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# Expanding MAM Readiness: Towards A Holistic Model for Metal Additive Manufacturing in the Fourth Industrial Revolution

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## Abstract

Metal Additive Manufacturing (MAM) is a transformative technology with the potential to revolutionize manufacturing through the production of complex, high-value components with unprecedented design freedom. However, the adoption of MAM is challenging due to its complex and multifaceted nature, which encompasses a wide range of advanced technologies, including Laser Powder Bed Fusion (LPBF), Direct Energy Deposition (DED), and Binder Jetting (BJ). To address this challenge, this research delves into a Systematic Literature Review (SLR) of $n = 71$ publications and expands upon a prominent existing MAM readiness model as theoretically proposed by the research literature. This enriched model offers a nuanced understanding of MAM readiness, catering to the intricacies of this rapidly evolving field. Notably, it provides a more fine-grained assessment of competency levels, enabling better strategic planning and resource allocation. The research also highlights the implications of these findings for Small and Medium-sized Enterprises (SMEs) operating in the realm of MAM, suggesting avenues for SMEs to enhance their competitiveness. The expanded MAM readiness model seeks to serve as a comprehensive and up-to-date tool for assessing an organization's readiness to adopt MAM technology. It is particularly valuable for SMEs, which may lack the resources and expertise to independently assess their MAM readiness. Furthermore, this research may be used to support SMEs in navigating their material, data, and personnel interface with Large System Integrators (LSIs).

## Keywords

Metal Additive Manufacturing, Decision-Making, Readiness Model, Technology Adoption, Industry 4.0

## 1. Introduction

The transformative tide of Additive Manufacturing (AM) has surged relentlessly, with Metal Additive Manufacturing (MAM) emerging as the avant-garde of industrial evolution (Zhao and Zong 2022). Propelled by its unparalleled precision and adaptability among other capabilities (Lin et al. 2022), MAM is poised to redefine manufacturing practices across industries (Frazier 2014). Plentiful examples exist for MAM use in widespread industries such as healthcare, aerospace, aeronautics, real estate development, and much more (Vafadar et al. 2021; Haleem and Javaid 2019). Nevertheless, this potential remains contingent upon a profound understanding of MAM readiness – a complex, multifaceted construct that transcends mere technological prowess. This research embarks on an ambitious endeavor to expand an existing readiness model for MAM proposed by the research literature, thereby enriching our

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comprehension of its multifarious competencies and elucidating its profound implications for Small and Medium-sized Enterprises (SMEs).

The dynamism inherent in MAM technology (Patil et al. 2023) necessitates a holistic reevaluation of readiness frameworks, underscoring the inextricable link between technological preparedness and operational excellence. MAM dynamism refers to the acceleration of change as well as the unique posturing of the technology to serve at various positions within supply chain models. Moreover, being known as one of the most adaptive technologies for diverse needs and applications areas adds to the natural dynamism of MAM technology. As the adoption of MAM continues to grow, the readiness assessment becomes imperative, offering stakeholders, especially SMEs, a compass to navigate the complexities of technological adoption and transformation (Lima et al. 2023). The expansion of this model is catalyzed by the relentless evolution of MAM technology, a domain characterized by relentless innovation, thereby demanding a more intricate and comprehensive readiness evaluation framework (Iqbal et al. 2020). Figure 1 depicts a broad overview of AM technologies and how they are used in a diverse range of sectors (with the most common being consumer production and electronics).

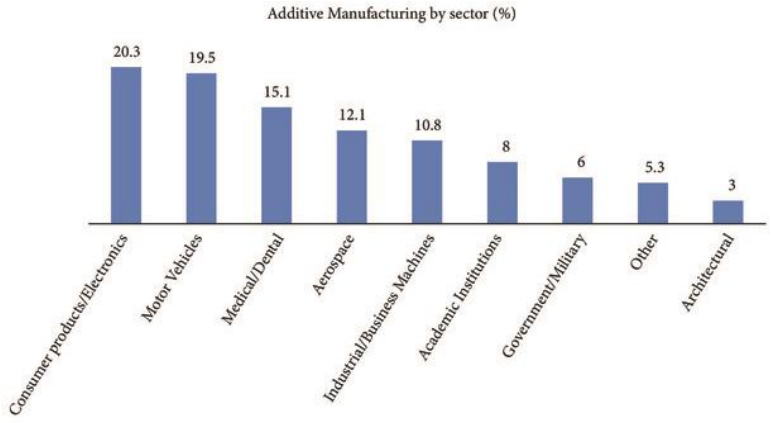


Figure 1. AM Materials Usage by Sector (Jimenez et al. 2019).

