

REVIEW

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A review of manufacturing technology readiness from 1986 to 2025

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Abstract

The rapid evolution of manufacturing technologies has fundamentally reshaped industrial processes, compelling firms to continuously evaluate their preparedness to adopt and integrate innovations. This study investigates the concept of Manufacturing Technology Readiness (MTR), an extension of Technology Readiness Levels (TRLs), which assesses how prepared manufacturing systems absorb new technologies across technical, organizational, and environmental dimensions. Despite increasing scholarly interest, the MTR domain remains fragmented and lacks consolidated theoretical foundation. To address this gap, we conducted a comprehensive literature review covering the period 1986 to 2025, analyzing 267 articles sourced from the Scopus database. We employ a hybrid methodology combining bibliometric analysis (via VOSviewer and the Biblioshiny R-package) with the theory–context–characteristics–methodology (TCCM) framework to systematically synthesize the existing knowledge base. Our findings revealed five major research clusters and clear thematic shifts over time, with agile manufacturing, supply chain integration, and sustainability emerging as dominant themes. We also propose an organizational framework that outlines the antecedents, dimensions, and outcomes of MTR. The study concludes by offering a targeted research agenda and theoretical implications to guide future research. This review contributes to the academic literature by clarifying the intellectual structure of MTR and by assisting practitioners in aligning technological investments with strategic readiness priorities.

Keywords Manufacturing technology readiness, TCCM framework, Bibliometric analysis, Comprehensive review

1 Introduction

The manufacturing industry is undergoing profound transformation driven by rapid advancements in automation, digitalization, and smart technologies. Innovations such as Artificial Intelligence (AI), the Internet of Things (IoT), robotics, additive manufacturing, and advanced data analytics are reshaping traditional production systems to enhance their efficiency, precision, and flexibility [9, 59]. These technological disruptions not only revolutionize production processes but also redefine competitive dynamics, compelling firms to adapt swiftly to sustain their market positions. Global megatrends, such as Industry 4.0, the growing urgency of sustainability imperatives, and the restructuring



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of global supply chains further amplify the need for firms to continuously evaluate their readiness to adopt and integrate emerging technologies. For instance, the industry 4.0 paradigm emphasizes cyber-physical systems, real-time monitoring, and interconnected supply networks, while sustainability concerns necessitate eco-efficient technologies and circular economy practices. The COVID-19 pandemic (2019–2020) has also accelerated digital adoption, reinforcing the importance of organizational resilience and technological adaptability in times of disruption.

A key framework guiding such assessments is the technology readiness level (TRLs) approach, originally developed by NASA to evaluate the maturity of emerging technologies. While widely used in the R&D context, TRLs in the manufacturing domain require a broader perspective that incorporates organizational, infrastructural, and environmental readiness. This has led to the emergence of Manufacturing Technology Readiness (MTR), which extends beyond technical maturity to encompass workforce skills, supply chain integration, strategic alignment, and institutional support. Despite its growing relevance, research on MTR remains fragmented and theoretically underdeveloped. Much of the literature examines individual technologies or isolated implementation scenarios, but lacks a comprehensive framework for assessing readiness. While recent studies have drawn upon theories such as the technology–organization environment (TOE) framework [2], Dynamic Capabilities Theory (Wong & Ngai, 2023), and Socio-Technical Systems Theory [20], there is still no integrative, theory-based synthesis of MTR research. This gap underscores the need for a structured review that not only maps the intellectual landscape, but also provides guidance for future theoretical and practical advancements.

To address this gap, the present study undertakes a hybrid review of MTR scholarship, combining bibliometric analysis with a TCCM (theory–context–characteristics–methodology) framework-based synthesis [66]. This approach enables both the quantitative mapping of intellectual structure and the qualitative integration of conceptual insights. By systematically analyzing publications from 1986 to 2025, this study highlights the evolution of themes, identifies underexplored areas, and proposes an organizational framework for understanding MTR.

The remainder of this paper is organized as follows. Section 2 outlines the research methodology, including database selection, keyword strategy, and bibliometric techniques. Section 3 presents the results of bibliometric analysis and thematic synthesis. Section 4 discusses the findings of the TCCM framework and highlights its theoretical and practical implications. Section 5 provides a future research agenda, and Sect. 6 concludes the study by outlining the key contributions, limitations, and directions for further inquiry.

2 Research methodology

2.1 Research design

This study adopts a hybrid review methodology that integrates bibliometric analysis with a theory–context–characteristics–methodology (TCCM) framework-based systematic review. This approach enables both a quantitative mapping of the intellectual structure of Manufacturing Technology Readiness (MTR) research and a theory-driven qualitative synthesis of its conceptual foundations. Bibliometric analysis identifies influential themes, clusters, and knowledge streams, while the TCCM framework supports theoretical integration and future research development. This dual approach follows established

best practices for conducting impactful literature reviews in management and engineering research.

2.2 Data source and search strategy

The Scopus database was selected as the sole data source due to its extensive coverage of high-quality peer-reviewed journals and its widespread use in bibliometric research. Data were retrieved in February 2025 to capture both historical and contemporary developments in the MTR domain. The search was conducted using the following reproducible query, applied to the TITLE-ABS fields: *TITLE-ABS (("manufacturing") AND ("technology readiness"))* The search was limited to publications between 1986 and 2025, reflecting the period during which structured technology readiness frameworks emerged and evolved. Only English-language journal articles, review papers, and conference proceedings were retained to ensure academic rigor and conceptual relevance.

2.3 Inclusion and exclusion criteria

The initial search yielded 470 records. A multi-stage filtering process was applied to ensure relevance and quality. First, publications were restricted to the subject areas of Engineering (323) Computer Science (98) and Business/Management (44) reducing the dataset to 374 records. Second, duplicate entries and publications lacking substantive relevance to manufacturing technology readiness, 43 were removed following abstract and keyword screening. English language removed (4) and left with 370. Third, editorial notes, book chapters, and non-peer-reviewed documents were excluded. This process resulted in a final dataset of 267 publications, which formed the basis for bibliometric and thematic analyses.

2.4 Bibliometric tools and parameter settings

To ensure full transparency and reproducibility, all bibliometric analyses were conducted using explicitly documented software tools and parameter settings. Bibliometric mapping and network visualizations were generated using VOSviewer, while descriptive statistics and thematic evolution analyses were performed using the bibliometrix R-package through its web interface, Biblioshiny. The following analytical parameters were applied: Counting method: Fractional counting; Normalization technique: Association strength normalization; Keyword co-occurrence threshold: Minimum of five occurrences; Citation and co-citation analysis: Default fractional citation weighting; Clustering algorithm: Modularity-based clustering with default resolution; Layout algorithm: LinLog layout for improved interpretability. A total of 62 author keywords met the co-occurrence threshold and were included in the final keyword network analysis. These settings are consistent with established bibliometric standards and allow independent replication of the reported maps and clusters.

