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Review Article

Rethinking Digital Transformation of Manufacturing Through Platforms: A Critical Review and Integrative Framework

Ourania ARETA HIZIROĞLU [a,*]

[a] *Department of Management Information Systems, Faculty of Economics and Administrative Sciences, Izmir Bakircay University, Izmir, TURKEY*
** Corresponding author's e-mail address: ourania.areta@bakircay.edu.tr*
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ABSTRACT

The digital transformation of manufacturing through platforms represents a paradigm shift in industrial operations, yet comprehensive frameworks for understanding and implementing these transformations remain fragmented. This study presents a systematic bibliometric analysis of 156 publications from Web of Science and Scopus databases (2011-2024), offering a critical review of digital manufacturing platform research. The analysis reveals three evolutionary phases: conceptual foundation (2011-2016), integration (2017-2020), and advanced implementation (2021-2024). While existing literature extensively addresses technical architectures and implementation methodologies, significant gaps remain in understanding the holistic integration of sustainability principles and standardization frameworks. This research contributes by proposing an integrative framework that synthesizes technological, organizational, and environmental dimensions of platform-based manufacturing transformation, encompassing five key elements: platform architecture, digital twin integration, interoperability standards, business model innovation, and sustainability integration. The findings indicate a shift from theoretical conceptualizations to practical implementation considerations, particularly for small and medium-sized enterprises. The study identifies emerging research directions, emphasizing standardized approaches to cross-platform interoperability and artificial intelligence integration in platform-based manufacturing systems, providing guidance for researchers and practitioners while considering sustainability imperatives.

Keywords: *Digital manufacturing platforms, Industry 4.0, digital transformation, bibliometric analysis, platform integration framework*

Platformlar Aracılığıyla Üretimin Dijital Dönüşümünü Yeniden Düşünmek: Eleştirel Bir İnceleme ve Bütünleştirici Çerçeve

ÖZ

Platformlar aracılığıyla üretimin dijital dönüşümü, endüstriyel operasyonlarda bir paradigma değişimini temsil etmektedir, ancak bu dönüşümleri anlamak ve uygulamak için kapsamlı

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çerçeveler hala parçalı durumdadır. Bu çalışma, Web of Science ve Scopus veritabanlarından (2011-2024) 156 yayının sistematik bibliyometrik bir analizini sunarak, dijital üretim platformu araştırmalarının kritik bir incelemesini ortaya koymaktadır. Analiz üç evrimsel aşamayı ortaya çıkarmaktadır: kavramsal temel (2011-2016), entegrasyon (2017-2020) ve ileri düzey uygulama (2021-2024). Mevcut literatür teknik mimarileri ve uygulama metodolojilerini kapsamlı bir şekilde ele almasına rağmen, sürdürülebilirlik ilkelerinin ve standardizasyon çerçevelerinin bütünsel entegrasyonunu anlamada önemli boşluklar bulunmaktadır. Bu araştırma, platform tabanlı üretim dönüşümünün teknolojik, organizasyonel ve çevresel boyutlarını sentezleyen ve beş temel unsuru (platform mimarisi, dijital ikiz entegrasyonu, birlikte çalışabilirlik standartları, iş modeli inovasyonu ve sürdürülebilirlik entegrasyonu) kapsayan bütünleştirici bir çerçeve önererek katkı sağlamaktadır. Bulgular, özellikle küçük ve orta ölçekli işletmeler için teorik kavramsallaştırmalardan pratik uygulama değerlendirmelerine doğru bir kayma olduğunu göstermektedir. Çalışma, platform tabanlı üretim sistemlerinde platformlar arası birlikte çalışabilirlik ve yapay zeka entegrasyonu için standartlaştırılmış yaklaşımlara vurgu yaparak gelişen araştırma yönlerini belirlemekte ve araştırmacılara ve uygulayıcılara sürdürülebilirlik gerekliliklerini göz önünde bulundurarak rehberlik sağlamaktadır.

Anahtar Kelimeler: *Dijital üretim platformları, Endüstri 4.0, dijital dönüşüm, bibliyometrik analiz, platform entegrasyon çerçevesi*

I. INTRODUCTION

The manufacturing industry has reached a very critical crossroads in its struggle with the consequences of digital transition. The most powerful, concurrently complex enabler lies at the heart of this transformation: digital platforms. Unlike simple technological infrastructures, digital platforms are a basic reimagining of how manufacturing value will be created, captured, and distributed [1]. Recent research has established that digital platforms are causing disruption in conventional manufacturing paradigms, creating new paths of collaboration, and innovating within the industrial ecosystem. Researchers like Lerch et al. [2] identified that recent developments in enabling technologies, such as digital twins, AI, and Internet of Things (IoT), have accelerated the implementation of the digital manufacturing platform. It is within this direction that rapid evolution has given way to a convoluted landscape of multiple approaches, architectures, and implementation frameworks, very often bringing in integration problems and issues relating to standardization. Heterogeneity in platform solutions allows for greater flexibility; this is along with great complexity regarding interoperability, data governance, and sustainability [3].