The evolution of MAM readiness within the broader framework of AM is emblematic of the incessant drive for technological advancement. In the epoch of the Fourth Industrial Revolution (also known as Industry 4.0), the fusion of digital technologies, advanced materials, and transformative processes redefines manufacturing paradigms (Dalenogare et al. 2018). MAM, an integral component of this revolution, enables fabrication of complex geometries, rapid prototyping, and on-demand production, while transcending traditional subtractive manufacturing constraints.

As this technological wave gathers momentum, the practical implementation of MAM assumes paramount importance. To realize the full spectrum of its advantages, organizations must possess a holistic understanding of their readiness to adopt and integrate this technology. In this regard, readiness is a multidimensional construct encompassing technological proficiency, operational excellence, workforce competencies, and strategic alignment. The significance of readiness is underscored by its role in ensuring optimal resource allocation, risk mitigation, and the seamless integration of MAM into existing production landscapes with the recognition that MAM influences business models (Savolainen and Collan 2020).

SMEs, often characterized by resource constraints and unique operational challenges (Kulkarni et al. 2021), are a focal point in the exploration of MAM readiness. The implications of adopting MAM for SMEs are multifaceted, ranging from opportunities for cost-effective customization to the imperative of achieving competitive parity with larger enterprises. Hence, the assessment of readiness assumes even greater significance for SMEs, serving as a guiding beacon in their quest for technological transformation.

## 1.1 Objectives, Structure, and Organization of Paper

This research commences with an introduction that provides the foundation for understanding the significance of MAM readiness as previously detailed. The literature review section serves as the second pivotal component, offering

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an exhaustive examination of the existing body of knowledge concerning MAM readiness. Drawing insights from an extensive review of $n = 71$ carefully curated papers, this section delves into the strengths and limitations of current readiness models, thereby setting the stage for the creation of an advanced, augmented model.

The existing MAM readiness model of concern comes from a prominent publication from the IEEE Conference on Technology for Sustainability (Sæterbø and Solvang 2023). This publication describes MAM readiness for SMEs as being indexed on a total of five pillars each carrying five levels of competency. These pillars include production, materials, construction, business model, and market. Figure 2 depicts the MAM readiness model as it is defined.

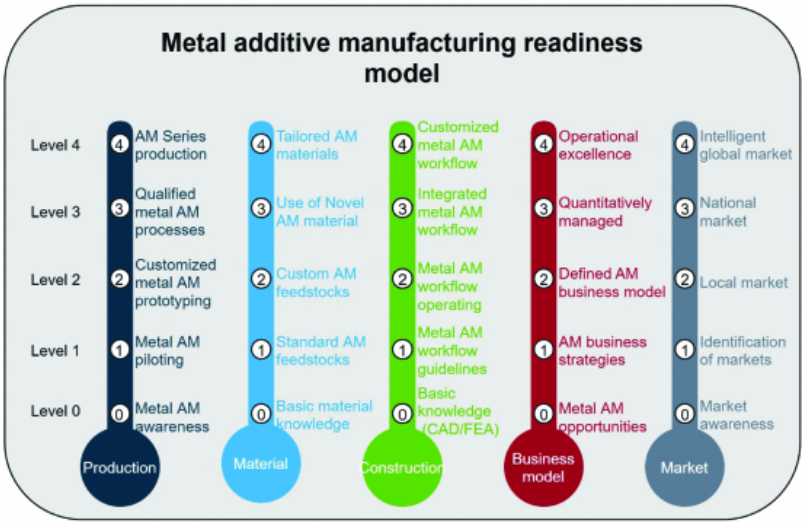


Figure 2. Readiness Model for MAM in SMEs (Sæterbø and Solvang 2023).

The culmination of our research unfolds in the results section, which unveils the newly expanded MAM readiness model. This heightened model comprises seven pillars, each characterized by seven distinct levels of competency. The intricate detailing of these pillars and competency levels equips stakeholders with a nuanced and holistic perspective of MAM competencies, thereby enabling an accurate assessment of readiness. The expansion and refinement of the model is geared toward addressing the intricate nature of MAM's technological landscape.

Subsequently, the section detailing areas of future research directs attention towards uncharted domains, where exploration is required to push the boundaries of MAM readiness assessment. In the ever-evolving world of MAM, the paper provides a compass for future research endeavors, offering a roadmap for the continual development of readiness models and practices. The research offers concluding remarks to synthesize fundamental findings, their far-reaching implications, and overarching contributions. The discussion within pertains to the relevance and practical applications of the expanded MAM readiness model, particularly concerning SMEs. It encapsulates the essence of this research paper and serves as a guiding light for future endeavors in the sphere of MAM readiness assessment.

