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ORIGINAL ARTICLE

Navigating the Complex Cloud Manufacturing Landscape: A Multi-Context Framework for Informed Adoption Decision-Making

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Abstract

The adoption of Cloud Manufacturing (CMfg), a service-oriented paradigm leveraging cloud and IoT technologies, is hindered by technical, organizational, human, and environmental challenges, as well as a lack of comprehensive adoption frameworks. This study develops and validates a multi-context conceptual framework to address these issues, incorporating insights from extensive literature and real-world practices. Using a qualitative multi-case study methodology, semi-structured interviews with platform providers, resource providers, and users were conducted to identify key adoption factors across five contexts: technological, organizational, environmental, business, and human. The framework was further operationalized into an Analytical Hierarchy Process (AHP)-based assessment tool, enabling decision-makers to evaluate CMfg adoption readiness systematically. Findings reveal shared motivators and barriers across stakeholder groups, while also highlighting context-specific priorities, underscoring the need for a holistic approach to CMfg adoption. This research contributes a validated framework and practical decision-support tool to advance CMfg adoption and provides actionable insights for diverse industrial contexts.

Keywords: Cloud Manufacturing, Internet of Things, Service-Oriented Manufacturing

Introduction

The manufacturing industry is undergoing a paradigm shift driven by globalization, technological advancements, and evolving customer demands. This shift moves the focus from traditional production models to service-oriented and resource-sharing paradigms, exemplified by Cloud Manufacturing (CMfg) [1], [2]. In response to these shifts, Cloud Manufacturing (CMfg) has emerged as a service-oriented paradigm that leverages cloud and IoT technologies to virtualize and pool manufacturing resources, providing on-demand access and fostering collaboration across global users [3], [4], [5].

This paradigm addresses the increasing complexity of modern manufacturing by minimizing idle resources and supporting eco-efficient operations [6], [7], reduces capital expenditure, allowing smaller companies to access advanced equipment without upfront investment [5], [6], [8]. And collaboration, democratizes manufacturing capabilities, and accelerates innovation [8], [9].

However, despite these benefits, CMfg faces several challenges that hinder its widespread adoption. Managerial challenges, such as trust issues with third-party providers and inefficient management of distributed resources, remain significant obstacles to implementation [3], [10]. From a technical and operational perspective, integrating diverse resources and ensuring interoperability pose substantial barriers that organizations must address [1], [6]. Security concerns, particularly related to data privacy and transaction security, further complicate the adoption process [4], [11]. Furthermore, human factors, such as perceptions, attitudes, and skills, play a critical role in influencing adoption decisions. Many organizations remain hesitant due to security concerns and a generally conservative attitude toward resource sharing [12], [13]. Building on these challenges, another critical issue is the lack of comprehensive frameworks that address the full spectrum of adoption factors. Existing studies predominantly focus on technical aspects, often neglecting organizational, human, and business dimensions critical to adoption [14], [15]. Furthermore, the collaborative roles of key stakeholder's platform providers, resource providers, and users remain underexplored, despite being central to the success of CMfg systems [7], [16]. Existing frameworks often fail to capture the unique characteristics of CMfg, particularly its reliance on the sharing economy and service-oriented collaboration [17].

To address these gaps, this research investigates the multifaceted factors influencing the adoption of Cloud Manufacturing (CMfg) through the development and validation of a comprehensive conceptual framework. Drawing on extensive literature and a multi-case study methodology, the research identifies key adoption considerations across five interconnected contexts: technological, organizational, environmental, business, and human. Semi-structured interviews with stakeholders shows in figure 1, including platform providers, resource providers, and users, reveal context-specific priorities and common adoption challenges, providing qualitative, yet real-world validation for the framework. Furthermore, the framework is operationalized into an Analytical Hierarchy Process (AHP)-based assessment tool, enabling decision-makers to systematically evaluate CMfg adoption readiness and prioritize critical considerations. This research contributes to advancing the understanding of CMfg adoption dynamics while offering a practical tool to facilitate informed, structured, and role-specific adoption strategies across diverse industrial contexts.

