A Readiness Model for Facilitating the Implementation of Metal Additive Manufacturing at SMEs

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***Abstract*—SMEs constitute the backbone of the global economy possessing a vital role in future economic prosperity. Today, with the increasing competition due to globalization of markets and mass customization, as well as the increasing focus on green shift and sustainability, the need to take advantage of new technological innovations has never been more prominent. Metal Additive Manufacturing (MAM) is one of these technologies that can game-change the current manufacturing industry. MAM, compared with the traditional production method, which depends on the final assembly of stepwise manufactured parts, provides a 'one-stop shop' from idea to end product underpinned by its unparalleled capability of comprehensive design and thereafter a significantly shortened supply chain. However, despite the obvious economic and competitive advantages of applying MAM, it seems SMEs are reluctant to adopt the technology. This paper starts with a literature review on additive manufacturing (AM) and MAM with the purpose of providing common ground for understanding the technologies and their potential value proposition for SMEs. The authors go further to discuss challenges for SMEs' adoption of MAM. A readiness model is finally provided to facilitate SMEs' self-evaluation for the purpose of preparing the uptaking of MAM. The authors have also offered some insights from businesses in the Kolarctic region.**

***Index Terms*—Metal additive manufacturing, sustainability, Kolarctic region, SMEs, readiness model**

I. INTRODUCTION

SMEs are seen as the main actors of both national and regional development in many countries. The importance of SMEs is well recognized globally due to its significant socio-economic contribution, vital for enhancing innovation, competitiveness and entrepreneurship in developing countries [1]. Statistics from World Trade Organisation (WTO) reveal that SMEs represent 90% of businesses and more than 60-70% of employment as well as accounting for 55% of GDP in developed economies [2]. With the increasing globalization of markets and operations as well as rapid industrial development, the competition has become extremely fierce in recent years [3]. Moreover, the increasing concerns towards global environmental and climate challenges urge businesses, in general, to become more sustainable by incorporating greener and more social-responsible strategies in their activities.

Technological innovations are essential for sustainable development [4]. Freeman [5] indicates that the innovation capability forms a major source of competitive advantage. For SMEs, their innovation capability can be manifested as the ability to adopt the latest technological advancement. A company's level of technological adoption is normally in proportion with its level of competitiveness. This is especially legitimate in the current transformation from Industry 4.0 to Industry 5.0 as the transformation expects that, not only the adoption of Industry 4.0 technologies contributes to largely increasing economic sustainability and therefore competitiveness, but all the improvement brought by the technological uptake also need to center around humanity, sustainability and resilience. With the position SMEs in global economy, it is undoubtedly crucial for any nation that its SMEs can effectively benefit from technological advancement for the purpose of sustainability and prosperity.

Leveraging sustainability can be especially difficult for SMEs due to their limited capital, competencies, and access to relevant network [6]. Numerous studies have evidenced that SMEs are reluctant to take up technological advancements. Many upfront technologies are still untapped by SMEs, especially those with the greatest potential for business transformation [7].

Metal Additive Manufacturing (MAM) is one of these technological advancements that have seen a significant rise in interest in recent years. It is asserted that MAM has a profound impact on businesses and has been associated with potentially strong stimuli for revenues and cost-saving [8]. Especially for SMEs, as they have the capability to transform themselves into direct digital supercenters [9]. However, implementing and fully benefiting from MAM techniques are challenging for businesses to manage and are a topic that is widely discussed within the scientific community. Several empirical studies demonstrate the difficulties of changing one core technology to another [10] [11] [12], and although companies have already embraced and invested in MAM [13] most of these are associated with niche uses in sectors such as aerospace [14], automobile [15], and medical [16].

As MAM has the potential to completely revolutionize the future of production [17], it deems essential that SMEs are provided with the necessary tools and clear instructions for facilitating their journey in adopting MAM.

The rest of this paper is structured as follows. Section II presents an overview of additive manufacturing (AM) and particularly MAM, for the purpose of understanding the technology. This also aims to uncover the limitations, and the potential value MAM offer SMEs. Section III presents an analysis of existing studies on the implementation of MAM. In section IV, the authors suggest a readiness model for SMEs to evaluate their premise on their path towards MAM implementation. Section V showcases MAM adoption in the Kolarctic region based on interviews conducted at the Kolarctic manufacturing industry. Finally, section VI concludes and suggests possible further research topics.

