making tools for digitalization adoption in O&P workflows.
2. Limited integration of patient-centered quality metrics with operational and financial considerations.
3. The need for context-sensitive frameworks that accommodate varying organizational readiness levels.

Building on Business Process Reengineering (BPR) principles, we developed and validated a decision-support framework that enables O&P providers to:

- Systematically evaluate their current workflows.
- Quantify potential benefits of digitalization across quality, time, and cost dimensions.
- Select appropriate digitalization strategies based on organizational context.

Our research contributes to both academic literature and industry practice by:

1. Providing the first comprehensive decision framework specifically designed for O&P digitalization
2. Demonstrating a novel application of BPR principles in healthcare manufacturing contexts
3. Offering empirically validated metrics for evaluating digitalization impact

LITERATURE REVIEW

The development of the decision tool requires a thorough review of existing literature, frameworks, and best practices related to digital transformation and business process improvement. It involves identifying key factors, such as cost-effectiveness, strategic alignment, technological feasibility, and customer impact, which influence the selection of the best area for improvement.

The digital transformation of healthcare manufacturing processes has gained significant traction, particularly through the integration of Industry 4.0 technologies. In the orthotics and prosthetics (O&P) domain, digital tools such as 3D scanning, CAD/CAM software, and additive manufacturing (AM) are increasingly being adopted to replace traditional, labor-intensive methods. Studies have shown that 3D scanning enhances anatomical accuracy and reduces patient discomfort during the casting phase (Telfer et al., 2012), while CAD-based modification provides reproducibility and reduces dependency on technician skill (Mavroidis et al., 2011).

Additive manufacturing, particularly selective laser sintering (SLS) and fused deposition modeling (FDM), enables complex geometries, material savings, and faster prototyping cycles (Gibson et al., 2015). Despite these advantages, barriers such as limited technical expertise, high equipment costs, and resistance to change have slowed widespread adoption in clinical settings (Paterson et al., 2020).

Decision-support systems (DSS) play a pivotal role in guiding digital adoption by integrating data-driven criteria into strategic planning. Multi-criteria decision-making (MCDM) tools allow organizations to weigh factors such as cost, time, quality, and feasibility when evaluating digital solutions (Triantaphyllou, 2000). This aligns with the core principles of Business Process Reengineering (BPR), which advocates for radical redesign of core business processes to achieve dramatic improvements in performance (Hammer & Champy, 1993).

In healthcare contexts, BPR has been used to streamline workflows, reduce redundancies, and enhance service quality (Al-Mashari & Zairi, 2000). Digitalization frameworks that combine BPR methodologies with data analytics and decision-support capabilities offer a structured pathway to sustainable transformation (Elshaer et al., 2021).

An emerging and valuable approach in decision-support literature is the Multi-Dimensional Criteria Analysis (MDCA) framework. MDCA provides a systematic method for evaluating alternatives against multiple, often conflicting, criteria, which is particularly relevant for digital transformation in complex healthcare environments. In the context of the O&P industry, MDCA offers a robust foundation for integrating diverse performance metrics—such as quality, time, and cost—into a coherent decision model. By enabling structured comparisons and prioritization, MDCA enhances the objectivity and reliability of technology adoption strategies (Kangas et al., 2001; Munda, 2004).

However, there remains a lack of industry-specific tools that guide O&P providers in determining where and how digital technologies should be applied for maximum benefit. This gap highlights the need for a structured, evidence-based framework tailored to the operational realities of O&P service providers.

METHODOLOGY

The research study aims to develop a digitalization framework specifically designed for the O&P (Orthotics and Prosthetics) industry. The research design focuses on outlining a strategy that businesses in the O&P industry can adopt to effectively leverage emerging technologies. The framework will guide how to navigate the digital transformation process and harness the potential benefits offered by these technologies.