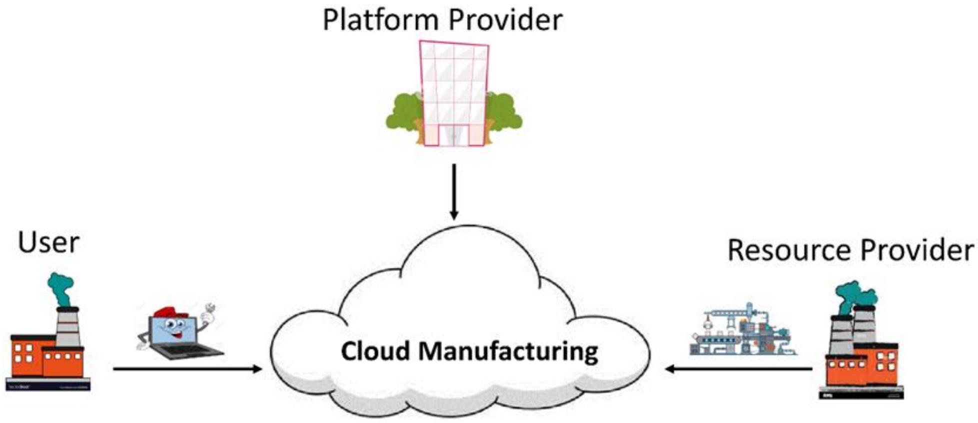

Figure 1 Cloud Manufacturing Stakeholders

The structure of this paper is outlined as follows: a brief literature review is presented in Section 2. In Section 3, we define the studied problem and present the proposed methodology. A real-world case is investigated in Section 4 using the conceptual framework. Section 5 introduces a framework testing to validate the model. Moreover, AHP-Based Assessment Tool Development is presented in section 6. Finally, concluding remarks and directions for future research are provided in Section 7.

2. Related Works

2.1 Evolution of Manufacturing Paradigms

Manufacturing has transitioned through several phases, starting from mass production in the 1960s to service-oriented approaches in recent decades, driven by globalization, technological advancements, and shifting customer demands [1], [2]. Traditional manufacturing models struggle to meet the increasing complexity of modern markets, necessitating innovative solutions such as agile, networked, and virtual manufacturing [3], [18]. The integration of IT solutions like Internet of Things (IoT) and Enterprise Resource Planning (ERP) systems and advancements in digital technologies has significantly transformed the manufacturing industry [9], [19]. These developments enable distributed, interconnected manufacturing activities, laying the foundation for paradigms like Cloud Manufacturing [2], [6], [9], [14].

2.2 Cloud Manufacturing (CMfg): Concept and Characteristics

Cloud Manufacturing (CMfg) is a service-oriented paradigm leveraging cloud and IoT technologies to virtualize and pool manufacturing resources, providing on-demand access and fostering collaboration across global users [3], [4], [5]. Since its introduction by Li et al. [20], it has been recognized as a customer-centric model offering flexible, scalable manufacturing capabilities. Researchers like Tao et al. [1] and Xu [21] have expanded its definition, emphasizing the integration of cloud computing, IoT, and virtualization to create a shared pool of configurable resources. This paradigm promotes efficiency, flexibility, and eco-friendliness while addressing challenges like resource optimization and cost reduction [6], [7], [18], [22].

The architecture of CMfg typically involves multiple layers (e.g., resource layer, virtual service layer) that interact to ensure seamless management across the product lifecycle [21], [23]. The paradigm operates through three main actors [5], [6]:

- Platform Providers: Facilitate the virtualization and delivery of resources and services.
- Resource Providers: Share their manufacturing resources as services.
- Users: Access the platform to complete manufacturing tasks.

The special feature of CMfg is offering significant operational, financial, and strategic benefits to all multiple involved actors simultaneously. It minimizes idle resources, supports eco-efficient operations, and enhances adaptability to market fluctuations [6], [7]. Financially, it reduces capital expenditure and enables smaller companies to access advanced equipment without upfront investment [5], [6], [8]. Strategically, it fosters collaboration, democratizes manufacturing capabilities, and accelerates innovation [8], [9].