2.5 Bibliometric analysis procedures

Three complementary bibliometric techniques were employed. First, descriptive analysis was used to examine publication growth, citation patterns, and authorship characteristics. Second, keyword co-occurrence analysis was conducted to identify dominant research themes and their interrelationships. Third, thematic mapping based on Callon's centrality and density metrics was used to classify themes into motor, basic, niche, and

emerging categories. The bibliometric results served as an empirical foundation for the subsequent qualitative synthesis. Rather than treating clusters as descriptive outcomes, they were used as analytical inputs for theory integration under the TCCM framework.

2.6 TCCM-based thematic synthesis

Following bibliometric mapping, all 267 publications were manually reviewed and coded using the TCCM framework, which organizes literature along four dimensions: Theory, Context, Characteristics and Methodology. This process enabled a systematic comparison of theoretical lenses, industrial and geographical contexts, readiness drivers and barriers, and empirical approaches. Coding was conducted iteratively to ensure consistency and analytical depth. The integration of bibliometric patterns with TCCM dimensions allowed this study to move beyond classification and to generate a theory-driven synthesis, highlighting causal mechanisms, research gaps, and opportunities for empirical advancement in MTR research.

3 Results

This section presents the review results, combining descriptive bibliometric insights, thematic clustering and findings structured under the TCCM framework. The descriptive analysis offers an overview of annual publication trends, helping map the scholarly development of the Manufacturing Technology Readiness (MTR) domain. Thematic analysis, including keyword co-occurrence and cluster interpretation, has uncovered dominant research areas and evolving topical focuses. Finally, the integration of the TCCM (theory–context–characteristics–methodology) framework provides a structured synthesis of the literature, offering deeper insights into the conceptual, contextual, and methodological dimensions of MTR research.

3.1 Overview of descriptive metrics

The field demonstrates an average of 20.12 citations per document and an annual publication growth rate of 6.27%, indicating a steady and growing interest in MTR scholarship particularly post-2015, in alignment with the rise of Industry 4.0. Table 1 presents the summary metrics derived from the dataset. An h-index of 41 further confirmed the emergence of a stable and influential body of work in the domain. This descriptive overview establishes the foundation for subsequent bibliometric mapping and thematic evaluation, helping to situate the evolution and impact of MTR research within the broader academic landscape.

3.2 Publication output

From 1986 to 2025, research on Manufacturing Technology Readiness (MTR) experienced substantial growth. As shown in Fig. 1, three distinct phases characterized the publication trend over this 40-year period. The total number of documents analyzed was 267, with an annual growth rate of 6.27% and an average of 20.12 citations per document, underscoring the increasing academic relevance and influence of this field. This review spans four decades and offers a longitudinal perspective on the conceptual and technological evolution of MTR. The starting point, 1986, reflects the emergence of structured technology assessment frameworks in manufacturing, laying the foundation for later developments, such as TRLs and MTR. Extending the analysis to 2025

Table 1 Main Information of the data

Description	Results
Timespan	1989:2025
Sources (Journals; Conference proceedings)	212;55
Documents	267
Annual Growth Rate %	6.27
Document Average Age	9.64
Average citations per doc	20.12
Document contents	
Keywords Plus (ID)	816
Author's Keywords (DE)	610
Authors	
Authors	594
Authors of single-authored docs	30
Authors collaboration	
Single-authored docs	32
Co-Authors per Doc	2.82
International co-authorships %	21.21
Document types	
Article	204
Conference paper	58
Review	5

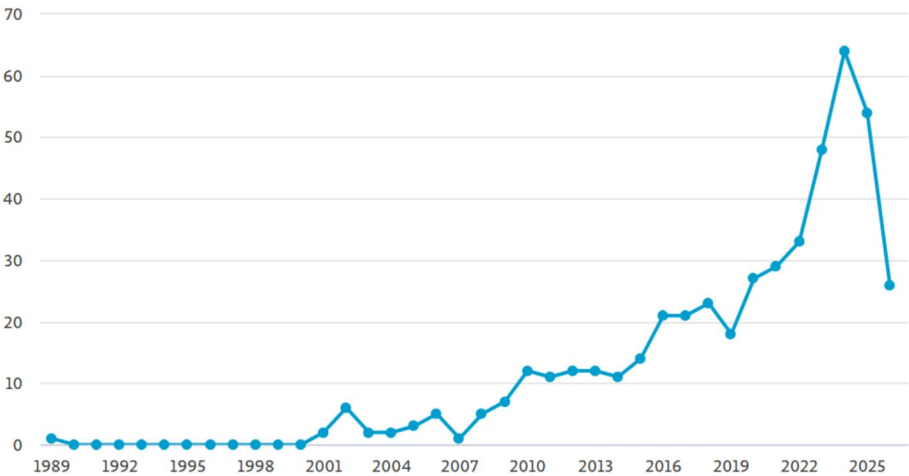


Fig. 1 Trend of publication output

allows the inclusion of early access and in-press articles, capturing the latest academic discourse, particularly on digital transformation and Industry 4.0. This comprehensive period enabled the tracing of thematic shifts, methodological trends, and technological milestones across distinct industrial eras.

During the initial phase, the publication growth was gradual. In the late 1980s, the convergence of Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) streamlined production with improved accuracy and speed [71]. The 1990s were marked by economic expansion and globalization, fueling interest in automation technologies. Despite external disruptions, such as the Asian financial crisis (1997) and the dot-com collapse (the early 2000s), manufacturing research remained active, with new focus areas emerging around nanotechnology and information technology integration [49]. The mid-2000s brought about a resurgence in global economic activity and

technological diffusion, particularly in emerging markets. However, the global financial crisis of 2008 exposed vulnerabilities in supply chains, prompting an interest in resilience, diversification, and risk mitigation. Simultaneously, increased environmental awareness has fueled the rise of sustainable manufacturing practices and green technologies [1]. The post 2015 period witnessed a sharp increase in publications, aligned with the proliferation of Industry 4.0. The COVID-19 pandemic (2019–2020) accelerated digital adoption. Remote operations, artificial intelligence (AI), robotics, and real-time monitoring are essential for maintaining business continuity. This period marked a strategic shift from efficiency to resilience and adaptability, with firms prioritizing technologies that enabled rapid responses to market volatility [76].