Data Collection

This study adopts a synthesis-based methodology, in which the development of the decision-support framework for digitalization is grounded in findings obtained from Research Question 2 (RQ2). RQ2 involved a comparative analysis of traditional versus digital workflows in the fabrication of prosthetic sockets, focusing on three key performance metrics: quality of product based on patient outcomes, process efficiency (time), and cost-effectiveness.

The results from RQ2 served as the primary data inputs for constructing the framework. These included:

1. Patient feedback analyzed using thematic analysis (Braun & Clarke, 2006) to extract qualitative indicators of comfort, fit, and satisfaction.
2. Operational time logs comparing manual and digital process durations across workflow stages.
3. Cost analysis evaluating material usage, labor input, and equipment investment.

Framework Development

Based on insights and findings from the previous research phase, this study focuses on developing a digitalization framework tailored for the orthotics and prosthetics (O&P) industry. To systematically translate these findings into a practical decision-support tool, the Multi-Dimensional Criteria Analysis (MDCA) framework was applied. MDCA enabled the integration of performance metrics such as quality, time, and cost into a structured model that guides strategic digital adoption.

MDCA is a systematic approach used to support decision-making by evaluating multiple, often conflicting, criteria in complex scenarios. In this context, MDCA enabled the integration of patient-centered quality indicators, operational efficiency, and cost data into a unified model for digital adoption assessment (Kangas et al., 2001; Munda, 2004).

These results were used to populate a multi-criteria scoring matrix. Each process stage (scanning, modification, fabrication, and fitting) was assigned a Quality Score (QS), Time Score (TS), and Cost Score (CS) based on its relative performance. The scoring matrix formed the foundation of a decision engine, which fed into a decision tree model. This tree stratifies companies into three digital adoption pathways: manual enhancement, hybrid workflow, or full digitalization based on cumulative scores.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue III March 2026

As no additional primary data was collected for RQ3, this methodology represents a design-validation approach that leverages earlier empirical findings and applies MDCA to produce a structured, decision-support tool grounded in real-world performance data.

The digitalization framework developed through this research study will serve as a valuable resource for O&P businesses seeking to embark on their digital transformation journey. By providing a strategic roadmap, it aims to enable organizations in the industry to effectively embrace and leverage emerging technologies to gain a competitive edge, drive innovation, and deliver improved services to their customers.

RESULT AND DISCUSSION

Digitalization Workflow Framework was constructed based on integrated findings across three core domains: quality analysis, cost-effectiveness analysis, and time-efficiency study. The aim is to propose a structured model that supports decision-making in the orthotics and prosthetics (O&P) industry, specifically guiding stakeholders on when and where digitalization should be adopted for optimal impact.

The framework integrates insights from:

1. Quality Thematic Analysis: Highlighting patient-centered indicators such as comfort, fit, pain-free usage, durability, and confidence in daily use.
2. Cost-effectiveness analysis: Comparing fixed and variable costs between traditional and digital workflows, including labor, materials, and technology investments.
3. Time Efficiency Analysis: Evaluating time taken across stages like scanning/casting, modification, fabrication, and final fitting.

The framework also employs a weighted scoring system to evaluate and prioritize potential areas for digitalization. It considers several decision-making criteria, including feasibility, cost-benefit ratio, and alignment with organizational goals, to support data-driven recommendations.

Digitalization Workflow Framework Model

The model was represented in the Figure 1 below:

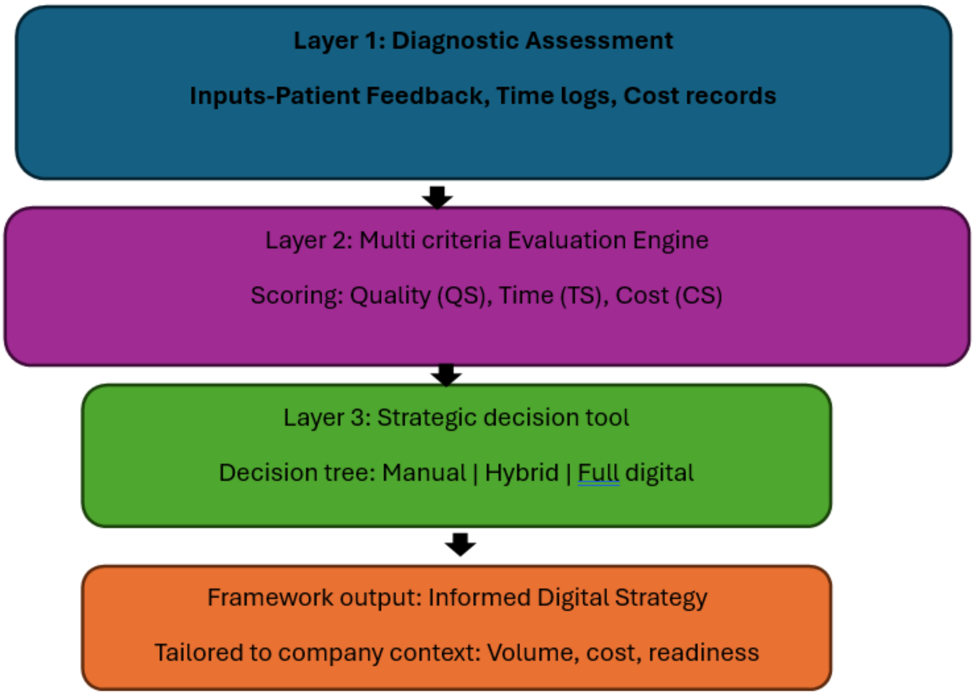

Figure 1 Digitalization workflow framework model.

The model consists of three sequential yet interactive layers:

Layer 1: Diagnostic Assessment

The Diagnostic Assessment represents the foundation of the digitalization workflow framework. Its purpose is to gather comprehensive data on the clinic's current operations, patient satisfaction, and resource utilization. This layer ensures that any recommendations for digital transformation are grounded in real-world evidence and tailored to the clinic's actual context. This stage involves the collection of three types of data:

Patient Feedback Surveys (Quality Analysis Input)

Data is collected using standardized patient satisfaction surveys and follow-up evaluations. The responses are analyzed using thematic analysis (Braun & Clarke, 2006) to extract key indicators such as:

- Comfort and fit of the socket
- Confidence in daily use
- Perception of pain or pressure
- Overall satisfaction with the fabrication method

These qualitative insights are coded into quality scores (QS) to be used in the Evaluation Engine. Clinics with recurring fit issues or dissatisfaction in manual workflows may be strong candidates for digital scanning or

CAD-based rectification.

Operational Time Logs (Time Efficiency Input)

This involves recording the time taken for each key process stage in both manual and digital workflows, such as:

1. Casting vs. 3D scanning
2. Manual mold rectification vs. CAD modification
3. Lamination vs. 3D printing
4. Initial fitting vs. final adjustment sessions

Time differences are converted into time scores (TS) that reflect the potential for time savings through digitalization. Significant time reductions in scanning, design, or production phases may indicate readiness for digital adoption in those areas.

Financial Records (Cost Effectiveness Input)

Cost data is obtained from company financial logs and feasibility studies. This includes:

1. Equipment acquisition and maintenance
2. Labor hours per patient
3. Material costs for both traditional and digital methods
4. Cost associated with reworks, refits, or remakes

From this, a cost score (CS) is derived to show whether digitalization would lower long-term operational expenses. For instance, high manual labor costs combined with a high rate of patient refits may justify investment in digital tools that improve accuracy and reduce rework.

This layer acts as the entry point to the framework and feeds directly into the Evaluation Engine, where scoring and comparison guide the ultimate digital strategy selection.