There is little exaggeration in underlining what this change really means. According to den Hartigh et al. [4], manufacturing organizations have increasingly had to consider how they will sustain success in ever-complex circumstances, in which operational excellence has to be recombined with the ability to orchestrate digital ecosystems. Unprecedented opportunities combine with formidable challenges, especially for those struggling to grasp or execute these platform-based means of transformation.

Digital platforms remain instrumental to manufacturing, while there is some fragmentation in views about how such platforms will contribute to digital transformation. Fragmentation is partly reflected in variant forms of implementation that range from one adoption success story to another, while there is limited consensus on the framework that underpins a common approach towards platform-enabled transformation in manufacturing [4]. Furthermore, while there is considerable literature on digital platforms in consumer markets, their application and implications in manufacturing settings pose various challenges and opportunities that are yet to be fully explored in greater detail [5].

This review article addresses these deficiencies by pursuing a critical state-of-the-art overview regarding digital platforms in manufacturing and their contribution to digital transformation. Thus, we seek to:

1. Synthesize extant research on digital platforms in manufacturing contexts.
2. Understand the mechanisms through which platforms achieve digital transformation.
3. Identify critical success factors and barriers that lead to the successful adoption of a platform.
4. Develop an integrative framework that captures the platform-enabled digital transformation.

This review is important because it provides a basis for advancement in both theory and practical implementation involving digital platforms in manufacturing. Through the integration of several streams of research, the study provides a holistic view of how an organization can benefit from digital platforms in driving digital transformation.

This research adds to what is already known in a number of important ways. First, it maps out the current state of research into digital manufacturing platforms to show what is known and what is new. Second, it suggests a new way to look at how platform architecture, sustainability, and business model innovation are connected. Finally, it points out the important research directions that both academic and practitioner communities need to pay attention to.
The rest of the paper unfolds as follows: the theoretical background for this study is explaind in Section 2; the methodology applied to conduct a bibliometric review is presented in Section 3; Section 4 describes the main findings of the analysis, focusing on the most distinguished thematic and trend insights that have emerged from the literature; the derived integrative framework is proposed in Section 5 and sets out implications for theory and practice. Section 6 concludes the paper with some suggestions for future research.

II. THEORETICAL BACKGROUND

A. UNDERSTANDING DIGITAL PLATFORMS IN MANUFACTURING

Digital manufacturing platforms are regarded as complex socio-technical systems, enabling various stakeholders to interact with each other while fostering the integration of digital technologies, data, and processes [6]. Digital platforms differ from traditional manufacturing systems in their ability to create value through network effects, ecosystem orchestration, and digital capability integration [7]. den Hartigh et al. [4] point out that such platforms make a new way in reshaping manufacturing operations by being uniquely capable of configuring or reconfiguring resources dynamically.

Most manufacturing digital platforms fall under different types, each catering to a definite set of functions within the industrial ecosystem. Deshmukh et al. [8] elaborate that the Industrial Internet of Things platforms provide the basic infrastructure to connect with and manage smart devices and sensors in manufacturing environments. According to Lerch & Heimberger [9], a manufacturing execution platform works on operational control and real-time management of production. In the view of van Dyck et al. [10], digital twin platforms provide a way for the virtual representation and simulation of actual physical manufacturing assets and processes. The work of Reim et al. [3] posits that collaborative manufacturing platforms enable interactions and sharing between different manufacturing entities. Also, Liu et al. [11]

investigated service-oriented manufacturing platforms that enable conventional manufacturing in transforming to service-oriented business models.

These different types of platforms indeed exhibit quite distinct characteristics along a number of dimensions. Their architectural design principles range from centralized to distributed approaches [6]. According to the review on digital economy upgrading strategies by Sturgeon [12], the value creation mechanisms range from efficiency improvement to innovation enablement. Moreover, the integration capabilities extends from basic data exchange to advanced cyber-physical system integration [13], while the stakeholder relationships varry from a simple supplier-customer interaction to complex ecosystem orchestration [14]. In the investigation of resilient and sustainable manufacturing supply chains, data-managing approaches range from simple data collection to advanced analytics and AI integrations [15].

This diverse landscape of digital manufacturing platforms reflects the ongoing development in Industry 4.0 and the increasing sophistication of digital manufacturing technologies themselves. These continuous developments, as observed by Tolio et al. [16], are at the very root of drastic changes in how manufacturing enterprises operate, cooperate, and co-create value in today's digital world.

B. DIGITAL TRANSFORMATION IN MANUFACTURING

All in all, the digital transformation of manufacturing involves interrelated dimensions that are jointly reimagining industrial operations and value creation. The work of Liu and Zhang [17] has indicated that technological integration indeed provides the backbone for this change, while the digitization of processes allows new operating models. Regarding the latter, business model innovation, as studied by Drewel et al. [5], develops new value propositions in the digital economy. Organizational change signifies the human and cultural attributes of transformation [18]. Value chain reconfiguration is about the essential remolding of the relationships and processes of manufacturing [3].

Several enabling technologies serve as the spine for contemporary manufacturing and hence traverse the path to metamorphosis. For example, the IoT serves as the foundational infrastructure for connectivity and data collection [8], while Artificial Intelligence enables advanced decision-making and process optimization [7]. Moreover, Cloud Computing provides the scalable infrastructure needed for digital operations [19], and Digital Twin Technology creates virtual representations for simulation and optimization [10]. Additionally, Advanced Analytics convert raw data into actionable insights, while blockchain provides confidence in trustworthy and transparent digital deals [6].