3.3 Thematic map

The thematic map visually depicts the intellectual structure of MTR literature based on Callon's centrality and density scores (Callon et al., 1983). Centrality reflects a theme's degree of interaction with other research areas, whereas density indicates the theme's internal development. The map was divided into four quadrants: motor themes (high centrality, high density), basic themes (high centrality, low density), niche themes (low centrality, high density), and emerging or declining themes (low centrality, low density) (G.D. [74]). Each quadrant provides insights into the maturity, importance, and future potential of the key topics in MTR research, as presented in Fig. 2.

3.3.1 Motor themes: core pillars of MTR research

Motor themes are well developed and deeply integrated with other areas of research. Notable topics in this quadrant include agile manufacturing, computer simulations, competition, product design, and manufacturing companies. Agile manufacturing represents a sector's strategic push for flexibility and rapid adaptation. It enables dynamic responses to changing market demands and supports the seamless integration of new technologies [22, 84]. Computer simulations allow manufacturers to model and optimize

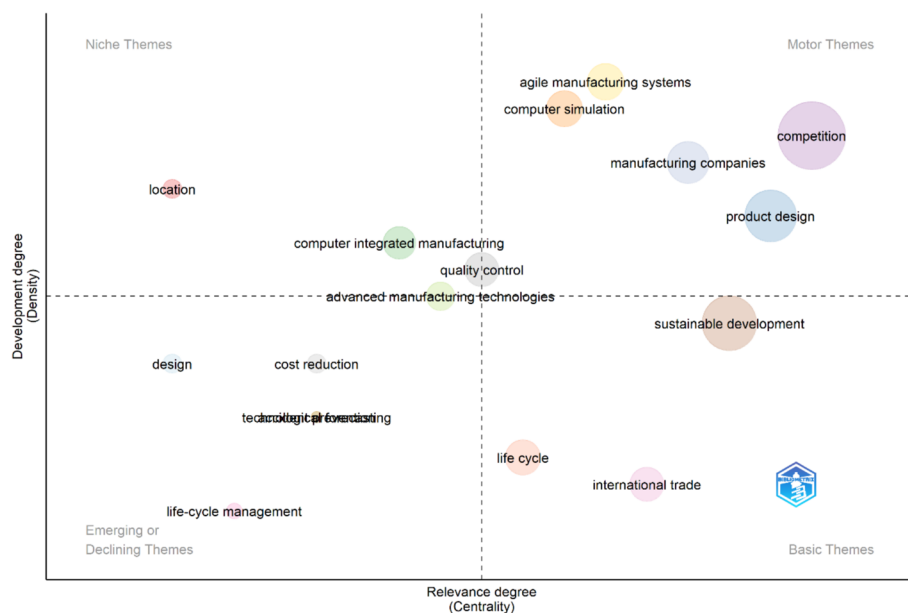


Fig. 2 Thematic map

processes before implementation, reducing risk and cost while improving decision-making [87]. Competition drives technology adoption by influencing firms to match or exceed their rivals' technological capabilities of rivals [72]. Product design is closely linked to manufacturing readiness, as it shapes how easily technologies can be integrated to meet market demand [19]. Research on manufacturing companies offers benchmarking opportunities and highlights the best practices for technological integration [17]. These themes are central to understanding MTR, because they reflect how market responsiveness, decision-making tools, and strategic priorities shape a firm's capacity for technology adoption.

3.3.2 Basic themes: foundational but underdeveloped areas

Basic themes are conceptually important, but require further theoretical development. These include sustainable development, life cycles, international trade, innovation, supply chain management, and competitive advantage. Sustainable development highlights the need to balance technological advancement with environmental and social responsibilities [36]. Life cycle analysis (LCA) plays a key role in evaluating ecological impacts across product life spans and guiding sustainable technology decisions (Fundin, 2005; [29]). International trade affects the flow of materials, products, and technologies, and understanding global trade dynamics is crucial for cross-border readiness [41, 79]. Innovation, supply chain management, and competitive advantage serve as strategic enablers of readiness, although theoretical integration into MTR research remains limited. These basic themes are essential for a broader understanding of MTR, and should be further integrated into models and empirical work.

3.3.3 Emerging or declining themes: underexplored or evolving topics

This quadrant includes themes that are either nascent or losing academic momentum, such as cost reduction, life cycle management, design, and advanced manufacturing technologies. Cost reduction remains a top priority as firms seek to balance efficiency with investment in new technologies [62]. Life cycle management enhances decision-making by forecasting long-term costs and sustainability outcomes [42]. Design plays a critical role in ensuring manufacturability and compatibility. Efficient designs enable smoother technological integration [24]. Topics such as manufacturing performance and advanced technologies (3D printing and AI) are emerging but under-analyzed in relation to MTR. Further empirical exploration is needed to validate and elevate these themes within broader readiness discourse.

3.3.4 Niche themes: high internal maturity, low external linkage

Niche themes demonstrate strong internal development, but limited cross-topic influence. Key themes include location, computer-integrated manufacturing (CIM), quality control, life cycle costing, decision-making, and project planning. Location affects resource access, logistics, and market reach. Its role in MTR lies in its strategic positioning [39]. CIM enhances integration across manufacturing processes, improving responsiveness and operational efficiency [12]. Quality control leverages technology to minimize defects and meet regulatory standards [85]. Life-cycle costing, decision-making, and project planning are sophisticated constructs that, while not widely integrated, provide crucial insights for readiness modeling and investment assessment. Bridging

these specialized areas with central MTR themes presents a valuable opportunity for future interdisciplinary research.

3.4 Keywords map

Keyword analysis helps uncover recurring research themes and core conceptual areas within the field of Manufacturing Technology Readiness (MTR). As symbolic representations of knowledge domains, keywords reflect the thematic convergence and intellectual structure of a field (Čater & Zupic, 2015). Their co-occurrence within documents indicates the presence of conceptual linkages and thematic interdependence (Bamel et al., 2020). Using VOSviewer, keyword co-occurrence analysis was performed based on 1241 author keywords. A threshold of five or more co-occurrences was applied, resulting in a short list of 62 keywords. These were organized into five distinct clusters, each representing a thematic area within the MTR literature. As suggested by Delecroix and Epstein (2004), thematic clustering enhances interpretability by grouping related topics and highlighting the dominant conversations within the field. The keyword network visualization (Fig. 3) illustrates this structure, where node size reflects frequency and color indicates cluster membership. Frequently occurring keywords include: “*Supply chain integration*” ($n=22$); “*Competitive advantage*” ($n=19$); “*Sustainability*” ($n=17$). These terms reflect central concerns in MTR research coordination across value chains, strategic outcomes, and environmental responsibility and validate their conceptual significance. Each cluster was further analyzed, where descriptive labels and interpretive summaries were assigned to highlight their individual and collective contributions to the field.