Layer 2: Multi-Criteria Evaluation Engine

The Evaluation Engine can be realized as a scoring matrix that quantifies quality, time, and cost across workflow components. This core component is designed to systematically evaluate the digitalization potential of each process stage by applying a scoring mechanism across three dimensions:

Quality Score (QS): Based on thematic frequency and feedback from patient satisfaction studies. Higher scores are assigned to processes that improve comfort, reduce pain, and enhance patient confidence.
Time Score (TS): Reflects the time savings between manual and digital operations in each stage. Higher scores indicate greater time efficiency.
Cost Score (CS): Evaluates the relative cost benefit of digitalization through ROI or operational cost reduction. This includes labor savings, reduced material waste, and minimized refitting.

Each score is applied to stages such as scanning, modification, fabrication, and fitting using a standardized matrix. The example of scoring shown in Table 1 below:

Table 1 Example of Digital evaluation scoring matrix

Process stage	QS (0-5)	TS (0-5)	CS (0-5)	Total score
Scanning	4	5	4	13
Modification	3	4	3	10
Fabrication	2	5	3	10
Fitting	5	3	4	12

The total score per activity helps determine if that segment is suitable for:

1. Immediate digitalization (score 12–15)
2. Hybrid integration (score 8–11)
3. Manual retention (score 0–7)

This analytical layer provides objective insight into the feasibility and prioritization of digital interventions.

Layer 3: Strategic decision tool

This layer operationalizes the results from the evaluation engine into a clear and visual decision-making structure, represented as a decision tree model (see Figure 2). The model guides stakeholders in selecting the most appropriate strategy based on their evaluation scores across quality, time, and cost dimension.

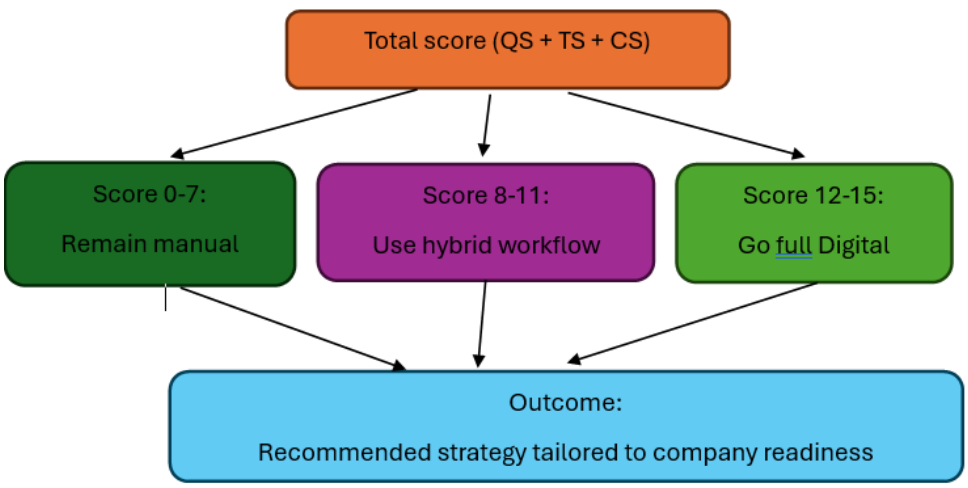

Figure 2 Decision tree model.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue III March 2026

The decision tree functions by categorizing total evaluation scores (QS + TS + CS) into three distinct digital adoption pathways:

1. Remain Manual (Score 0–7): Recommended for company with low scores across all criteria, suggesting that digitalization may not yield immediate or significant improvements. Company in this category may prioritize staff training or foundational upgrades before digital transition.

2. Hybrid Digital Workflow (Score 8–11): Suitable for company that exhibit moderate digital readiness and partial benefits from digital tools. These company may benefit from implementing scanning and CAD technologies while retaining manual processes for fitting or final adjustments.

3. Full Digital Adoption (Score 12–15): Applicable for company with strong performance gains in all dimensions, supported by available infrastructure and trained personnel. These company are in a prime position to shift fully to digital workflows, leveraging automation and scalability.