The mechanisms for value creation within the platform-enabled transformation are manifold. Resource orchestration and integration allow for effective resource allocation across manufacturing networks [4], while knowledge-sharing and collaboration mechanisms enable collective learning and innovation [14]. According to Lerch et al. [2], it is process optimization and automation that drive operational excellence by the use of digital capabilities. Data-driven decision-making enhances strategic and operational choices, while ecosystem development creates sustainable competitive advantages through network effects [15].

In the manufacturing context, there are several major challenges that the implementation journey usually confronts. Technical integration complexity stands in the way of the smooth adoption of digital solutions, as observed by Stratmann et al. [20]. Organizational resistance emerges from cultural and structural barriers to change [21]. Furthermore, data security and privacy concerns create hesitation in data sharing and integration [22]. Interoperability issues also arise from diverse technical standards and systems [16]. The capability development and skill gap require huge investment in human capital, while on the other side, investment justification requires a clear demonstration of return on digital investments [23].

This section has formed the theoretical basis for explaining how digital platforms enable and shape digital transformation processes within manufacturing contexts. Therefore, it throws light into the multi-faceted nature of both the platforms and the transformation processes, hence setting the ground for the in-depth investigation of their interaction and outputs.

III. METHODOLOGY

This study employs a systematic bibliometric analysis approach to examine the evolution and current state of digital manufacturing platform research. The methodology consists of four distinct phases: data collection, data preprocessing, bibliometric analysis, and thematic synthesis (see Figure 1).

Figure 1. *Phases of undertaken methodology*

A. DATA COLLECTION

The research utilized two primary academic databases: Web of Science (WoS) and Scopus, chosen for their comprehensive coverage of peer-reviewed literature in engineering and technology management. The search strategy employed the following boolean search string:
("digital platform*" OR "digital manufactur*" OR "smart manufactur*") AND ("Industry 4.0" OR "smart factor*" OR "digital twin*" OR "industrial internet")
The initial search was conducted in January 2024, covering publications from 2011 to 2024. The search parameters were restricted to:

- Document types: Journal articles, conference proceedings, and book chapters
- Language: English

B. DATA PREPROCESSING

The initial search yielded 312 documents (176 from WoS and 136 from Scopus). The preprocessing phase involved:

- Removal of duplicates between databases (93 overlapping documents)
- Manual screening of titles and abstracts for relevance
- Application of inclusion/exclusion criteria as shown in Table 1:

Table 1. *Inclusion and Exclusion criteria applied for data preprocessing*

Inclusion criteria	Exclusion criteria
Studies focusing on digital manufacturing platforms	General digitalization studies without platform focus

Research addressing platform architecture and implementation	Non-manufacturing applications
Papers discussing integration with Industry 4.0 technologies	Opinion pieces and non-peer-reviewed content

After applying these criteria, the final dataset comprised 156 unique publications (63 from WoS and 93 from Scopus).

C. BIBLIOMETRIC ANALYSIS

The bibliometric analysis was conducted using multiple analytical dimensions as presented in Table 2:

Table 2. *Analytical dimensions*

1. Temporal Analysis:	• Publication trends over time • Evolution of research themes
2. Content Analysis:	• Co-word analysis of keywords and abstracts • Topic modeling using data analysis and visualization tool
3. Collaboration Analysis:	• International collaboration patterns

D. THEMATIC SYNTHESIS

The thematic synthesis involved a three-stage process as shown in Figure 2:

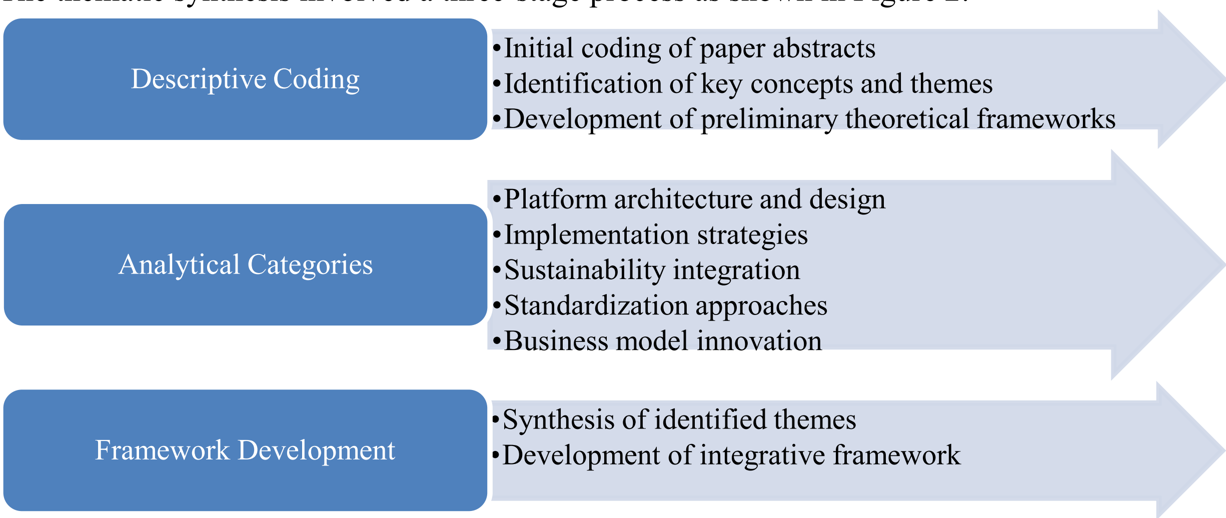

Figure 2. *Stages of the thematic analysis*

Within the framework of analysis, this study utilised VOSviewer, a specialised tool for bibliometric mapping and visualization.