## 2. Literature Review and Methodology

In drawing upon the vast amount of metadata that is essential to construct the necessary generalized relationships that govern MAM readiness, we conduct a literature review of a large volume of established research literature. Other approaches and methods lend favorable opportunities to gather unique insights. For instance, expert interviews offer company-specific insights and more precisely identify the barriers that are faced in relation to the situational circumstances of the organization and competitive environment. On the other hand, drawing findings from large workshop events on MAM challenges also provides means by which barriers can be characterized and overcome. Although extensive data from both resources are available internally, we elect to pursue the Systematic Literature Review (SLR) process and augment findings with insights from expert sources and workshop findings. In evaluating the various research methodologies available, this provides the most nearly unbiased approach (Pickering and Byrne

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2013) to assessing MAM tendencies across all industries and the corresponding posturing of SMEs. The literature review type selected is the SLR due to the ability to harmonize keywords across domains.

The SLR is a cornerstone of our research, a structured and rigorous method designed to accumulate, synthesize, and analyze pertinent scholarly literature (Williams Jr. et al. 2021). It acts as a pivotal process that will guide the findings on knowledgeable expansion of the MAM readiness model, a critical endeavor to cater to the evolving landscape of MAM. In this section, we delve into the intricate details of our SLR process, starting from the formulation of search queries, choice of databases, the yield of the initial searches, and ending with systematic curation of the final dataset.

## 2.1 Elected Search Queries and Databases

At the core of our SLR lies the quest to explore a significant aspect of AM relevant to SMEs: the business model. The SME's chosen business model is the central element of any organization that must include MAM adoption plans to establish successful implementation and technology deployment (Sobota et al. 2021). Our primary aim is to unearth how MAM intertwines with and shapes the business models of diverse enterprises, with an explicit focus on SMEs. To achieve this, we have meticulously devised a search query that links two pivotal keywords: "Metal Additive Manufacturing" and "Business Model". The "AND" operator serves to interconnect these keywords, thus narrowing the search scope to publications that explore the confluence of both technological and business aspects of MAM. The deliberate breadth of our search criteria aims to encompass the multifaceted dimensions of MAM readiness, including its ramifications for business models, strategic orientations, and operational efficiencies.

## 2.2 SLR Search Process

The preliminary execution of our search queries on two prominent scholarly databases, ScienceDirect and ProQuest, yielded a cumulative $n = 132$ publications. The scholarly benefits of these two databases are noted by existing research (Gusenbauer and Haddaway 2020) and these two databases seem uniquely beneficial for the context of this analysis and associated SLR. Specifically, ScienceDirect contributed 92 publications, while ProQuest returned 40. In confining the results, only publications occurring in 2016 or later were included to ensure a MAM readiness model calibrated to modern tendencies and considerations for SMEs. Similarly, the results on both scholarly databases were confined to only include reports, scholarly journals, dissertations and theses, books, and conference papers and proceedings. This criteria is specified in order to exclude irrelevant company earnings reports or other publications that are similarly irrelevant. A variety of best practices (Snyder 2019; Kondaveeti et al. 2021) are considered.

To maintain the utmost precision in our dataset, a meticulous examination of the 132 publications was conducted to identify and remove any duplicate entries present across the ScienceDirect and ProQuest scholarly databases. This rigorous process resulted in the elimination of 3 publications that were recognized as redundant records. Consequently, the refined dataset was composed of 129 publications that were broadly aligned or subject-adjacent to the primary focus of our stated research. Subsequent to the initial search results, the 129 publications underwent a comprehensive title and abstract screening process. This meticulous review sought to identify publications that directly addressed the intersection of MAM and business models, with the aim of eliminating materials that did not align with our research objectives. This phase resulted in the exclusion of 44 publications from the dataset, leaving 85 publications that showed promise for further analysis. After the title and abstract screening, the remaining 85 publications were subjected to a meticulous review of their full texts. This crucial stage involved a comprehensive examination to determine the depth and relevance of each publication concerning our research goals. This phase was instrumental in identifying materials that closely aligned with the research objectives and those that did not. It resulted in the removal of 14 publications that were deemed to be less relevant. Following the aforementioned meticulous filtration stages, the dataset was refined to include 71 publications that closely adhered to the research objectives.

## 2.3 Analysis of Research Method Selection

The SLR process is a systematic, methodical approach to literature review that offers several distinct advantages in the context of our research on expanding the MAM readiness model. In detail, these advantages include:

- Comprehensiveness: The SLR process is designed to be all-encompassing, ensuring that we cast a wide net to capture relevant literature from a variety of sources. This inclusivity enables holistic understanding of the topic and consideration of a broad spectrum of perspectives.
- Structured Approach: SLR provides a structured framework for conducting the literature review. It involves predefined search criteria, inclusion and exclusion criteria, and a systematic process of data selection. This

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structured approach reduces the potential for bias and ensures that the review is conducted in an organized and methodical manner (Williams Jr. et al. 2021).