Despite its advantages, CMfg faces several challenges that hinder its widespread adoption. Managerial challenges, such as trust issues with third-party providers and inefficient management of distributed resources, remain significant obstacles to implementation [3], [10]. From a technical and operational perspective, integrating diverse resources and ensuring interoperability pose substantial barriers that organizations must address [1], [6]. Security concerns, particularly related to data privacy and transaction security, further complicate the adoption process [4], [11]. Additionally, human factors play a critical role, as perceptions, attitudes, and skills significantly influence adoption decisions. Many organizations remain hesitant due to concerns about security and a generally conservative attitude toward resource sharing [12], [13].

2.3 Existing Adoption Frameworks

The adoption of CMfg requires comprehensive frameworks to address technical, organizational, and human factors. Existing adoption theories include:

- Diffusion of Innovations (DOI): Explains the adoption process but lacks emphasis on organizational factors [24], [25].
- Technology Acceptance Model (TAM): Highlights perceived usefulness but overlooks social influences [26], [27].
- Technology-Organization-Environment (TOE): Offers a holistic perspective on adoption but neglects human factors [28].
- HOT-fit: Incorporates human factors but misses broader business considerations [29].

2.4 Challenges in CMfg Adoption

Integrating these theories can provide a robust framework to address adoption complexities [30], [31]. Despite the increasing interest in Cloud Manufacturing, significant research gaps remain unaddressed. One of the primary issues is the lack of comprehensive frameworks that consider the full spectrum of adoption factors. Existing studies predominantly focus on technical aspects, often neglecting organizational, human, and business dimensions critical to adoption [14], [15]. Additionally, the perspectives of key stakeholders—platform providers, resource providers, and users—are underexplored, even though their collaborative roles are essential to the success of Cloud Manufacturing systems [7], [16]. Furthermore, most available frameworks are generic and fail to capture the unique characteristics of Cloud Manufacturing, such as its reliance on the sharing economy and service-oriented collaboration [17]. This oversight limits their applicability in practice. Integrating these principles into adoption frameworks, alongside addressing the specific requirements and challenges of Cloud Manufacturing, remains an essential area for future research. Table 1. Summarizes the contribution of the most related adoption framework studies.

This research adopts a qualitative approach to explore the multi-context considerations influencing Cloud Manufacturing (CMfg) adoption, aligning with a relativist ontology and relational epistemology. A case study strategy was employed to examine adoption practices across three primary actor groups in the CMfg scheme: Platform Providers, Resource Providers, and Users. By integrating theoretical foundations with real-world validation, this research provides a robust, actionable tool for evaluating CMfg adoption across various organizational contexts.

Table 1 Summary of related literature

Study	Focus	Methodology	Key Findings	Limitations
A Framework to Assess Readiness of Firms for Cloud Manufacturing	Framework for readiness of resource providers for Cloud Manufacturing	Literature review of frameworks for Cloud Computing and Industry 4.0; validated with academic experts	Identified six dimensions: Service, Manufacturing, Operation, Business, Strategy, and Legal, subdivided into 36 factors assessed across 4 levels	Framework focuses on resource providers and does not address other actors (e.g., users or platform providers). Limited validation.
Evaluation of enablers of cloud technology to boost industry 4.0 adoption in the manufacturing micro, small and medium enterprises	Enablers for adopting cloud technologies to boost Industry 4.0 adoption	Literature review and expert consultation; applied Interpretive Structural Modeling and MICMAC analysis	Identified 14 enablers, with system integration, project management, and competitive pressure as the most influential	Focuses on generic cloud technologies, not Cloud Manufacturing. Expert input may introduce bias, and practical validation is limited.
Design and Development a Model to Present Practices for Implementation Cloud Manufacturing System	Practices for implementing Cloud Manufacturing	Literature review; Delphi method to identify practices; Fuzzy Cognitive Mapping to study relationships	Highlighted 20 practices, emphasizing customer scoring, R&D, and method development as critical	Focuses primarily on implementation practices without addressing pre-adoption considerations or specific roles of stakeholders.
Cloud manufacturing: a myth or future of global manufacturing?	Barriers to adopting Cloud Manufacturing	Survey of 218 US manufacturers using integrated adoption theories (DOI, TOE, TAM)	Emphasized pre-installation preparation as key to adoption success; reluctance due to lack of sharing economy consideration	Doesn't address specific stakeholder roles; lacks contextual factors such as human and business considerations.
Cloud manufacturing	Comprehensive literature	Systematic review of 111	Identified gaps in frameworks	Findings highlight gaps but