II. An overview of Additive Manufacturing

AM is the formalized term of what used to be called rapid prototyping (RP), and is more commonly known as three-dimensional (3D) printing. A commonly accepted definition was provided by the American Society for Testing and Materials (ASTM) as ”a manufacturing process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies” (ISO/ASTM 52900:2021 standard) [18].

AM was first introduced by Charles Hullin in 1984 with the concept of stereolithography (SLA) [19] which was primarily focused on rapid prototyping of plastic fabrications. After over 30 years of development, AM has gained its prominence among users. The growing popularity is mostly in recognition of the increased availability of 3D printers with significantly reduced costs and wider accessibility of associated technologies (i.e., design software, 3D scanners internet, etc.) [20]. One evidence of this prominence is its exponential increasing awareness among users catalyzed by the COVID pandemic in an attempt to enhance company resilience and address supply chain vulnerabilities [21].

AM represents a large portfolio of technologies and processes. These are categorized and defined by ASTM (ISO/ASTM 52900:2021) in seven classifications, based on machine architecture and material transformation physics [18]. They are powder bed fusion (PBF), sheet lamination (LOM), material extrusion, material jetting (MJ), binder jetting (BJ), directed energy deposition (DED), and VAT polymerization (expansion of SLA). Each differentiates by its array of approaches, applications, printers, and available materials. Despite the differences, all AM technologies use the same basic principle of using a CAD model to fabricate a 3D model layer-wise by fusing materials.

A generalized process chain can be defined for all processes. Gibson et al. [22] identified eight key steps transferable to most AM processes:

- Conceptualization and CAD
- Conversion to STL
- File transfer to machine
- Machine Setup
- Build
- Removal
- Post-Processing
- Application

The process chain covers several aspects, from the need for appropriate materials [23] to a proper understanding of the design process [24]. The process can be complex with an increasing number of AM technologies and variants, and different products often call for different ways of utilizing AM. These processes can also change as technologies develop or new technologies emerge to substitute [25].

A. Metal additive manufacturing

Metal additive manufacturing (MAM) is conceptually similar to other AM methods [22]. It takes the AM principle and employs it exclusively on metals. According to published data by Cherdo [26] the most popular metal processes available today is PBF, material extrusion, DED, and BJ/MJ. As shown in Figure 1, VAT polymerization and sheet lamination also occupied a minor fraction of the market.

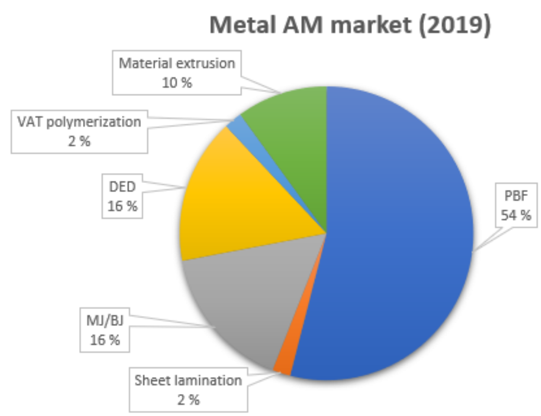

Fig. 1: Metal AM market 2019 [26]

According to Figure 1, PBF is by far the most applied MAM process and dominates 54% of the global metal market [26]. PBF can manufacture intricate parts with complex geometrical properties compared to traditional manufacturing techniques [22]. However, the printing speed is relatively slow, and the investment cost is high. Consequently, integration can mostly be found in high-value product for niche markets where lightweight, complexity, and customization are crucial to even out the expense associate with its application [27]. Benefits that today are often seen realized in sectors such as aerospace and defense, healthcare and automotive sectors.

BJ, DED, and material extrusion processes all occupy a smaller part of the market. However, there are rapid developments in these fields. For instance, it is expected that BJ to join PBF in the coming years, potentially surpass it in the next decade [28] for being more suitable for larger volume production [29] and potentially being more cost-effective than other MAM processes [30].

B. MAM benefits

The various MAM processes possess a wide array of advantages and benefits over traditional production methods (forming, casting, cutting). While conventional production methodologies are limited by production run size, complexity, and often sees high production cost and production methods that rarely comply with sustainable manufacturing (recycling, contamination) [31]. MAM offers an entirely new paradigm for engineering design and manufacturing [32] providing a substantial competitive advantage through greater design freedom [33] [31], cost savings, and a shorter product life cycle [34]. The increased attention to sustainable benefits complemented by environmental regulations also acts as a catalyst for the increased use of MAM [35] [36].