- Relevance and Applicability: The curation of the dataset through various stages of screening and curation, from initial search results to full-text assessment, ensures that the final dataset comprises highly relevant and applicable materials. This process helps avoid including irrelevant or outdated sources (Davies 2019).
- Diversity of Sources: The use of multiple databases, in our case ScienceDirect and ProQuest, broadens the range of sources and perspectives. This diversity enhances the robustness of our review and exposes a wider array of research methodologies, findings, and insights.
- Transparency and Replicability: The systematic and transparent nature of the SLR process allows for easy replication by other researchers. This transparency ensures that our research methods are open to scrutiny and verification, reinforcing the reliability of our findings.
- Informed Decision-Making: The synthesis of information obtained through SLR offers a well-informed basis for decision-making. It identifies trends, gaps in the literature, and areas requiring further exploration, all of which inform the expansion of the MAM readiness model (Ryan 2010).

In summary, the SLR process is a systematic and structured approach that provides numerous advantages, including comprehensiveness, transparency, and a high level of quality assurance (Xiao and Watson 2019; Taherdoost 2023; and Paul and Barari 2023). Each stage serves a specific purpose, contributing to the overall rigor and relevance of the literature used in our research.

Despite these acknowledged disadvantages, SLR remains an indispensable methodology for this research. The unique advantages far outweigh the limitations. The robustness of SLR is suited to the goal of expanding the MAM readiness model, especially regarding SME implications. The advantages of SLR for comprehensiveness, structure, relevance, quality assurance, diversity of sources, and transparency far outweigh its disadvantages. The commitment to minimizing bias and maintaining objectivity, coupled with our systematic approach, ensures that the insights derived from this process will be invaluable in advancing our understanding of MAM readiness and its implications for SMEs.

## 3. Categorical Synthesis of MAM Readiness

The SLR, in serving as the bedrock of this research, led to meticulous scrutiny of 71 publications to uncover insights that illuminate the unique considerations for SMEs seeking to adopt MAM technologies. Through this rigorous examination of the literature, additional facets for consideration of MAM readiness assessment are identified, seeking to enable the technology tailored to the intricate demands of contemporary industrial landscapes. In addition, the literature also suggests additional levels of readiness for the existing 5 pillars to refine the assessment. This expansion is a testament to the shifting landscape of MAM (McLaughlin 2023) and the intricate demands it now places upon SMEs. In accordance with the SLR findings, Figure 3 depicts the enhanced model.

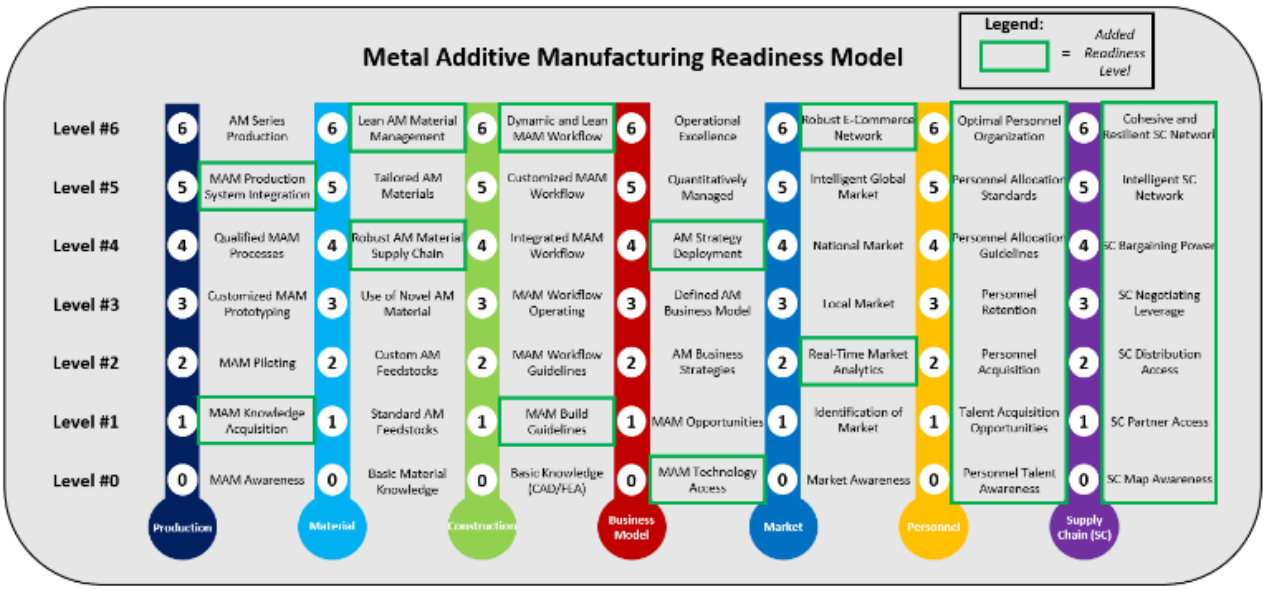


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Figure 3. MAM Readiness Model Augmented with SLR ($n = 71$), Expert Interview, and Workshop Findings.