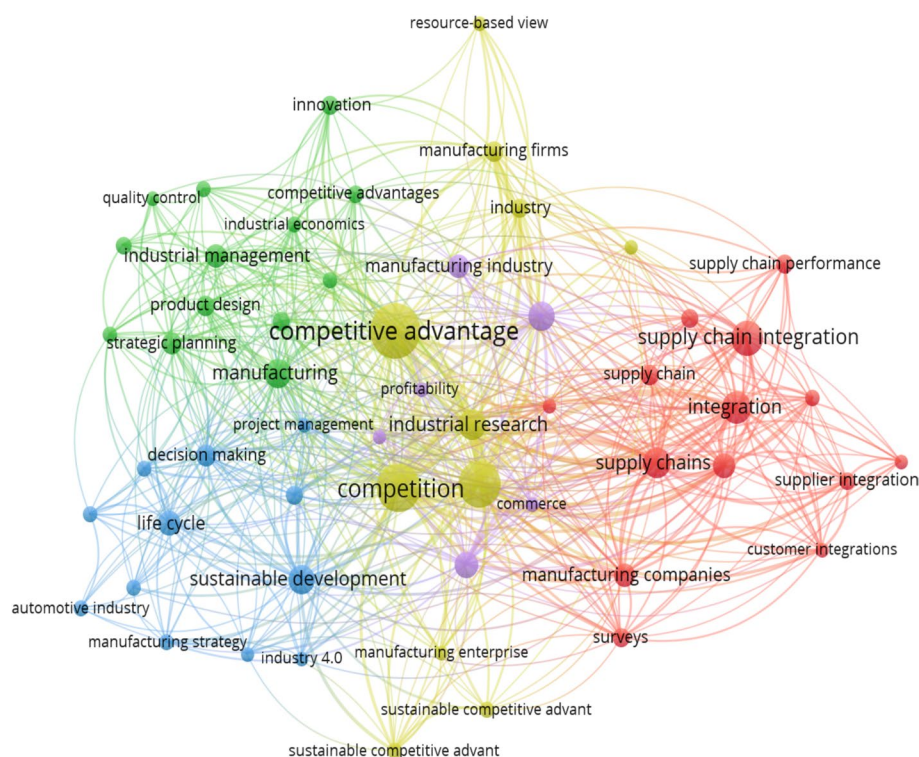


Fig. 3 Keyword network analysis map

3.4.1 Red cluster—integrated supply chain

This cluster comprises keywords, such as supply chain integration (22), supplier integration (17), customer integration (14), internal integration (11), supply chain performance (15), surveys, and investments. These terms reflect the critical role of supply chain coordination in achieving readiness for manufacturing technologies. Technology readiness enables a smooth process alignment across supply chain functions. Supplier integration extends readiness across the upstream value chain [88], whereas customer integration enhances responsiveness to market needs [55]. Internal integration reflects coherence within firm-level processes [15]. Technological investments amplify these linkages and support agile and scalable operations [50]. The use of surveys indicates a methodological focus on empirical readiness assessment. Together, these keywords illustrate how MTR is both a technical and relational capability that shapes performance across organizational boundaries [30].

3.4.2 Green cluster—industrial innovation strategies

This cluster included keywords such as innovation (19), competitive advantage (18), product design (15), computer-integrated manufacturing (13), industrial management (12), strategic planning, quality control, and information systems. This cluster highlights the strategic use of technology to drive innovation and competitiveness. Innovation enables firms to exploit their technological capabilities to gain market advantage [40]. Computer-integrated manufacturing (CIM) fosters automation and precision [31], whereas information systems support data-driven operations [77]. Marketing, product design, and quality control ensure that technological capabilities translate to customer-centric values and regulatory compliance. This cluster underscores how MTR is leverage strategically to improve efficiency, differentiation, and organizational agility [44, 52].

3.4.3 Yellow cluster—holistic sustainable management practices

Comprising terms such as sustainable development (20), life cycle (18), decision-making (16), project management (13), costs, and international trade, this cluster captures the intersection of sustainability, strategy, and global context. Sustainable development frames MTR within broader environmental and societal goals [48]. Life cycle assessment and management tools provide insights into the ecological and economic impacts of technology across its full lifespan [39]. Decision-making and project management guide technology implementation and ensure alignment with long-term objectives. Cost considerations emphasize financial implications, whereas international trade links technology selection to global market dynamics, standards, and regulatory pressures. This cluster reflects how technological decisions are embedded in global and ethical contexts, pushing manufacturing toward integrated sustainability [47].

3.4.4 Purple cluster—strategic industry performance

Keywords in this cluster include firm performance (14), competition (13), the manufacturing industry (12), industrial research (11), and sustainable competitive advantage. This cluster focuses on the organizational outcomes of technological readiness. MTR directly influences firm performance in terms of profitability, innovation, and operational excellence. Competition drives technology adoption as firms seek differentiation and cost leadership [82]. Industrial research supports long-term capability building

and innovation readiness [80]. When managed effectively, MTR leads to a sustainable competitive advantage, in which technology becomes a unique, valuable, and hard-to-replicate asset. This cluster highlights the strategic imperative of MTR as a driver of industrial success [51].

3.4.5 Blue cluster—knowledge-driven supply chains

This cluster includes supply chain management (17), knowledge management (15), profitability (12), commerce (10), and manufacturing industry. The focus is on how information flow and organizational learning support MTR. Knowledge management enables firms to capture, distribute, and apply technological insights [78]. Effective supply chain management ensures agility, resilience, and collaboration in response to digital transformation [77]. Profitability is closely related to the efficient deployment of new technologies. Commerce- and industry-specific practices shape readiness requirements across markets and segments. This cluster represents the cognitive and systemic side of MTR, emphasizing the importance of information integration, digital capabilities, and learning systems [14, 21].

3.5 TCCM framework

To provide a structured synthesis of the fragmented literature on Manufacturing Technology Readiness (MTR), this study employs the TCCM framework. Paul and Rosado-Serrano (2019) developed theory, Context, Characteristics and Methodology. This framework is widely used in literature reviews to organize scholarly contributions and generate future research agendas by combining conceptual, contextual, and empirical dimensions (Table 2). We systematically applied the TCCM framework by manually reviewing and coding all the 267 selected articles. Our coding strategy included Theory: Identifying primary theoretical lenses (TOE, Dynamic Capabilities, Innovation Diffusion). Context: Articles are classified by geographic region, industry type, and digital maturity level. Characteristics: Extracting variables such as readiness drivers, barriers, and outcomes. Methodology: Documenting research designs, data sources, and analytical approaches. This framework enabled us to go beyond descriptive listing and to draw deeper interpretive insights into the intellectual landscape of MTR research.