adoption: a comprehensive review	review on Cloud Manufacturing adoption	journal papers, categorized into real-life applications, simulations, and theoretical studies	addressing Cloud Manufacturing; many studies focused on general cloud or digital technologies	do not propose specific solutions or frameworks tailored to Cloud Manufacturing adoption.

3. Methodology

This study adopts a qualitative approach to explore the multi-context; technical, business, organizational, environment, and human, considerations that influence Cloud Manufacturing (CMfg) adoption, aligning with a relativist ontology and relational epistemology.

A case study strategy was employed to examine adoption practices across three primary actor groups in the CMfg scheme: Platform Providers, Resource Providers, and Users. This strategy allows for a detailed investigation of adoption decision-making within distinct organizational contexts while enabling cross-case comparisons. By addressing the "how" and "why" questions central to CMfg adoption, the case study approach offers a holistic understanding of the interplay between organizational, technical, and human factors in the decision-making process [32], [33], [34].

The research process was carried out in two primary stages shows in figure 2. First, a framework development stage was conducted, drawing insights from an extensive literature review. The review synthesized existing studies on CMfg, cloud computing, and technology adoption, identifying critical enablers and barriers and highlighting gaps in previous research [35], [36]. The outcome was a multi-context conceptual framework encompassing five key contexts—business, human, technology, organizational, and environmental—each with its respective considerations.