The methodological rigor of the present study is increased by several important strategies adopted during the data collection and analytical processes. Using both the Web of Science and Scopus databases adds to the reliability and validity of the research on several dimensions [5, 14]. The dual-database approach ensures a wide coverage of relevant literature, crossing regional boundaries to enable the inclusion of a diverse spectrum of publication sources; crossvalidation approach to maintain uniform quality standards; offset biases related to specific databases, since Web of Science is known for having better coverage of North American and Western European literature, while Scopus has broader coverage of publications from other geographical regions. These methodological choices collectively strengthen the study's reliability and validity, providing a robust foundation for our analysis of digital manufacturing platform research.

The study acknowledges several methodological limitations. The restriction to English-language publications potentially excludes valuable insights from non-English research communities, particularly from emerging manufacturing economies [11]. The selection of Web of Science and Scopus as primary databases, while comprehensive, may not capture all relevant publications in specialized regional journals [16].

Notwithstanding these, the methodological framework integrates quantitative bibliometric analysis with qualitative thematic synthesis for comprehensive insight into established knowledge and emerging trends in digital manufacturing platforms [10]. It gives insight into the evolution of the field, while at the same time evincing awareness of the dynamic nature of the platform-based manufacturing transformation.

IV. FINDINGS AND ANALYSIS

This section presents the results of the bibliometric analysis, organized into three main subsections: publication trends and patterns, thematic evolution, and research focus areas.

A. PUBLICATION PATTERNS AND TEMPORAL DISTRIBUTION

The analysis reveals that a marked research interest in digital manufacturing platforms is evident for the last decade. Figure 3 depicts the yearly distribution of publications during 2011-2024, showing three distinctive phases of the evolution in research.

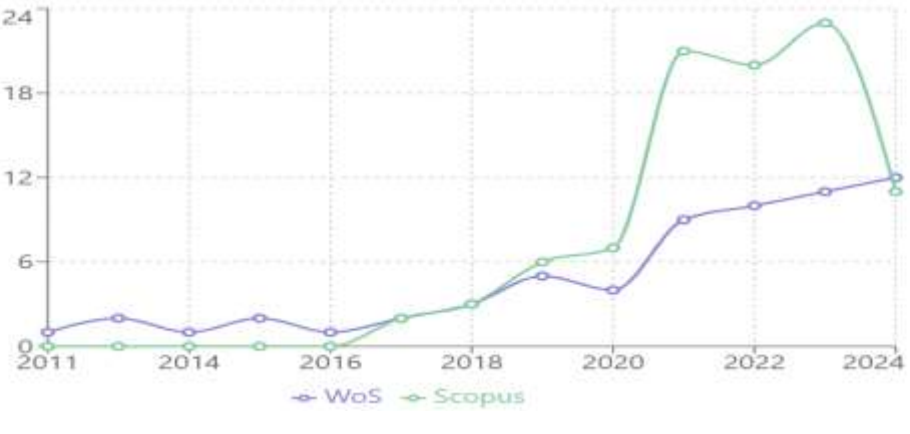

Figure 3. *Publication Trends in Digital Manufacturing Platforms Research*

The temporal analysis indicates three distinct phases:

a. Initial Phase (2011-2016):
- Limited research activity focusing on basic platform concepts and manufacturing IT movement towards service-orientation [19]
- Early exploration of integrated product design and manufacturing platforms [24]

- Initial conceptualization of platform architectures for smart manufacturing [25]
b. Growth Phase (2017-2020):
- Substantial increase in research output, particularly in platform implementation studies [19]
- Integration of digital twin concepts and virtual manufacturing [26]
- Development of reference models for industrial internet frameworks [13]
c. Maturation Phase (2021-2024):
- Exponential growth in research addressing sustainability challenges [20]
- Focus on cross-platform integration and standardization [8]
- Advanced implementation frameworks incorporating AI and machine learning [27]

The analysis also identified the following distribution of research methodologies that have been employed in related studies, as shown in Table 3:

Table 3. *Distribution of the Methodological Approaches*

1. Empirical Studies (35%)	- Case studies - Survey research - Field experiments
2. Conceptual Research (30%)	- Framework development - Theoretical modeling - Architecture design
3. Literature Reviews (20%)	- Systematic reviews - Meta-analyses - Narrative reviews
4. Mixed Methods (15%)	- Combined approaches - Multi-phase studies - Hybrid methodologies

The geographical distribution of research, as shown in Figure 4, revealed significant regional variations:

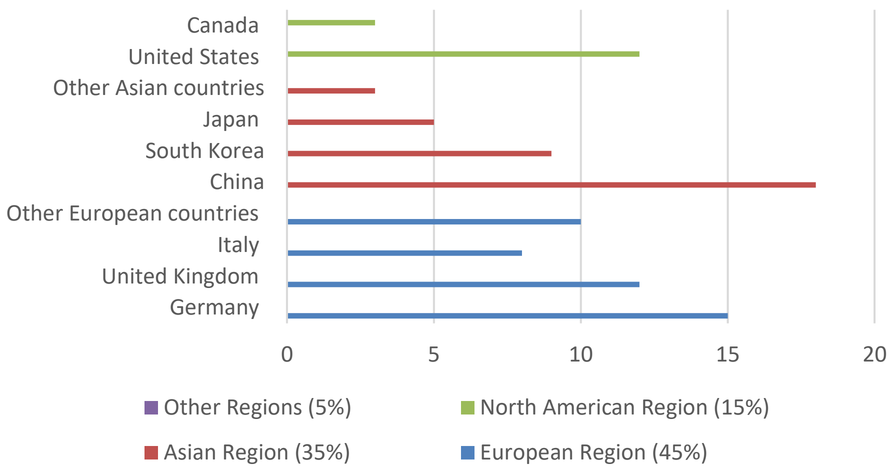

Figure 4. *Geographical distribution of research*

Moreover, the analysis of international collaboration revealed the following:

- Strong intra-European collaboration networks
- Significant Asia-Europe collaborative projects

- Growing North America-Europe research partnerships
- Limited involvement from developing regions

Fınally, the journal distribution of the research appears in the following journal categories:

- Manufacturing Technology Journals (35%)
- Information Systems Journals (25%)
- Operations Management Journals (20%)
- Engineering Journals (15%)
- Other Domains (5%)

B. THEMATIC EVOLUTION AND RESEARCH FOCUS

Through this analysis, five dominant themes emerge in the landscape of research into digital manufacturing platforms over time (see Figure 5).

First, the theme of Platform Architecture and Design started with setting basic architectural principles and reference models [6], shifted toward system integration capabilities and then service-oriented architectures [28], up to multi-sided digital manufacturing platforms [29].

Digital Twin Integration emerged as the second major theme, marked by the introduction of digital twin concepts in manufacturing environments [3]. This area progressed through developments in real-time data synchronization and virtual modeling capabilities [30], and further advanced into the creation of collaborative virtual environments [10].

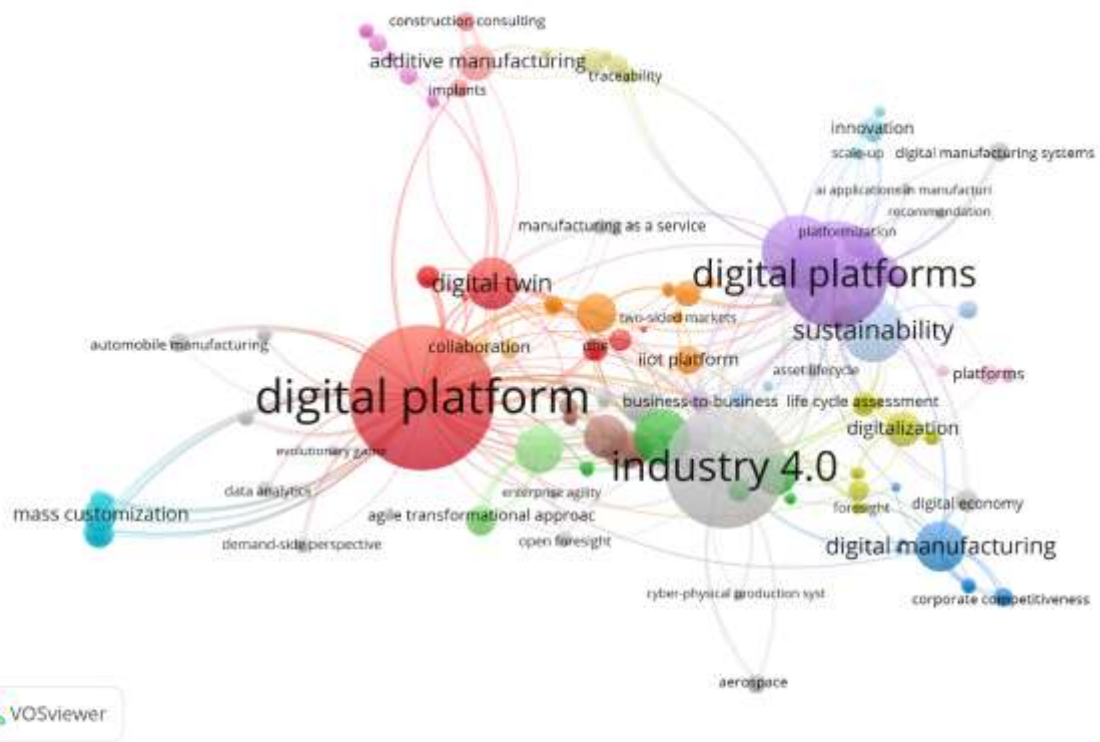

Figure 5. *Network Visualization of research themes*

The third theme, Industry 4.0 Integration, was about the integration of IIoT technologies and CPS into manufacturing platforms [31]. In this respect, the theme has also evolved to reflect

smart manufacturing implementation frameworks [32] and platform-based perspectives on industrial digitalization [5].
Sustainability and Circular Economy emerged as the fourth significant theme, incorporating environmental impact considerations in platform design [21]. This area developed to address resource
optimization through digital platforms [14] and the integration of circular economy principles into manufacturing processes [33].