3.5.1 Theory

Although a wide range of theoretical lenses has been employed to examine Manufacturing Technology Readiness (MTR), the reviewed literature reveals that these theories are often applied in a fragmented and instrumental manner, limiting their explanatory power. Rather than developing new theory, most studies rely on established frameworks to justify variable selection or empirical models. This section critically examines how MTR research engages with four dominant theoretical streams and highlights their limitations and extension opportunities.

A. Technology adoption and diffusion theories: beyond initial uptake

Innovation Diffusion Theory and UTAUT are frequently used to explain early-stage technology adoption decisions in manufacturing contexts. While these theories effectively capture factors such as perceived usefulness, ease of use, and social influence, the reviewed studies reveal a significant limitation: they conceptualize readiness as a pre-adoption condition rather than an evolving organizational capability. Manufacturing

Table 2 TCCM table with theories, context, characteristics, methodology

TCCM dimension	Elements	Description
Theory	Innovation Diffusion Theory Unified Theory of Acceptance and Use of Technology (UTAUT) Disruptive Innovation Theory Social Network Theory Dynamic Capabilities Theory Technology–Organization–Environment (TOE) Framework Socio-Technical Systems Theory Path Dependency Theory Structuration Theory Institutional Theory Resource Dependence Theory Absorptive Capacity Theory	Explains adoption behavior, organizational adaptability, institutional pressures, and strategic capability. These theories span individual, organizational, and systemic levels.
Context	Industry 4.0 Smart Manufacturing Additive Manufacturing Digital Transformation Predictive Maintenance Human–Machine Interaction Cybersecurity in Manufacturing Advanced Robotics Internet of Things (IoT) Sustainable Manufacturing Supply Chain Integration	Represents the technological and operational settings where MTR is applied. Defines readiness scope, digital maturity, and sector-specific challenges.
Characteristics	Technological Infrastructure Organizational Culture Technological Knowledge & Skills Leadership Support Technological Complexity Financial Resources Regulatory Environment Collaboration & Networking Employee Resistance Strategic Alignment Market Demand Risk Perception Data Security & Privacy Innovation Culture Supply Chain Integration Adoption Cost Training Programs Information Systems Integration Technology Monitoring & Evaluation Environmental Sustainability	Enablers and constraints influencing MTR at firm level. Includes both internal factors (leadership, culture) and external forces (regulations, market).
Methodology	Surveys Experimental Research Field Studies Systematic Reviews Longitudinal Designs Regression Analysis Structural Equation Modeling (SEM) PLS-SEM Interviews Focus Groups Mixed Methods Observational Research Case Studies	Reflects methodological diversity. While surveys and SEM dominate, qualitative and mixed methods offer rich contextual insights. Longitudinal and network-based designs are underutilized.

technologies often require prolonged integration periods, iterative reconfiguration, and workforce adaptation processes that extend well beyond the scope of individual acceptance models. MTR research thus exposes a theoretical gap in diffusion-based models, which inadequately account for post-adoption dynamics such as learning curves, system interoperability, and operational scaling. This suggests that traditional adoption theories require extension toward process-oriented readiness models that incorporate temporal progression, organizational learning, and feedback mechanisms.

B. Organizational capability frameworks: static constructs vs. dynamic readiness

Dynamic Capabilities Theory and the TOE framework dominate firm-level MTR studies, emphasizing resource orchestration, leadership support, and environmental pressures. However, the reviewed literature indicates that these frameworks are often applied statically, using cross-sectional surveys to measure inherently dynamic phenomena. MTR research highlights a disconnect between the theoretical emphasis on sensing, seizing, and reconfiguring capabilities and the empirical treatment of readiness as a fixed state. Few studies operationalize readiness as a continuous capability development trajectory, despite the iterative nature of manufacturing technology integration. This mismatch suggests that MTR scholarship offers an opportunity to reconceptualize dynamic capabilities as readiness pathways, capturing how firms progressively build, deploy, and realign technological competencies over time.

C. Institutional and social perspectives: under-theorized multi-level pressures

Institutional Theory and Social Network Theory provide valuable insights into how regulatory pressures, industry norms, and inter-firm relationships shape technology adoption. However, MTR studies applying these lenses often stop at identifying external pressures without examining how firms internally translate these pressures into readiness actions. The reviewed literature indicates that institutional forces influence not only adoption decisions but also the sequencing, pace, and scope of readiness investments. Yet, these mechanisms remain under-theorized. MTR research therefore challenges institutional theory to move beyond compliance logic toward explaining strategic interpretation and selective enactment of external pressures within manufacturing organizations.

D. Resource-based and path dependency perspectives: constraints on readiness evolution

Resource Dependence Theory and Path Dependency Theory are less frequently used but provide critical insights into structural constraints on MTR. Studies employing these lenses reveal that legacy systems, historical investment patterns, and supplier dependencies can significantly limit readiness options, even in technologically advanced firms. MTR research extends these theories by demonstrating that readiness is not solely a function of resource availability, but also of resource flexibility and reversibility. Firms locked into rigid technological paths may exhibit high technical maturity but low readiness for emerging paradigms. This finding suggests that future theoretical work should explicitly integrate path plasticity and strategic disengagement mechanisms into readiness models.

3.5.2 Contexts: contextual contingencies in manufacturing technology readiness

The reviewed literature demonstrates that Manufacturing Technology Readiness (MTR) is deeply contingent on contextual factors; however, these contexts are often treated as

background descriptors rather than as theoretically meaningful conditions shaping readiness outcomes. Three dominant contextual dimensions emerge geographical, industrial, and digital maturity contexts each of which introduces distinct readiness mechanisms and constraints.

A. Geographical context: readiness embedded in institutional and infrastructure regimes

Most MTR studies are concentrated in developed manufacturing economies, particularly Europe and East Asia, where institutional support, advanced infrastructure, and coordinated Industry 4.0 policies are well established. In these contexts, readiness is often framed as an optimization challenge how firms can refine existing digital capabilities rather than build them from scratch. In contrast, the limited studies conducted in emerging economies reveal a fundamentally different readiness logic. Here, MTR is shaped by infrastructural gaps, skill shortages, fragmented supply chains, and weak institutional support. The literature suggests that the same readiness indicators do not operate uniformly across regions, challenging the implicit assumption of contextual neutrality embedded in many MTR frameworks. This reveals a theoretical gap: MTR models rarely account for institutional asymmetry, yet such asymmetry critically influences the feasibility, sequencing, and payoff of readiness investments.