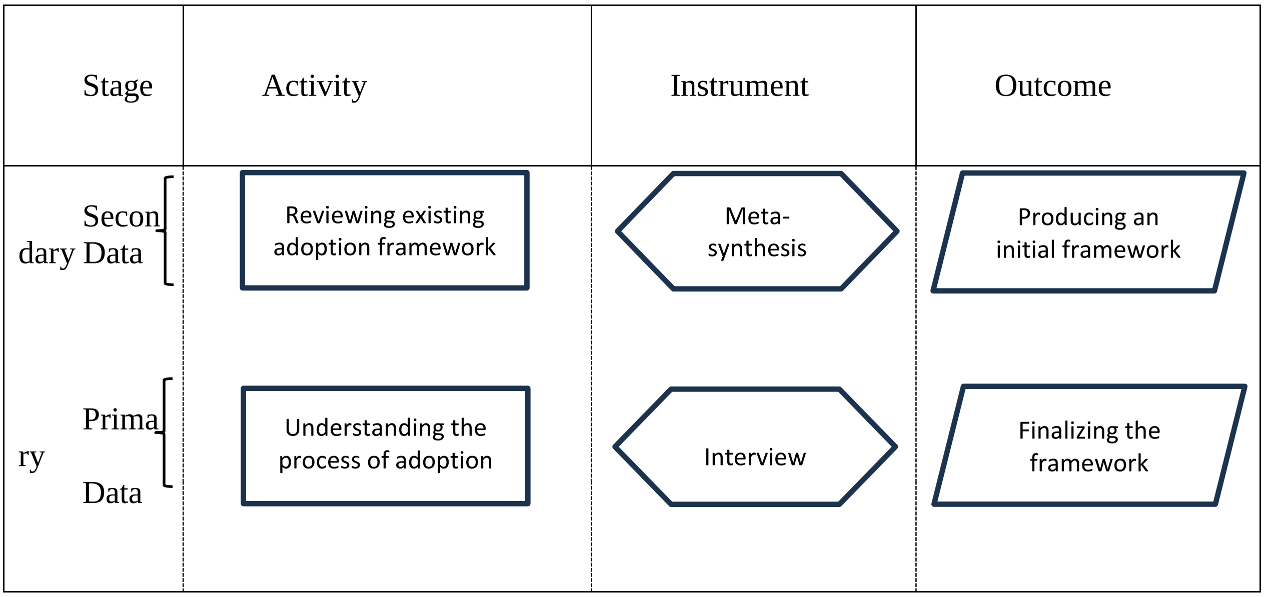

Figure 2 Methodology Chart

Second, the proposed framework was validated and refined through semi-structured interviews with 27 high-level decision-makers from organizations representing the three actor groups. These interviews, conducted online via Microsoft Teams, facilitated a detailed exploration of participants' real-world experiences and perspectives. Questions were designed to explore their decision-making processes, priorities, and the relevance of the framework's considerations to their unique roles. This approach allowed for flexibility to uncover new insights while ensuring alignment with the study's objectives [37], [38].

To analyse the interview data, a thematic analysis method was employed using NVivo software. Themes were identified based on the research objectives and structured to align with the multi-context framework. The analysis emphasised the considerations significance, revealing patterns and key factors influencing adoption decisions. Insights gathered from the interviews were instrumental in refining the framework, ensuring its comprehensiveness and practical applicability [34], [37].

This methodology ensures that the resulting framework is grounded in real-world evidence, capturing the challenges and opportunities faced by decision-makers. By integrating theoretical foundations with real-world validation, the study provides a robust, actionable tool for evaluating CMfg adoption across various organizational contexts. The focus on qualitative insights contributes to a deeper understanding of the complex factors shaping CMfg adoption decisions, making the framework a valuable resource for industry leaders.

4. Cloud Manufacturing Adoption Framework Development

4.1 Conceptual Framework

The conceptual framework developed in this study provides a comprehensive understanding of the multi-faceted considerations for adopting CMfg. Synthesizing existing theoretical frameworks and integrating insights from extensive literature, the framework identifies critical factors across five contexts—technology, organization, environment, business, and human—aimed at enabling stakeholders to assess the feasibility of CMfg adoption. This integration is particularly necessary given the limitations of existing frameworks, which often focus narrowly on specific aspects of adoption, neglecting the broader multidimensional nature of CMfg.

Cloud Manufacturing is an emerging cloud-based innovation. Therefore, some researchers developed frameworks depending on the similarity between Cloud Manufacturing and Cloud Computing and Industry 4.0 applications [10], [12], [39], [40]. Others built their frameworks for adopting cloud services on the concept of innovation diffusion [41], [42], [43], [44]. However, a key aspect of CMfg is the idea of the sharing economy, where some participants share their resources, and others access them remotely. The sharing economy significantly impacts the CMfg scheme by introducing different concerns and perceptions regarding the physical utilization of shared resources. Despite this, most existing frameworks fail to comprehensively address the unique factors associated with sharing-based business models like CMfg.

Popular frameworks such as the Technology-Organization-Environment (TOE) framework by Tornatzky and Fleischer [45] and the Diffusion of Innovations (DOI) theory by Rogers [46] have been widely applied to explore the adoption of technological innovations. The TOE framework emphasizes three dimensions—technological, organizational, and environmental factors—but does not adequately address the human and business contexts, which are crucial for CMfg adoption. Similarly, DOI theory provides a basis for understanding innovation characteristics such as compatibility, complexity, and relative advantage but lacks emphasis on organizational and external market factors that shape the adoption process. Other frameworks, such as the Human-Organization-Technology fit (HOT-fit) framework [29], highlight human behaviour and organizational alignment but do not extend to the external market dynamics or business considerations essential for CMfg. Furthermore, the Information Systems Strategy Triangle [47] underscores the importance of aligning organizational strategy with technology but does not address the complexities of sharing-based models like CMfg. These limitations necessitate the development of a more holistic framework that integrates the strengths of these existing models while addressing their gaps.