The fifth theme, Standardization and Interoperability, related to developing common standards that will permit different platforms to interoperate. This theme has further evolved into frameworks for cross-platform integration [34], and comprehensive data governance and security approaches [8].

This change marks clear progress from purely technical underpinning to advanced implementation with attention paid to such aspects as sustainability and standardization. The ability of digital manufacturing platforms to combine technological capabilities with sustainability and assure standardized [15].

C. RESEARCH FOCUS DISTRIBUTION

As Table 5 shows, the analysis revealed distinct patterns in research focus areas across the digital manufacturing platforms:

Table 4. *Research Focus Distribution in Digital Manufacturing Platforms*

Research Focus Area	Distribution	Key Topics and Representative Studies
Technical Architecture	35.3%	• Platform design and microservices [34,6] • Cyber-physical systems integration [35,13] • Smart manufacturing frameworks [36,16] • Asset administration shell integration [22,37]
Business Model Innovation	24.8%	• Value creation mechanisms [12,4] • Platform ecosystem development [1,14] • Service-oriented transformation [38,11] • Innovation-driven manufacturing [9,5]
Implementation Strategies	18.6%	• Platform adoption frameworks [39,28] • Change management approaches [18,3] • Cross-platform collaboration [40,33] • Digital twin implementation [30,10]
Sustainability Integration	12.4%	• Environmental optimization [20,21] • Resource efficiency [41,15] • Sustainable manufacturing [42,17] • Circular economy integration [43,44]
Standardization Efforts	8.9%	• Interoperability protocols [45,8] • Data exchange standards [6,31] • Industrial data spaces [8,7] • Platform federation [11,23]

Research evidence shows technical architecture takes precedence with 35.3% dominance because it concentrates on platform design and microservices integration and cyber-physical system unification. Business model innovation stands as a major research topic since it comprises 24.8% of total entries, highlighting the need for technological deployment alongside business model transformation. Implementation strategies take up 18.6% of the research scope by examining adoption frameworks together with change management strategies. Research efforts must expand into sustainability integration and standardization approaches since they represent minor percentages (12.4% and 8.9%) respectively. Research on digital manufacturing platform technology reaches advanced stages yet more efforts are needed to explore how these platforms can merge sustainability principles together with standardization frameworks for cross-platform interoperability.

D. RESEARCH GAPS AND EMERGING TRENDS

The analysis identified several critical research gaps and emerging trends in the field, which are presented in Table 6:

Table 5. *Research Gaps and Emerging Trends*

Research Gaps and Representative Studies	
1. Limited Integration of Sustainability Metrics:	- Absence of standardized sustainability assessment frameworks [14] - Insufficient integration of environmental impact measures [21] - Limited consideration of lifecycle assessment in platform design [44]
2. Standardization Challenges:	- Fragmented approaches to platform interoperability [44] - Inconsistent implementation of data exchange protocols [6] - Limited standardization of digital twin interfaces [3]

Table 6 (cont). *Research Gaps and Emerging Trends*

3. SME Implementation Barriers:	- Resource constraints in platform adoption [18] - Limited scalability considerations [28] - Insufficient focus on cost-effective implementation strategies [17]
Emerging Trends and Representative Studies	
1. Advanced Technology Integration:	- Artificial intelligence and machine learning applications [7] - Edge computing integration for real-time processing [13] - Advanced analytics for predictive maintenance [10]
2. Enhanced Security and Trust Mechanisms:	- Blockchain integration for supply chain transparency [11] - Advanced data security protocols [8] - Distributed ledger technologies for platform trust [7]
3. Platform Ecosystem Development:	- Cross-industry collaboration frameworks [2] - Value co-creation mechanisms [5] - Platform-based innovation ecosystems [23]

First, the limited integration of sustainability metrics reveals a significant opportunity to develop standardized frameworks for assessing environmental impact throughout platform lifecycles. Second, standardization challenges persist, particularly regarding interoperability protocols and consistent implementation of data exchange standards. Third, SME implementation barriers highlight the need for more research on cost-effective adoption strategies tailored to resource-constrained organizations. These gaps are counterbalanced by three promising emerging trends: advanced technology integration (particularly AI and edge computing), enhanced security mechanisms leveraging blockchain and distributed ledger technologies, and platform ecosystem development focusing on cross-industry collaboration.

These gaps and trends indicate a very great shift in the focus of research from purely technical consideration to a more holistic approach, considering such aspects as sustainability, standardization, and ecosystem development. The evolution of digital manufacturing platforms in the future will have to address these gaps by leveraging new, evolving technologies to improve both the capability and sustainability of the platforms [11, 25].

It therefore lays the foundation for understanding the present status and future directions of research related to digital manufacturing platforms, considering that integrated approaches will have to be developed taking into consideration technical, organizational, and environmental issues all at once.