B. Industrial context: sectoral path dependencies and readiness trajectories

Industry context strongly conditions how readiness is conceptualized and measured. High-technology sectors such as aerospace, automotive, and electronics dominate the literature, reflecting their capital intensity and innovation-driven competitiveness. In these industries, readiness is often associated with system integration, automation, and digital twins. However, MTR research in traditional manufacturing sectors such as textiles, food processing, and construction materials—is sparse. Where examined, readiness in these sectors is constrained by low margins, labor-intensive processes, and resistance to technological disruption. This sectoral imbalance highlights a critical limitation: current MTR models implicitly reflect high-tech industrial logics, reducing their generalizability. The literature thus suggests the need for sector-sensitive readiness frameworks that incorporate capital intensity, workforce composition, and supply chain complexity as contextual moderators.

C. Digital maturity context: nonlinear readiness progression

The reviewed studies often segment firms according to discrete digital maturity levels, ranging from basic automation to advanced cyber-physical systems. While useful, this approach masks the nonlinear and discontinuous nature of readiness progression. Firms do not move smoothly across maturity stages; instead, they experience setbacks, partial adoption, and hybrid states. MTR research reveals that readiness challenges differ substantially across maturity levels. Early-stage firms struggle with infrastructure and skill development, while advanced firms face issues of system interoperability, cybersecurity, and organizational complexity. Yet, few studies examine transitional dynamics between maturity stages. This omission limits theoretical understanding of how readiness evolves and suggests that MTR should be conceptualized as a path-dependent, adaptive process, rather than a linear progression.

3.5.3 Characteristics: interacting drivers and constraints of readiness

The characteristics dimension captures the organizational, technological, environmental, and strategic factors shaping MTR. While prior studies identify numerous drivers and barriers, they often treat these factors independently. Our synthesis reveals that readiness emerges from the interaction of characteristics, rather than their isolated presence.

A. Human and organizational capabilities as foundational enablers

Human capital and organizational competence consistently emerge as primary readiness enablers. Workforce skills, digital literacy, and leadership commitment are not merely supporting conditions; they function as multipliers that amplify or suppress the effectiveness of technological investments. The literature indicates that identical technologies yield vastly different readiness outcomes depending on managerial alignment and change leadership. However, many studies conceptualize these characteristics as static variables. MTR research suggests instead that organizational readiness is co-evolutionary, shaped by continuous learning, experimentation, and cultural adaptation. This challenges conventional readiness assessments and underscores the need for dynamic capability-based measurement approaches.

B. Technological infrastructure and integration complexity

Infrastructure readiness extends beyond the presence of digital tools to include interoperability, data architecture, and cybersecurity. The reviewed literature shows that integration complexity often becomes the primary bottleneck in advanced manufacturing contexts. Technologies such as IoT, robotics, and additive manufacturing require coordinated system alignment; without it, readiness remains superficial. Notably, technological complexity interacts with organizational capacity. Firms with limited integration skills experience readiness fatigue, where partial implementations fail to scale. This interaction suggests that MTR cannot be accurately assessed without jointly considering technology sophistication and organizational absorption capacity.

C. Environmental and institutional pressures as conditional forces

Regulatory environments, policy incentives, and market volatility shape readiness by altering perceived risks and returns. Institutional support accelerates readiness by reducing uncertainty, whereas regulatory ambiguity delays investment. Yet, MTR studies often treat environmental factors as exogenous pressures rather than as interpreted signals filtered through managerial cognition. The literature indicates that firms respond selectively to institutional pressures, translating them into readiness actions based on strategic priorities. This finding implies that environmental factors exert indirect effects, mediated by leadership perception and organizational strategy an insight largely under-theorized in existing MTR research.

D. Strategic alignment and financial constraints

Strategic alignment determines whether readiness efforts generate sustained value. Technologies adopted without alignment to competitive priorities frequently result in underutilization. Financial resources further condition readiness by shaping technology scope and implementation pace. MTR research reveals a paradox: firms with abundant resources may overinvest in technologies without achieving integration, while resource-constrained firms adopt more focused and effective readiness strategies. This challenges simplistic resource-based assumptions and suggests that strategic discipline, rather than resource abundance alone, is a critical readiness determinant.

3.5.4 Methods: what current methods reveal and conceal about MTR

Methodological choices significantly shape how MTR is conceptualized and understood. While the reviewed literature employs diverse methods, methodological patterns reveal structural limitations in how readiness is studied.

A. Dominance of cross-sectional quantitative designs

Survey-based studies using regression analysis and SEM dominate MTR research. These approaches effectively identify associations between readiness drivers and performance outcomes, but they inherently treat readiness as a static condition. As a result, they fail to capture temporal evolution, learning effects, and adaptive reconfiguration core elements of manufacturing readiness. This methodological bias reinforces theoretical stagnation, as dynamic phenomena are examined using static tools.

B. Qualitative insights and their underutilization

Case studies and interviews provide rich insights into readiness processes, including resistance, learning curves, and system failures. However, these methods are under-represented and often disconnected from theory development. Qualitative findings are rarely used to refine constructs or challenge dominant models, limiting their cumulative contribution. The literature suggests significant potential for process-based and ethnographic approaches to deepen understanding of how readiness unfolds in practice.

C. Limited use of longitudinal and system-level designs

Longitudinal studies, network analyses, and ecosystem-level models are rare. This is a critical limitation, as MTR is inherently evolutionary and inter-organizational. Without longitudinal data, it is impossible to assess causality, readiness decay, or capability accumulation. The absence of system-level designs further obscures how readiness propagates across supply chains and industrial networks. MTR research thus remains largely firm-centric, despite readiness being a collective capability in modern manufacturing ecosystems.

4 Discussion

The bibliometric analysis revealed five macro-clusters that structure Manufacturing Technology Readiness (MTR) research. To move beyond descriptive reporting, this Discussion interprets these clusters through the Theory–Context–Characteristics–Methodology (TCCM) framework. Each subsection synthesizes how the five macro-clusters collectively shape theoretical perspectives, contextual contingencies, readiness drivers, and methodological approaches in the MTR literature.

4.1 Theory: theoretical foundations and extensions across macro-clusters

Across the five macro-clusters, MTR research draws on a diverse yet fragmented set of theoretical lenses, including Dynamic Capabilities Theory, Innovation Diffusion Theory, Resource-Based View, Institutional Theory, and Knowledge-Based perspectives. However, the contribution of each theory varies systematically across clusters. Clusters emphasizing supply chain integration and knowledge-driven readiness primarily extend Dynamic Capabilities and Absorptive Capacity theories by demonstrating that readiness is not a firm-level attribute but a relational and cognitive capability. In contrast, clusters focused on industrial innovation strategies and performance outcomes rely heavily on adoption and performance theories, often treating readiness as a precondition rather than a developmental process. Sustainability-oriented clusters highlight the relevance of

Socio-Technical Systems and Institutional Theory, revealing how normative pressures and lifecycle considerations reshape readiness priorities. Collectively, the macro-clusters expose a critical theoretical gap: existing theories inadequately capture the dynamic, multi-level, and evolutionary nature of manufacturing readiness. MTR research therefore offers fertile ground for integrative theory development that bridges adoption, capability evolution, and institutional embeddedness.