In summary, Figure 3 shows the enhanced MAM readiness model. As suggested by the emergent findings of the SLR, the seven pillars depicted in the figures above (Production, Material, Construction, Business Model, Market, Personnel, and Supply Chain) represent the fundamental dimensions that SMEs must master to successfully navigate the MAM landscape. Each of the 49 levels of competency encapsulates a distinct set of skills, knowledge, and strategies, contributing to the overall preparedness of SMEs. They collectively serve as the theoretical basis for further experimentation in the field in seeking to offer MAM readiness assessment at higher granularity and specificity.

### 3.1 MAM Readiness in Production

The inclusion of two additional levels of competency, MAM knowledge acquisition (Lu et al. 2018) and MAM production system integration, within the Production pillar of the MAM readiness model is imperative to capture the intricacies and evolution of MAM processes in contemporary industrial settings.

- MAM Knowledge Acquisition: In the swiftly evolving landscape of MAM, knowledge acquisition assumes paramount importance. This level recognizes the necessity for SMEs to actively pursue, assimilate, and stay abreast of the latest developments, materials, and processes in MAM. MAM knowledge acquisition encompasses continuous learning, technology scouting, and an adept understanding of emerging trends and innovations. It empowers SMEs to make informed decisions and optimize resource allocation.
- MAM Production System Integration: MAM is no longer a standalone process but an integral part of modern manufacturing ecosystems. This level underscores the need for seamless integration of MAM within existing production systems. It involves the harmonization of MAM processes with conventional manufacturing processes, ensuring synergy and optimizing resource utilization. MAM production system integration also encompasses the development of interoperable software and hardware interfaces, enabling data exchange and collaboration between various production systems.

The addition of these two levels of competency reflects the contemporary industrial reality where MAM is a dynamic and integrated component of manufacturing operations (Kumar et al. 2021). SMEs must not only possess technical competencies but also the agility to assimilate new knowledge and the capacity to weave MAM seamlessly into their production systems (Martinsuo and Luomaranta 2018). These levels bridge between MAM's technical complexities and its real-world application, equipping SMEs with the capacity to thrive in the intricate MAM landscape.

### 3.2 MAM Readiness in Materials

In surplus, the SLR found it necessary to add two further levels of competencies to the Material pillar. The addition of two supplementary levels of competency, "Robust AM Material Supply Chain" and "Lean AM Material Management," within the Material pillar of the MAM readiness model is indispensable to meet the exigencies of contemporary MAM practices (Ghobadian et al. 2020).

- Robust AM Material Supply Chain: The conventional AM feedstocks and materials have transmuted into a complex ecosystem, demanding a robust supply chain. Ensuring a robust AM material supply chain is vital to guarantee uninterrupted material access, quality control, and compliance with stringent industry standards. It necessitates efficient sourcing, vendor relationships, inventory management, and risk mitigation strategies to avert material shortages and disruptions, which can profoundly affect production efficiency for SMEs.
- Lean AM Material Management: Lean AM material management is a core competency to optimize resource utilization. In the age of sustainability and cost-efficiency, SMEs need to minimize material waste and overspending. This level of competency incorporates techniques such as demand forecasting, waste reduction, and efficient material allocation which have been shown to relate positively with AM success.

These supplementary levels accentuate the dynamic transformation of the material landscape in MAM. Material considerations are no longer confined to the properties of raw materials but extend to intricate supply chain orchestration and resource optimization (Mladenovska et al. 2021). They mirror the maturation of MAM and necessitate SMEs to exhibit dexterity in material acquisition and management, preserving resources and competitiveness in the evolving MAM arena.

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### 3.3 MAM Readiness in Construction

The integration of two additional levels of competency, "MAM Build Guidelines" and "Dynamic & Lean MAM Workflow," within the Construction pillar is essential. For the MAM readiness model, these components are instrumental to address the evolving intricacies of MAM workflows (Sini 2020). Accordingly, this enhances the granularity of the MAM readiness model.