V. INTEGRATIVE FRAMEWORK FOR DIGITAL MANUFACTURING PLATFORMS

This section presents a comprehensive framework for understanding and implementing digital manufacturing platforms, synthesizing the findings from the bibliometric analysis and addressing identified research gaps. The proposed framework integrates technological, organizational, and environmental dimensions, while considering standardization requirements and implementation challenges.

A. FRAMEWORK OVERVIEW

In the proposed Digital Manufacturing Platform Integration Framework (DMPIF) (see Figure 6), five integrated dimensions are proposed to solve the comprehensive problem of transforming manufacturing based on a platform. These are:

A.1. Technological Infrastructure

Figure 6. *Digital Manufacturing Platform Integration Framework (DMPIF)*

It does this by providing a basis for three levels within the technology dimension of the framework: the architecture of the platform with integrations of microservices design principles [34], followed by integrations of the Asset Administration Shell [22], and interoperability protocols [8]. The second element refers to the integration of the digital twin through real-time synchronization mechanisms [3], including virtual modelling capabilities [30] and the integration of predictive analytics [7]. The third part is the Data Management developed around the needs of the industrial data space [8]. Also under this header fall the security mechanisms [6], and cross-platform data exchange mechanisms researched [11].

A.2. Organizational Architecture

For instance, the organizational dimension embraces structural and operational elements which can be given by governance mechanisms and respective methods of change management. Governance Mechanisms: platform leadership model [29]; decision-making framework [18];

and risk management protocol [1]. Change Management: Implementation strategies [36]; Capability development approaches [12]; Organizational learning process [5].

A.3. Sustainability Integration

The sustainability dimension incorporates the elements of environmental performance and circular economy considerations. The environmental performance considers the metrics for resource efficiency [20], energy optimization protocols [21], and waste reduction mechanisms [14]. This would encompass product life cycle management approaches [43], resource recovery systems presented [33], and value creation mechanisms under sustainability [15].

A.4. Standardization Mechanisms

The dimensions of standardization will, therefore, include the technical and process standards that would be required for the integration of the platforms. Technical Standards include interface protocols [6], development of the data exchange format [8], and security requirements [22]. Process Standards include an operating procedure [36], a proposition of the quality management system [32], and performance metrics [10].

A.5. Ecosystem Development

The key enablers of the ecosystem dimensions towards the sustainable development of the platform are stakeholder integration and platform economics. Some topics included in stakeholder integration include value co-creation mechanisms [2]; partnership framework [28]; and innovation network [23]. Platform economics look at business model innovation [38], value capture mechanisms outlined [12], and market development strategies [1].

B. FRAMEWORK IMPLEMENTATION

The implementation of the DMPIF follows a systematic staged approach that encompasses four distinct phases namely as Assessment, Foundation, Integration and Optimization. This staged implementation approach for the DMPIF framework was chosen based on several key considerations identified in recent literature:

- Complexity Management:

- Digital platform implementation involves multiple interconnected components that cannot be effectively deployed simultaneously [4]
- Staged implementation allows organizations to manage technical and organizational complexity incrementally [36]
- Enables focused attention on critical success factors at each stage [3]

- Risk Mitigation:

- Sequential implementation reduces exposure to implementation risks [18]
- Allows for learning and adjustment before proceeding to more complex stages [8]
- Enables early identification and resolution of challenges [11]

- Resource Optimization:

- Staged approach allows for better allocation of limited resources [28]
- Enables organizations to build capabilities progressively [1]

- Facilitates more effective budget management and ROI tracking [2]

- Organizational Learning:

- Sequential implementation supports systematic knowledge acquisition [5]
- Enables development of internal expertise over time [20]
- Facilitates cultural adaptation and change management [15]

The four stages have the following characteristics:

- Assessment and Planning: it covers organizational readiness assessment, review of the current technological infrastructure, and further stakeholder needs and expectations analysis.
- Foundation Building: it involves the basic construction of the platform architecture from the technical and organizational point of view. Besides that, this stage will provide appropriate governance structures, alignment of industry standards and protocols, and lay the ground for subsequent implementation phases.
- Integration and Deployment: it deals with the systematic integration of the different systems and subsystems in the platform's framework. During this stage, major process transformation initiatives are allowed while building the necessary capabilities across the organization. The integration requires a lot of attention in detail, especially technical and organizational matters, if it is to be smooth.
- Optimization and Scale: it emphasizes continuous performance monitoring and systematic improvement of platform operations. This phase incorporates rigorous evaluation mechanisms and implements strategic initiatives for ecosystem expansion, ensuring sustainable growth and development of the platform infrastructure. The stage focuses on optimizing operational efficiency while facilitating scalable growth across the manufacturing ecosystem.

The approach to staged implementation allows for a structured and orderly transition from initial assessment through to full-scale deployment and optimization. This helps organizations to manage quite effectively the complexity inherent in the implementation of a digital manufacturing platform.

C. THEORETICAL IMPLICATIONS

The proposed framework provides rich theoretical contributions in comprehensively adding to the development of digital manufacturing platform theory [4, 16]. The theoretical importance of the proposed framework is basically expressed along two core dimensions: the integration of various theoretical approaches and the extension of knowledge boundaries.