To address these gaps, the conceptual framework proposed in this study was developed through an extensive review of the literature on CMfg, cloud computing, the sharing economy, and innovation adoption. The process involved identifying adoption considerations commonly discussed in the literature and grouping them into five distinct but interconnected contexts. This multidimensional framework provides decision-makers with a robust tool for evaluating the feasibility of CMfg adoption.

The resulting framework, shown in Figure 2, integrates 28 considerations, which are grouped into their respective contexts:

1. The environmental context focuses on external pressures and regulations that impact CMfg adoption. The considerations are: Market pressure, market uncertainty, consumer readiness, government regulations, and clear cloud usage policy.
2. The organizational context captures internal factors related to an organization's characteristics and capacity for innovation. The considerations are: Organization size, innovation atmosphere, previous experience, strategic planning, top management support, and buyer-supplier relationships.
3. The business context examines the financial and marketing justifications for CMfg adoption. The considerations are: Cost-benefit analysis, demand analysis, competitive advantage, and brand image.
4. The technological context addresses technical requirements and challenges. The considerations are: Compatibility, IT support, security and data protection, complexity and architecture, resource readiness, and cloud readiness.
5. The human context addresses the role of individual and organizational behaviours in shaping adoption decisions. The considerations are: Perceived usefulness, perceived risk, perceived ease of use, attitude toward sharing, attitude toward change, digital skills, and training.

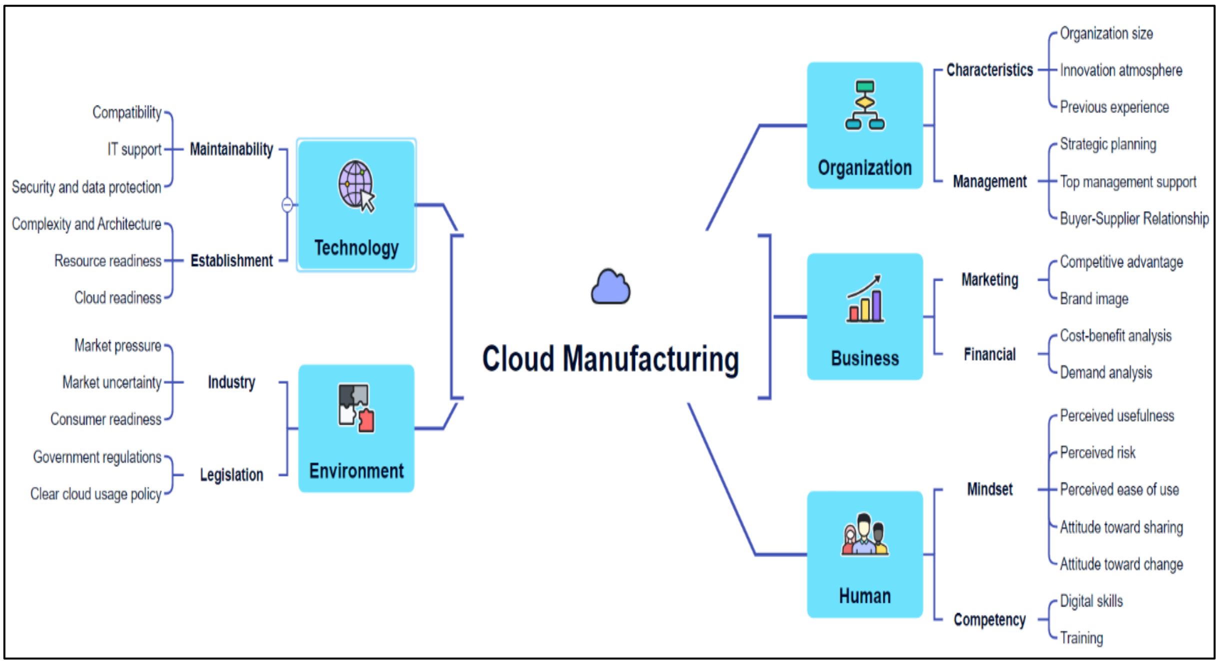

Figure 3 A Mind-Map of the Proposed Framework

This framework advances existing literature by addressing the unique characteristics of CMfg, particularly its reliance on the sharing economy and distributed resource models. By integrating financial implications, technical requirements, external market dynamics, organizational readiness, and human factors, the framework offers a holistic perspective for evaluating CMfg adoption. It serves as a practical tool for decision-makers, enabling them to make informed and balanced decisions tailored to their organizational and market contexts.