III. Previous studies

Despite the obvious benefits of utilizing MAM, significant effort is still required in order for SMEs to integrate MAM into their existing system [37]. Today, still many SMEs fail to incorporate MAM into their manufacturing system. Take, Northern Scandinavia, as an example, currently, there are hardly any SMEs that have managed to use MAM as their business advantage, nor do they include MAM as their core competence.

While the barriers towards SMEs adoption are quite varied, a majority of SMEs are struggling with the uncertainties associated with MAM. For this reason, it is vital to understand the current landscape and unveil gaps in the literature related to the implementation of MAM.

Ruffo, Tuck, and Hague [38] described three specific areas in which firms might face challenges when looking towards adopting AM.

- Manufacturing processes and materials
- Design
- Management, organization, and implementation

Saberi [39] proposed in 2010 a framework that managers and investors could use to increase the performance of the AM implementation process. The aim was to provide an overview of issues related to the successful implementation. Within their study, they group issues related to implementation into three groups. Technological, organizational, and external/internal. Further work has been carried out by Mellor, Hao, and Zhang [40] in 2014. They created and tested a conceptual framework of important characteristics that might influence companies' journey towards AM implementation. This framework was explicitly created for AM adoption and consisted of five factors: strategic factors, technological factors, organizational factors, operational factors, and supply chain factors. The framework gives vital insight into key implementation areas that should be understood by firms willing to embark on the AM journey. However, the framework has some shortcomings, as suggested by Deradjat and Minshall [41]. It is quite generalized (does not account for technical factors) and fails to include the interdependencies between the various variables.

Martinsuo [42] reviewed previous studies on barriers and challenges towards SMEs implementation of AM and provided a framework for categorizing and finding ways to overcome these challenges based on an interview survey. They identified and categorized 33 challenges into six groups, technology-related, strategy, supply chain-related, operational, organizational, and external challenges. According to their review, the challenges of AM implementation vary significantly from literature to literature. Moreover, SMEs' challenges seem to differ according to their supply chain position. Consequently, they underline the operative and strategic challenges as the key where more extensive AM adoption only are accomplishable when the broader supply chain adopts AM.

Another example is a decision support framework developed by Harry [43] in 2019 to help evaluate and select the optimal AM process category. Their framework consisted of three levels. Level 1 describes a probability model of whether companies should consider using AM or not. Level 2 included the selection of the appropriate AM processes. Level 3 includes process planning for hybrid manufacturing if AM alone is unsuitable for the users' operations. Harry's [43] decision framework relates heavily to whether a product can be manufactured using AM or not. In other terms, it mostly covers the technological factor as mentioned in Mellors [40] conceptual framework.

There are also studies with the aspiration to provide firms with specific tools to help adopt AM. For instance, Mahadik [44] provided a cost estimation tool for evaluating the cost of producing using AM. A tool that helps in the selection of appropriate AM process considering time and cost constraints.

Another example is a readiness model developed by Timothy Simpson [45]. The model was created to help firms better understand their readiness in AM. This model focuses on four pillars. Materials, design, people, and machines. This model only covers a small area of AM adoption and fails to incorporate many of the areas as identified in frameworks by Saberi, Mellor, and Martinsuo.

As seen, several studies have explored barriers and provided tools and frameworks for facilitating the increased implementation of AM. Although the previous studies give valuable insight and contribute to increasing the knowledge of MAM implementation, it seems firms easily get lost in all the available and different literature and still find themselves reluctant or unable to adopt the technology. Moreover, it seems no works connect the generalized overview from the frameworks with specific models and tools developed by various authors. Nor does it give SMEs a tailored idea of their existing strengths and weaknesses in terms of MAM.

Most of the identified studies focus on AM and companies without explicitly targeting MAM or SMEs. They offer vital insight towards understanding AM adoption and are, to some degree, transferable to SMEs looking towards MAM. However, there are still fundamental differences between SMEs and LEs. According to Martinsuo [42], it is precise because most literature on AM implementation is not specifically focused on SMEs that AM is so poorly understood in these firms.

They further state that the limited resource, experience related to technological innovations, and supply chain position of the firms differentiates SMEs from their larger counterparts.