From a theoretical integration point of view, this paper integrates several established theories together, thereby enriching an understanding of digital manufacturing platforms. This includes the integration of platform economics theory that would provide valuable insight into value creation and network effects within a manufacturing context [12]. Digital transformation theory brings valued understanding of technological adoption and organizational change processes [11]. Sustainability transition theory adds relevant aspects of environmental and social issues in manufacturing change [20]. Furthermore, organizational change theory lays the basic outlook on how institutional adaptation and development take place regarding digital transformation initiatives [18].

In extending existing knowledge, the framework furthers present understanding along a number of key dimensions. It improves the understanding of platform governance mechanisms, and provides new theoretical perspectives on how digital manufacturing platforms are managed and controlled [29]. The framework also extends the theoretical knowledge on approaches to integrate digital twins [10], within the body of knowledge on virtual-physical system synchronization. It also develops theoretical standpoints of the Sustainability Assessment Framework [15], hence giving new insights into assessing and implementing sustainable manufacturing practices.

Such a linked theoretical contribution enhances the academic understanding of digital manufacturing platforms significantly while providing a robust foundation for future research efforts in this domain [3, 14]. Considering the theoretical implications of the framework, there is a possibility to increase both scientific and practical stakes in digital manufacturing.

D. PRACTICAL IMPLICATIONS

The framework brings also important practical implications to the manufacturing organizations undergoing digital transformation initiatives. The main practical contributions come through the three major dimensions, which collectively support organizational implementation and strategic development.

The first dimension retains specific guidance for organizational implementation: structured methodologies for the adoption of platforms, within the investigation into the implementation of integrated platforms [36]; the extensively documented mitigation strategies for risks enable organizations to take systematic approaches toward overcoming the challenges of implementation [18]; finally, performance measurement methods enable organizations to better assess and optimize their implementation of digital platforms [10].

The second major practical dimension relates to strategic planning support. Systematic evaluation frameworks must accompany technology investment decisions in order to ensure optimal resources allocation [29]. Organizational change management provides important guidance on dealing with technological transitions [3]. More than that, ecosystem development strategies give organizations structured approaches to building and maintaining sustainable platform ecosystems [14].

The third dimension covers the integration of sustainability into manufacturing operations. In this respect, for example, the environmental performance metrics offer tangible ways for organizations to quantify and monitor their environmental performance [20]. Resource optimization approaches provide applicable tools to further operational performance [21]. In addition, strategies for the implementation of a circular economy identify tangible ways in which organizations can actually come up with sustainable manufacturing processes [43].

These practical implications will enable manufacturing organizations to apply digital platforms holistically with a view toward sustainable operations. This will be very helpful with respect to increased calls for sustainable manufacturing practices [15], and rising complexity in the initiatives of digital transformation in manufacturing contexts [16]. Therefore, the organization can establish, through the practical implications, structured approaches toward digital platforms that keep a focus on operational efficiency and environmental sustainability.

This integrated framework allows a holistic approach in understanding and implementing a digital manufacturing platform that includes the identified gaps in research and emerging trends in the field. This holistic view will allow organizations to negotiate the complications of digital transformation along with ways to ensure that such implementation approaches will be sustainable and standardized.

VI. CONCLUSION AND FUTURE RESEARCH DIRECTIONS

The comprehensive bibliometric analysis of digital manufacturing platforms provides a clear evolutionary trajectory in three distinguishable developmental phases, from the initial conceptualization phase (2011-2016) via the phase of technical integration (2017-2020) to the latest phase of advanced implementation (2021-2024), showing a maturation process toward holistic platform solutions considering sustainability issues and standardization requirements.

This study contributes to the academic literature in the following three ways. First, it systematizes the categorization of research on digital manufacturing platforms using the proposed DMPIF framework, hence providing an overall foundation for the technical, organizational, and environmental dimensions [4]. Second, it extends the platform theory by adopting both the sustainability and standardization perspectives [20]. Third, this paper provides the theoretical basis for understanding the role of digital platforms in manufacturing transformation [11].

The findings have significant practical implications in organizational implementation dimensions, including structured methodologies for platform adoption [36], approaches to integrating sustainability [15], and standardization protocols [8]. However, some limitations should be acknowledged regarding the methodology: for instance, it is based only on English-language publications and views originated mainly from developed economies [3].

Five key areas emerge for future research. Technical integration will involve the exploration of integration with artificial intelligence [7] and advanced applications using digital twins. Enhancement of sustainability will develop assessment frameworks in a standardized manner [15] and integration of the circular economy [14]. The development of standardisation needs to focus on universal interoperability standards [8] and security mechanisms for the platforms [11]. Implementation strategies should focus on SME-specific frameworks [18] and affordable approaches to adoption [28]. Ecosystem development calls for research on governance models [2] and value co-creation mechanisms [1].

The successful development of digital manufacturing platforms will require further collaboration between academics and practitioners. Standardized implementation approaches should be one of the priorities in future research, ensuring that sustainable practices and emerging technologies are integrated. This evolution toward sophisticated, sustainable, and standardized platforms is one of the important developments in manufacturing transformation and requires systematic investigation in the technical, organizational, and environmental dimensions.

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