4.2 Framework Validation

The framework testing involved a multi-case study approach to validate the proposed CMfg adoption framework. This methodology was chosen to address the varying roles and perspectives of the three main actors in CMfg: Platform Providers, Resource Providers, and Users, as each has unique considerations and decision-making processes. This approach aligns with Yin's recommendation that multiple case studies provide richer data and enhance validity through cross-case comparisons [33]. Each actor group represented a separate case study. Platform providers were selected for their expertise in cloud services, resource providers for their capacity to offer diverse and scalable resources, and users for their reliance on advanced manufacturing solutions. Participants were selected based on specific criteria reflecting their expertise, technology adoption history, and relevance to the CMfg paradigm.

Semi-structured interviews served as the primary data collection method, as they allowed for open-ended discussions while maintaining focus on key research objectives [34]. Interviews were conducted with senior decision-makers using a semi-structured format to capture insights into their decision-making processes, the enablers and barriers they encounter, and their perceptions of the proposed framework. The interviews also leveraged the Funnel model to transition from general decision-making discussions to specific considerations for Cloud Manufacturing adoption [48].

Thematic analysis was employed to interpret the interview data, identifying patterns and recurring themes related to CMfg adoption. The analysis revealed key insights across three main themes: decision-making approaches, awareness and perceptions, and adoption decision considerations.

1. Decision-Making Approaches: Leaders acknowledged the complexity of adoption decisions, noting the absence of structured processes in many organizations. While decision-making often relied on situational analysis and personal judgment, the lack of formal frameworks led to inconsistencies. For instance, platform providers focused on market opportunities and technical readiness, whereas resource providers and users emphasized operational and organizational considerations.
2. Awareness and Perceptions: All actor groups demonstrated a foundational understanding of cloud services but lacked familiarity with Cloud Manufacturing as a distinct concept. Platform providers had the deepest understanding, highlighting cloud infrastructure and service models as core strengths. Once introduced to the concept, leaders across all groups recognized its potential benefits, including cost optimization, resource efficiency, and new business opportunities. However, sectors with sensitive data expressed caution due to security concerns.
3. Adoption Decision Considerations: The multi-case study highlighted variations in context prioritization. Platform providers focused on technology readiness and business opportunities, resource providers on human factors like change management and workforce training, and users on organizational alignment and operational efficiency. Common across all groups was the importance of business needs and market alignment, with leaders emphasizing demand-driven decision-making and cost-benefit analyses.

The framework testing validated the comprehensiveness of the proposed model, highlighting its relevance and adaptability across the three actor groups. By revealing shared motivators, barriers, and context-specific priorities, the study reinforced the need for a structured, multi-context framework to guide Cloud Manufacturing adoption decisions. These findings contribute to the refinement of the framework and underscore its practical applicability in diverse organizational settings.

6 Framework Application: An AHP-Based Assessment Tool

To ensure the research findings are practical and usable, the proposed multi-context framework has been transformed into an interactive assessment tool. This tool enables decision-makers to evaluate CMfg 's suitability for their organization, aligning with the objective of providing an actionable, organization-specific framework for adoption decision-making.

The tool employs the Analytic Hierarchy Process (AHP), a methodology suitable for multi-criteria decision-making, to assign weights to contexts and considerations [49]. The process begins with pairwise comparisons among the five contexts—business, human, technology, organization, and environment—to determine their relative importance. Following this, users conduct another series of pairwise comparisons among considerations within each context to assign their respective weights.