- MAM Build Guidelines: The MAM process is not merely about following existing guidelines but also about creating guidelines specific to the complex geometries and material considerations in MAM. As a necessary step, SMEs must develop a profound understanding of MAM build guidelines, encompassing Design for Additive Manufacturing (DfAM) principles, material requirements, and machine-specific parameters.
- Dynamic & Lean MAM Workflow: The world of manufacturing is evolving at an unprecedented pace, demanding adaptable and lean workflows. This level of competency signifies the agility of SMEs in orchestrating dynamic and lean MAM workflows that can promptly adapt to changing customer demands, design variations, and technology advancements.

The inclusion of these competencies accentuates the metamorphosis of MAM from a purely technical operation to a dynamic and responsive process that necessitates continual adaptation and optimization. It's not just about understanding existing rules; it's about crafting new ones and maintaining the operational agility to meet the challenges of the contemporary MAM realm (Schrand 2016). These competencies underpin the Construction pillar's evolution, thereby fortifying SMEs with the skills needed to thrive in the swiftly evolving MAM domain.

### 3.4 MAM Readiness in Leveraging Business Models

As uncovered by the SLR, the levels of competency, "MAM Technology Access" and "AM Strategy Deployment" are essential for inclusion for SMEs within the Business Model pillar of the MAM readiness model (Heinen et al. 2023). Especially for SMEs, this is paramount to cater to the nuanced dynamics of MAM in the challenging contemporary industrial dynamics that disadvantage regionally-spanning organizations.

- MAM Technology Access: In the modern era, gaining access to cutting-edge MAM technologies is a critical dimension of business model considerations. SMEs must not only recognize the existence of these technologies but also have the capability to integrate them into their operations. This competency highlights the imperative of staying informed about the latest MAM innovations, establishing partnerships with technology providers, and effectively incorporating these technologies into the overarching business model.
- AM Strategy Deployment: Beyond crafting strategies, deploying them effectively is the keystone to successful MAM integration. This competency accentuates the execution of well-defined strategies, encompassing the allocation of resources, the management of projects, and the establishment of key performance indicators. AM strategy deployment ensures that the formulated strategies are translated into tangible actions that drive operational excellence and business success.

The incorporation of these competencies recognizes the business model as a dynamic and adaptive framework that necessitates SMEs to be at the forefront of technology adoption and strategy execution (Cremona et al. 2016). It is not merely about envisioning strategies but also about having the dexterity to implement them effectively in the context of rapidly evolving MAM technologies. These competencies add depth and flexibility to the Business Model pillar, equipping SMEs with the proficiency to harness MAM's transformative potential effectively and remain competitive in a dynamic industrial landscape.

### 3.5 MAM Readiness in Market

"Real-time Market Analytics" and "Robust E-commerce Network" were found to be essential components to incorporate within the Market pillar of the MAM readiness model. Pivotally, acknowledging the rapid digital transformation and globalization trends that are reshaping the landscape of MAM have become essential aspects of widespread adoption and industrialization of these technologies (Ekren et al. 2023) in the modern landscape.

- Real-time Market Analytics: In the contemporary industrial milieu, where data reigns supreme, real-time market analytics is an indispensable competency. SMEs must not only possess a holistic understanding of market dynamics but also the capability to gather, process, and act upon real-time data. This level

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underscores the significance of employing advanced data analytics tools to monitor market trends, consumer behaviors, and competitive landscapes.
- Robust E-commerce Network: The digital era has revolutionized business-to-business (B2B) and business-to-customer (B2C) interactions, emphasizing the necessity for a robust e-commerce network. This level of competency underscores the importance of establishing a digital marketplace where MAM products and services can be seamlessly marketed, distributed, and transacted.

These additional competencies encapsulate the reality of the contemporary marketplace, where digitalization and data-driven decision-making are paramount (Eyers and Potter 2015). The market is no longer a static entity but a dynamic and interconnected ecosystem, demanding SMEs to not only be market-aware but also digitally savvy in the current era. These competencies empower SMEs to leverage real-time data for informed decision-making and establish a robust digital presence that extends their reach to a global audience. They enhance the Market pillar's relevance and resonance, ensuring that SMEs are well-prepared to navigate the complexities of today's MAM marketplace as it continues to develop and undergo transformative dynamic change.

### 3.6 MAM Readiness in Knowledgeable Personnel

The introduction of the "Personnel" pillar and its associated seven levels of competency is a significant enhancement to the MAM readiness model, addressing the intricate human resource considerations required for effective MAM technology adoption within an organization (Verboeket and Krikke 2019). Especially with emerging technologies such as MAM, there is much competition between large, resourceful organizations and SMEs in the area of talent acquisition. SMEs are underleveraged in the competitive arena, so identifying the sequential steps of competency in this domain are essential components to a MAM readiness model for SMEs as implied by the findings of the SLR.