4.2 Context: contextual contingencies shaping readiness pathways

The macro-clusters also reveal strong contextual patterning in MTR research. Studies clustered around advanced manufacturing ecosystems predominantly examine readiness in developed economies and high-technology industries, where infrastructure maturity and policy support shift readiness challenges toward integration and optimization. In contrast, clusters addressing sustainability and supply chain coordination emphasize regulatory environments, global value chains, and institutional complexity. These contexts expose how readiness pathways differ substantially across geographical regions and industrial sectors. Notably, several clusters reveal that readiness indicators derived from developed economies do not translate seamlessly to emerging markets, underscoring the need for context-sensitive readiness models. The cluster-based analysis thus demonstrates that context is not merely a boundary condition but a core determinant of readiness trajectories, influencing technology prioritization, sequencing, and performance outcomes.

4.3 Characteristics: interacting drivers and constraints of MTR

Across clusters, MTR characteristics emerge as interdependent and mutually reinforcing rather than isolated factors. Human capital, leadership commitment, and knowledge management dominate clusters focused on cognitive and relational readiness, while infrastructure, interoperability, and system integration are central to technology-intensive clusters. Importantly, the macro-clusters reveal interaction effects: technological sophistication amplifies readiness only when organizational and strategic characteristics are aligned. Sustainability-oriented clusters further highlight how environmental and social considerations reshape readiness priorities, extending beyond efficiency-driven logics. These findings challenge reductionist readiness models and suggest that MTR should be conceptualized as an emergent capability, shaped by the alignment of organizational, technological, environmental, and strategic characteristics across contexts.

4.4 Methodology: methodological patterns and their implications

Methodological choices vary systematically across macro-clusters. Performance- and strategy-oriented clusters rely predominantly on cross-sectional survey designs and regression-based modeling, reinforcing static conceptualizations of readiness. In contrast, sustainability and knowledge-oriented clusters more frequently employ qualitative and conceptual approaches, offering deeper process insights but limited generalizability. Across all clusters, longitudinal, network-level, and ecosystem-based methodologies remain scarce, despite the inter-organizational and evolutionary nature of MTR. This methodological imbalance constrains theory development and obscures readiness dynamics over time. The cluster-based TCCM synthesis thus highlights an urgent need for methodological diversification, including longitudinal designs, mixed methods, and

system-level analyses to better align empirical approaches with the complexity of manufacturing readiness.

By structuring the Discussion around TCCM dimensions and explicitly linking them to bibliometric macro-clusters, this study demonstrates that Manufacturing Technology Readiness is a dynamic, context-dependent, and multi-level capability. The integration clarifies why fragmented findings persist and provides a coherent foundation for future theory-building and empirical research.

5 Future research agendas

These research agendas contribute to understanding the level of technological readiness in manufacturing on a global scale and may pave the way for novel approaches and strategies in this dynamic domain. Future researchers can propel advancements in knowledge and innovation within the manufacturing sector by utilizing these focal points. Further exploration and advancement in the manufacturing technology readiness landscape between 1986 and 2023 can be facilitated through the delineation of several future research agendas.

5.1 Sustainable readiness mechanisms

Manufacturing technology readiness positively influences environmental and social sustainability outcomes through the mediating role of lifecycle-oriented decision-making capabilities.

There is an urgent need to further explore the concept of sustainable development in relation to the use of technology. Future researchers can examine the intricate dynamics between technological advancement and sustainable practices with a specific focus on societal well-being and ecological balance. Understanding these dynamics has the potential to provide valuable insights for encouraging the adoption of more responsible technologies in the industrial sector. This research agenda centers on identifying frameworks that guide manufacturers in making environmentally and socially responsible decisions through the adoption of emerging technologies [6, 27].

Proposition 1 *How can frameworks guide manufacturers toward environmentally and socially responsible decisions during the adoption of emerging technology, promoting societal well-being and ecological balance?. Theoretical grounding: Socio-Technical Systems Theory; Institutional Theory. Empirical testing: Survey-based SEM or longitudinal sustainability performance analysis*

Rationale and Importance: This proposition is informed by the “Holistic Sustainable Management Practices” cluster, highlighting sustainability as a critical dimension of MTR. By developing and applying robust frameworks, manufacturers can integrate environmental and social considerations into their technology adoption processes, ensuring that technological readiness contributes to operational efficiency, as well as long-term societal and ecological goals. Practically, such frameworks help decision-makers balance innovation with responsibility and align strategic objectives with global sustainability standards.

5.2 Technology integration strategies and competitiveness

Manufacturing technology readiness enhances firm-level competitive advantage by strengthening supply chain integration capabilities across upstream and downstream partners.

One potential avenue for investigation is to examine the impact of technology integration techniques on attaining competitive advantage within the manufacturing sector. This agenda aims to explore the relationship between technology readiness and market positioning, focusing on how technical decisions influence a firm's ability to differentiate itself and sustain its performance [1, 11].

Proposition 2 *Manufacturing technology readiness positively influences competitive advantage through the mediating role of supply chain integration capabilities. Theoretical grounding: Dynamic Capabilities Theory; Resource-Based View. Empirical testing: Multi-respondent supply chain surveys; mediation analysis*

Rationale and importance: Derived from the “industrial innovation strategy cluster, this proposition underscores the strategic role of technological integration in achieving market differentiation. Investigating these relationships helps firms identify the integration strategies that optimize operational efficiency, innovation, and long-term competitiveness. For researchers, this provides opportunities to test theoretical linkages between technical readiness and performance outcomes, while managers gain actionable insights into aligning technology adoption with strategic goals.

5.3 Global context and strategic alignment

The relationship between manufacturing technology readiness and operational performance is moderated by international regulatory complexity and global supply chain exposure. Another promising research avenue involves examining the convergence of technological readiness and holistic management practices in the global commerce context. This agenda might explore decision-making processes, financial strategies, and project management techniques that promote the seamless integration of technology adoption with sustainable practices. Additionally, analyzing the effects of international trade dynamics on technology choices and methods can provide businesses with critical insights for effective operations within a global context [10, 83].

Proposition 3 *What strategies foster the seamless integration of technology adoption with sustainable practices in global manufacturing, considering international trade dynamics?. Theoretical grounding: Institutional Theory; TOE framework. Empirical testing: Cross-country comparative studies; multigroup SEM*

Rationale and importance: Informed by the “Strategic Industry Performance” and “holistic sustainable management practice” clusters, this proposition highlights the importance of aligning internal practices with external global pressures. Investigating these strategies can help firms navigate regulatory, financial, and market challenges, while maintaining sustainability and operational efficiency. Theoretically, it encourages the examination of multilevel interactions in MTR, and practically, it equips managers to implement globally informed, sustainable technology adoption practices.