Each consideration is then evaluated by the user based on three qualitative impact levels: "in favour," "neutral," and "against." These are numerically converted to scores of 2, 1, and 0, respectively. The weighted score for each consideration is computed as the product of the context weight, the consideration weight, and the user evaluation score, reflecting the consideration's overall impact within the adoption decision.

The measure proposed in this study is the Overall Suitability Level, which gives an initial indication regarding how well adopting Cloud Manufacturing aligns with the organization’s circumstances and business needs. It is expressed as a percentage and is calculated using the following formula:

$$\text{Overall Suitability Level} = \left(\frac{\sum \textit{weighted scores of all considerations}}{\textit{maximum weighted score}}\right) \times 100$$

Where:

- $\sum \textit{weighted scores of all considerations}$: is the total sum of all weighted scores based on the organization’s evaluation of the 28 considerations within the framework.
- $\textit{maximum weighted score}$: is the highest possible weighted score assuming that all considerations are evaluated as "in favour." For the 28 considerations in the framework, this value is 56 (28 × 2).

This measure offers a straightforward way for decision-makers to gauge their organization’s suitability for adopting Cloud Manufacturing. A higher percentage suggests that, based on the framework's considerations, the organization's circumstances are more supportive of adoption. Conversely, a lower percentage indicates that the organization's current conditions may present challenges or barriers to successful adoption.

The tool was coded in JavaScript and deployed as a web-based application accessible via the CMAAT website (CMAAT.solutions). Users begin by selecting their role within the CMfg scheme (platform provider, resource provider, or user). They then proceed to compare contexts and considerations through pairwise comparisons, followed by evaluating their organization's circumstances against each consideration.

The output includes an overall suitability level and a pie chart visualization. Each segment in the chart represents a consideration, with its size and colour—green, yellow, or red—indicating the weighted score. This visual representation helps decision-makers identify strengths, weaknesses, and priority areas, enabling focused planning to address gaps and improve readiness for adoption. Figure 2 shows an example of the visual output.

Figure *4* An Example of the Tools's Visual Output

The tool's validation involved a pilot study with a panel of three experts representing the three actor groups. The panel acknowledged the tool's comprehensiveness, its user-friendly structure, and its value in making complex frameworks actionable. While they appreciated the clarity and logical flow, they noted the high number of pairwise comparisons as a drawback inherent to AHP. Suggestions for improvement included adding a save-and-resume feature and integrating AI for weight assignments based on industry-specific data and market trends.

The tool's development and validation underscore its practicality in guiding organizations through the Cloud Manufacturing adoption decision-making process. By incorporating structured evaluation, actionable outputs, and user-friendly design, CMAAT transforms the theoretical framework into a valuable resource for industry leaders.

7. Conclusion

A comprehensive conceptual framework has been developed and validated to examine the multifaceted factors influencing the adoption of Cloud Manufacturing (CMfg). Through a multi-case study methodology and extensive literature review, the research identifies five interrelated contexts for adoption. A real-world validation of the framework is provided by semi-structured interviews with stakeholders, including platform providers, resource providers, and users, which revealed context-specific priorities and common adoption challenges. A thorough literature review was conducted in order to develop the conceptual framework for this study to address these gaps in manufacturing, cloud computing, sharing economies, and innovation adoption. Initially, an extensive literature review was conducted to develop a framework. CM, cloud computing, and technology adoption were reviewed, identifying critical enablers and barriers as well as highlighting gaps in previous research. As a result, a multi-context theoretical framework was developed encompassing five key contexts-business, human, technological, organizational, and environmental. NVivo software was used to analyse the interview data using a thematic analysis method. As a result of the research objectives, themes were identified and structured in accordance with the framework of multi-contexts. In order to gain insights into senior decision-makers' decision-making processes, enablers and barriers they encounter, and perceptions of the proposed framework, semi-structured interviews were conducted. Results showed the conceptual framework effectively supports Cloud Manufacturing adoption with a comprehensive, user-friendly design.

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