- Personnel Talent Awareness: This level reflects the imperative of cultivating a comprehensive understanding within Small and Medium-Sized Enterprises (SMEs) regarding the paramount role of human capital in MAM. Personnel talent awareness encompasses recognizing the specific skills and competencies crucial for successful MAM integration.
- Talent Acquisition Opportunities: In the pursuit of MAM readiness, identifying opportunities for talent acquisition is pivotal. SMEs must possess the discernment to identify potential sources of individuals possessing the requisite expertise, be it through recruitment, partnerships, or collaborations.
- Personnel Acquisition: The strategic hiring or onboarding of individuals with specialized knowledge in additive manufacturing, materials, and associated technologies forms the core of this level. Personnel acquisition ensures that the right expertise is integrated into the organization.
- Personnel Retention: Attracting talent is essential, but equally vital is the ability to retain such talent. Personnel retention involves creating an organizational environment and incentives structure that ensures the acquired talent remains engaged and committed. As a necessary condition, competency in personnel acquisition and personnel retention are independent levels of achievement as proposed by the model.
- Personnel Allocation Guidelines: Efficient allocation of personnel across various roles is fundamental. SMEs must establish guidelines for the assignment of individuals to specific tasks and projects, aligning their competencies with the requirements of the MAM initiative.
- Personnel Allocation Standards: This level instills consistency in personnel allocation procedures. SMEs define standardized practices to ensure that personnel are placed in roles that align with their competencies and that these standards are consistently applied throughout the organization.
- Optimal Personnel Organization: The ultimate objective is to achieve an optimal personnel organization, wherein the workforce is structured efficiently to support MAM initiatives. Personnel are allocated to roles that maximize their contributions to MAM adoption, optimizing human resources in the process.

These levels of competency not only underscore the critical role of human capital in MAM readiness but also provide SMEs with a structured approach to managing their personnel effectively. In a landscape characterized by rapidly advancing technology and multifaceted requirements, the ability to identify, acquire, retain, allocate, and organize the right talent is of paramount importance (Tripathi et al. 2023). The "Personnel" pillar bridges the gap between technical proficiency and human resource management, offering SMEs a comprehensive strategy to cultivate MAM readiness in a holistic and strategic manner. In this dynamic and competitive era, these competencies ensure that SMEs possess the necessary human capital to navigate the complexities of MAM technology adoption adeptly.

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### 3.7 MAM Readiness in Supply Chain Management

The addition of the "Supply Chain" pillar and its seven levels of competency is a crucial augmentation to the MAM readiness model, recognizing the intricate demands of MAM technology integration, particularly within the context of the supply chain. These competency levels characterize the multi-faceted dimensions of supply chain management imperative for successful MAM adoption in an organization.

- Supply Chain Map Awareness: SMEs must have a profound understanding of the intricacies within their supply chain. This level of competency entails mapping the entire supply chain landscape, identifying key nodes, processes, and stakeholders. It enables SMEs to comprehend the flow of materials and information.
- Supply Chain Partner Access: Effective integration of MAM necessitates establishing connections with essential supply chain partners. This competency reflects SMEs' capability to forge collaborations, ensuring that they have access to the right partners capable of providing MAM-relevant materials and components.
- Supply Chain Distribution Access: To ensure the smooth flow of materials, SMEs need access to an efficient distribution network. This level encompasses the ability to secure and maintain distribution channels for MAM materials and products, optimizing the flow from production to market.
- Supply Chain Negotiating Leverage: The dynamics of procurement and negotiation play a pivotal role in supply chain management. SMEs must possess the competency to negotiate effectively with suppliers, leveraging favorable terms, costs, and quality for MAM-related materials and components.
- Supply Chain Bargaining Power: Building on negotiating leverage, this level underscores the strategic positioning of SMEs to exert influence within the supply chain. It involves strategies to enhance bargaining power by cultivating relationships, ensuring reliability, and diversifying sources of supply.
- Intelligent Supply Chain Network: The contemporary supply chain is not static but an intelligent network that demands adaptability. This level underscores SMEs' capability to develop dynamic and responsive supply chain networks, integrating real-time data, predictive analytics, and IoT technologies to enhance visibility, efficiency, and resilience.
- Cohesive & Resilient Supply Chain Network: Resilience is a fundamental aspect of modern supply chains. This competency level reflects SMEs' adeptness at building cohesive and resilient supply chain networks that can withstand disruptions, whether due to market fluctuations, geopolitical factors, or unforeseen events.