By using this structured model, decision-makers can ensure that digital transformation initiatives are aligned with both operational performance and organizational readiness. It also minimizes the risks of overinvestment or underutilization by providing a context-sensitive roadmap for change.

Linking the Framework to Business Process Reengineering (BPR)

The proposed Digitalization Workflow Framework aligns strongly with the core principles of Business Process Reengineering (BPR), which seeks to radically redesign business processes for improved efficiency, cost reduction, and service quality (Hammer & Champy, 1993; Al-Mashari & Zairi, 2000).

BPR Stage 1: Process Diagnosis

Layer 1 of the framework (Diagnostic Assessment) mirrors the first stage of BPR, in which existing workflows are mapped and pain points are identified. By integrating patient feedback, time studies, and cost logs, this layer offers a data-driven foundation for identifying inefficiencies - similar to BPR's emphasis on process discovery and benchmarking (Davenport, 2013).

BPR Stage 2: Redesign and Optimization

Layer 2 (Evaluation Engine) reflects BPR's mandate to redesign processes using performance metrics. The scoring system aligns with current best practices in healthcare reengineering, where clinical and operational indicators guide redesign decisions (Elshaer et al., 2021). It ensures that redesign choices (e.g., moving to digital scanning or 3D printing) are evidence-based.

BPR Stage 3: Implementation and Transformation

Layer 3 (Strategic Decision Tool) translates evaluation outcomes into actionable strategies, corresponding to the implementation phase in BPR. This ensures that digital transitions are not only technically feasible but aligned with clinical readiness and strategic priorities (Zairi, 2022).

As a conclusion, the analysis for Research Question 3 was conducted through the synthesis of findings obtained in earlier stages of the study, particularly those addressing quality, time, and cost performance in both traditional and digital workflows. By triangulating data from thematic coding of patient feedback, time logs across clinical activities, and comparative cost analysis, a pattern emerged identifying specific process stages where digital tools offer measurable improvements.

The results indicated that scanning, modification, and fabrication were consistently rated higher in digital workflows across all three criteria - comfort and fit (quality), reduced process duration (time), and labor/material efficiency (cost). For instance, digital scanning was reported to improve patient experience while significantly reducing casting time, while CAD-based rectification offered better repeatability and reduced technician dependency. Fabrication via 3D printing demonstrated substantial time savings and reduced rework incidents compared to traditional lamination methods.

These findings directly informed the construction of the evaluation engine within the decision tool. Each process stage was scored on a 15-point scale using standardized Quality (QS), Time (TS), and Cost (CS) metrics. This scoring matrix enabled a comparative view of which areas are most suitable for digital adoption. The final decision tool, developed as a logic-based tree model, uses these scores to recommend one of three pathways: remain manual, adopt a hybrid digital workflow, or transition to full digitalization. This approach not only answers RQ3 but also serves as a validation of the framework's ability to guide strategic digital transformation in business practice.

CONCLUSION

The framework helps organizations classify their current workflow and adopt one of three strategies:

1. Manual Enhancement: Optimize existing manual practices with minor tech support.
2. Hybrid Integration: Combine digital scanning and CAD design with traditional fitting.
3. Full Digital Workflow: For high patient volumes and advanced facilities.

Beyond tactical implementation, the framework delivers strategic value by enabling the O&P industry to align technology adoption with operational goals and resource capacities. It serves as a structured roadmap for leveraging emerging technologies not just for efficiency but also for long-term innovation and competitiveness. This includes reducing dependency on manual labor, improving consistency and scalability, and responding to national healthcare digitalization goals. By positioning digital transformation as a business process strategy, the framework empowers local O&P providers to evolve sustainably in response to patient demands, industry pressures, and global standards of care. and adopt one of three strategies suggested in this study.

This framework is particularly relevant to small and medium-sized enterprises (SMEs) in the Malaysian O&P sector, where resource constraints often make technology adoption a high-stakes decision. The decision tool not only supports internal prioritization but also serves as a communication bridge between technical, financial, and managerial stakeholders.

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