5.4 Knowledge management as an enabling mechanism

Knowledge management capability mediates the relationship between manufacturing technology readiness and supply chain efficiency, leading to improved profitability outcomes. A further avenue for research is to explore the impact of knowledge management on enhancing supply chain efficiency through technological readiness. Examining knowledge exchange and application within supply chains can illuminate how these processes affect technological integration, operational performance, and financial outcomes [21, 78]. Additionally, studying the influence of knowledge management on profitability in the context of technology adoption presents a significant potential for investigation.

Proposition 4 *How does knowledge management impact supply chain efficiency and profitability through technological integration?. Theoretical grounding: Absorptive Capacity Theory; Knowledge-Based View. Empirical testing: Mixed-method designs combining surveys and case studies*

Rationale and importance: Based on the “Knowledge-Driven Supply Chains” cluster, this proposition emphasizes the cognitive and systemic aspects of MTR. Effective knowledge management ensures that technological insights are captured, shared, and applied throughout the supply chain, thereby enhancing coordination, responsiveness, and overall performance. This opens avenues for researchers to examine the mechanisms linking knowledge flows to operational outcomes, whereas practitioners can leverage knowledge management strategies to drive both efficiency and profitability in technologically advanced manufacturing environments.

6 Conclusion, implications and limitations

This review adopts the TCCM (theory–context–characteristics–methodology (TCCM) framework as an analytical lens to uncover deeper theoretical, contextual, and methodological gaps in the literature on Manufacturing Technology Readiness (MTR). Through a structured synthesis of 267 articles spanning 1986 to 2025, this study offers a holistic understanding of how manufacturing firms assess, implement, and advance technology readiness. By integrating the TCCM framework, this review not only maps the intellectual structure of MTR research but also establishes the foundation for theory-driven, practice-relevant, and methodologically robust advancements in the field. As manufacturers continue to navigate digital transformation, a nuanced understanding of technology readiness grounded in interdisciplinary theory and empirical rigor remains essential. This study aimed to achieve these research objectives. Identification and analysis of key research trends and thematic clusters within the MTR domain. The bibliometric and thematic analysis revealed five major clusters: integrated supply chains, industrial innovation strategies, holistic sustainable management practices, strategic industry performance, and knowledge-driven supply chains, providing a comprehensive map of the research landscape. To examine the theoretical frameworks and methodologies applied in MTR research. The review highlighted that while multiple theories, such as TOE and Dynamic Capabilities, are referenced, their integration and operationalization are limited. This study underscored gaps in empirical validation and the need for multilevel, longitudinal approaches. To propose research agendas and practical recommendations for advancing MTR. This study developed four propositions focusing on sustainable technology adoption, technology integration for competitiveness, holistic management

in global manufacturing, and knowledge management in supply chains, providing actionable insights for both researchers and practitioners.

6.1 Theoretical and practical contributions

Collectively, the reviewed literature indicates that no single theory sufficiently captures the multi-dimensional and evolutionary nature of Manufacturing Technology Readiness. MTR research challenges existing theories to (a) Treat readiness as a dynamic, multi-level capability, not a binary adoption condition (b) Integrate post-adoption transformation processes into adoption models (c) Account for historical constraints and institutional interpretation mechanisms. By synthesizing insights across theoretical streams, MTR research provides a foundation for developing integrative readiness theory that bridges technology adoption, organizational capability development, and institutional embeddedness. Collectively, these methodological patterns constrain theoretical advancement in MTR research. Progress requires (a) Longitudinal designs to capture readiness evolution (b) Mixed-method approaches to integrate depth and generalizability (c) Network and ecosystem-level analyses to reflect interdependence. By aligning methodological choices with the dynamic nature of readiness, future studies can more accurately model the complexity revealed by the MTR literature.

We propose an organizing framework that integrates the antecedents, dimensions, and outcomes of MTR. Grounded in the TCCM, this framework consolidates fragmented insights and guides future research toward a more structured and theory-informed understanding of technology readiness. The bibliometric and content analyses revealed thematic shifts over time from early CAD/CAM integration in the 1980s to digital transformation, sustainability, and resilience in the post-COVID-19 era. Thematic maps and keyword analyses highlight dominant themes, such as agile manufacturing, supply chain integration, and sustainable development, while identifying underexplored areas, such as employee adaptability, inter-firm collaboration, and cross-national readiness variation. For practitioners, this review offers actionable insights into the current state of readiness, key barriers and enablers, and emerging trends. By aligning organizational strategy with readiness indicators, such as leadership commitment, digital literacy, and infrastructure maturity, firms can better prepare for the complexities of Industry 4.0.

Despite the comprehensive scope and rigorous methodology employed in this review, several theoretical, contextual, and methodological gaps persist in the literature on Manufacturing Technology Readiness (MTR). These gaps form the basis for targeted future research and reflect the limitations of current scholarly discourse. While theories such as TOE, Dynamic Capabilities, and Innovation Diffusion are frequently cited, few studies have deeply integrated or adapted them to the specific nuances of MTR. Their application often remains descriptive, rather than explanatory. No dominant theory currently holistically integrates the technological, organizational, and supply chain dimensions of readiness. There is scope for developing multilevel theoretical models that accommodate cross-functional interdependencies. High-tech sectors (aerospace and electronics) dominate MTR studies, while traditional sectors, such as textiles, automotive supplies, and construction manufacturing, remain underexplored. The bulk of the research is concentrated in developed economies, with minimal focus on MTR practices in emerging or low-income countries. This skews findings toward resource-rich contexts and ignores regional readiness barriers. Most studies adopt a one-time, self-reported survey design,

limiting the ability to capture the temporal evolution of readiness. MTR is often examined at the firm level, while ecosystem dynamics, interorganizational linkages, and policy influence remain largely absent.

6.2 Limitation

This study had several limitations. It relies primarily on Scopus-indexed publications and author keywords, and potentially excludes relevant studies from other databases. Bibliometric and thematic analyses provide insights into research patterns but cannot fully capture causal relationships among MTR variables. The cross-sectional design limits the assessment of longitudinal trends. Additionally, dimensions such as co-authorship networks, institutional affiliations, and temporal topic evolution were not analyzed. Future research could address these gaps by incorporating multiple databases, alternative keyword types, longitudinal or mixed-method designs, and meta-analytical approaches to quantify the impacts of MTR drivers and barriers.

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Data availability

The data that support the findings of this study are available from the corresponding author [Seema Bhardwaj], upon reasonable request.

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