These competencies go beyond the traditional understanding of supply chain management. In the age of MAM, the supply chain must be intelligent, adaptive, and interconnected (Maryniak and Bulhakova 2020). The "Supply Chain" pillar equips SMEs with the skills needed to navigate the complexities of MAM adoption, ensuring that their supply chain is not just a logistical operation but a strategic asset. These levels empower SMEs to secure, optimize, and adapt their supply chain for demands of MAM, enhancing their readiness in a dynamic and competitive industrial landscape.

As a case example of the necessity of the added pillars, consider the case of Stryker, a leader in the application of MAM to healthcare and other domains (Epperson 2021). Stryker engages in close collaboration with healthcare professionals in order to most closely integrate additive manufacturing in the healthcare context. In these circumstances, this integration is the core driver of competitive success for Stryker. As such, these involvements draw heavily upon the levels of competency outlined in the two new pillars (personnel and supply chain) of the MAM readiness model. In the context of Stryker, the original readiness model as proposed by the literature is insufficient to characterize MAM adoption. Thereby, this necessitates the urgency for a model of higher resolution such as the one this research provides.

## 4. Areas of Future Research

The research paper's exploration and expansion of a MAM readiness model to encompass the dimensions of personnel and supply chain highlights a plethora of opportunities for future research that can advance our understanding and provide SMEs with enhanced tools for adopting MAM technologies. Widespread research (Khorram Niaki and Nonino 2017) points to extensive opportunities for enhanced MAM domain development and understanding. Notably, the emergent outcomes of the SLR conducted here also lead to unique opportunities for future research endeavors. Accordingly, these future research areas span from experimental studies to comprehensive modeling approaches:

- Quantitative Analysis of Competency Levels: Future research can delve deeper into each of the competency levels within the expanded MAM readiness model. Quantitative studies can be conducted to establish

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benchmark levels of competence across various industries and SME sizes. This will help SMEs gauge their readiness more accurately and offer insights into industry-specific variations.

- Machine Learning for Readiness Prediction: Applying machine learning algorithms to MAM readiness assessment can enable predictive modeling. By analyzing historical data on MAM adoption in SMEs, algorithms can predict readiness levels and highlight areas that require immediate attention. This approach can help SMEs be proactive in their adoption strategies.
- Scenario-Based Readiness Assessments: Developing scenario-based readiness assessments can provide SMEs with insights into their preparedness for specific MAM applications or market situations. By simulating scenarios, SMEs can identify potential challenges and opportunities, allowing them to fine-tune their readiness strategies.

Future research in these areas can enhance the MAM readiness landscape for SMEs, facilitating their successful adoption of these transformative technologies. By addressing these aspects comprehensively, the research community can contribute to the evolution of readiness models and the advancement of MAM adoption, ensuring that SMEs remain competitive and sustainable in an ever-changing industrial environment.

## 5. Concluding Remarks

In conclusion, this research has journeyed through a comprehensive exploration of MAM readiness, addressing the complex and multifaceted nature of this transformative technology. MAM offers unprecedented design freedom and the potential to revolutionize manufacturing by producing intricate, high-value components. However, the path to MAM adoption is fraught with challenges, particularly for SMEs. This paper's systematic and thorough examination, as well as the expansion of the existing MAM readiness model, contributes significantly to the understanding of MAM readiness and offers valuable insights for SMEs and the broader industrial landscape. The SLR of 71 high-profile publications has been instrumental in broadening our comprehension of MAM readiness. Through this meticulous analysis, we have unveiled nuanced competency levels that go beyond the surface of readiness assessment, allowing for more strategic planning and resource allocation. The newly enriched MAM readiness model we present here reflects the complex reality of MAM adoption, accounting for diverse competencies necessary for success.

Our journey through the seven pillars - Production, Material, Construction, Business Model, Market, Personnel, and Supply Chain - each with seven levels of competency, has emphasized the interplay of various aspects in MAM readiness. Production incorporates not only the technical aspects but also the knowledge and integration needed. Material highlights the significance of supply chain considerations, fostering an ecosystem that enables MAM success. Construction integrates the intricate nature of CAD/FEA with dynamic workflows. The Business Model pillar emphasizes the strategic planning required for a successful MAM venture. Market underscores the importance of real-time analytics and e-commerce networks. Personnel illuminates the role of human resources and their strategic allocation. Supply Chain accentuates the need for a dynamic, resilient, and intelligent supply network.

In essence, the journey through MAM readiness assessment is one of comprehensive understanding, meticulous analysis, and strategic insight. It is a testament to the significance of MAM as a transformative technology, and the importance of readiness models to guide organizations (Sharretts 2020), particularly SMEs, in their pursuit of MAM adoption. This research contributes to the evolution of readiness models and, by extension, to advancement of MAM adoption, positioning organizations to thrive in the dynamic and competitive landscape of advanced manufacturing.

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