For example, SMEs neither have the financial capabilities nor the human resources to invest in MAM activities that involve R&D or development programs, unlike LEs. SMEs innovative activities and problem-solving link directly to their production process [46]. Essentially meaning, their implementation and development would involve their current production. thus, the implementation procedures will be different.

A. Integrating MAM in SMEs

It is an undisputed fact that manufacturing SMEs are facing many challenges in their daily operations. From the lack of skilled personnel, scarcity of raw material, lack of infrastructure, limited access to finance, and low R&D expenditures [47] [48]. Still, SMEs occupy several niche characteristics that make them excellent candidates for more widespread use of MAM. Characteristics that in combination with MAM, can contribute to solving many of these challenges.

- SMEs tend to be more flexible with less bureaucracy than LEs that enable a quick change over from one technology to another.
- MAM is well suited for SMEs smaller workforce, as design changes and manufacturing of an entire product can easily be done by only one person [48].
- SMEs typically have limited resources, and by incorporating MAM the production process can become more resource-efficient (less material waste) [34].
- SMEs production is typically focused on high-mix low-volume manufacturing and is often performed by using traditional production methods such as CNC machines. However, with the customization and flexibility offered by MAM these systems can potentially be improved.

IV. MAM READINESS MODEL

On the basis of the previous literature we propose a redefined readiness model. Not only to aid SMEs in their journey towards MAM adoption but also to offer SMEs a tool to self-evaluate their strengths and weaknesses for preparing MAM uptake.

The proposed readiness model is inspired by the work of Timothy Simpson [45]. It uses the basic principle from the frameworks developed by Saberi [39], Mellor [40], and Martinsuo [42]. It incorporates technical factors, suggested by Deridjat [49] to be critical when working with AM. Insight from an interview survey with the Kolartic manufacturing industries is also incorporated to create a specifically tailored route for firms within each of these elements in one model. Moreover, the model targets specifically SMEs and on answering whether these firms are mature enough to embark on the journey of adopting AM.

Fig. 2 presents the proposed readiness model. It consist of five pillars:

1) Production (see table I)
2) Materials (see table II)
3) Construction (see table III)
4) Business model (see table IV)
5) Market (see table V)

The model heavily leans towards the technical side of MAM both due to the importance of understanding the MAM process [41] and the limited awareness and competence of MAM within SMEs today. The production pillar (see table I) covers the production methodology, type of printer, and process qualification. The material pillar (see table II) covers the material selection, including the shape, composition, mechanical and chemical properties [22]. The construction pillar (see table III) covers the processes connected to the creation of the part (AM process chain as presented by Gibson [22]).

The business model/management pillar (see table IV) incorporates the organizational, strategic, operational, and supply chain aspects highlighted in various AM implementation frameworks. For the adopting organization to gain a competitive advantage from implementing MAM, linking the technology benefits to the business strategy is essential. However, it is equally important that the SMEs understand the trade-offs in using new manufacturing technology. Frazier [50] states that ultimately, it is the business case assessment that will determine the success of AM. Because of the rapid technological growth, research on business model development has been unable to keep up [51] [52] [53]. As a result, knowledge on the impact and challenges the technology has on business models are still incipient [51], and companies that require guidance in business model innovation lack the needed literature to leverage the potential of MAM (E.g., through benchmarking or evaluation processes).

Lastly, the market pillar (see table V). Highlighted as necessary through previous implementation frameworks, but also unveiled from the interview survey with the Kolarctic manufacturing industry (presented in section: V) as one of the most important factors for SMEs considering MAM adoption.

The model is further divided into five levels. The levels are inspired by the Capability Maturity Model Integration (CMMI) developed by the ”Software Engineering Institute” [54] that compromise of the following five steps:

- Initial - Processes are usually ad hoc and chaotic.
- Managed - The projects have ensured that processes are planned and executed in accordance with policy
- Defined - Processes are well characterized and understood and are described in standards, procedures, tools, and methods.
- Quantitatively managed - The organization and projects establish quantitative objectives for quality and process performance and use them as criteria in managing projects.
- Optimized - The organization continually improves its processes based on a quantitative understanding of its business objectives and performance needs.

Although the CMMI act as the starting point for the new readiness model, it is specifically tailored to the different pillars of MAM. The first level is general knowledge of

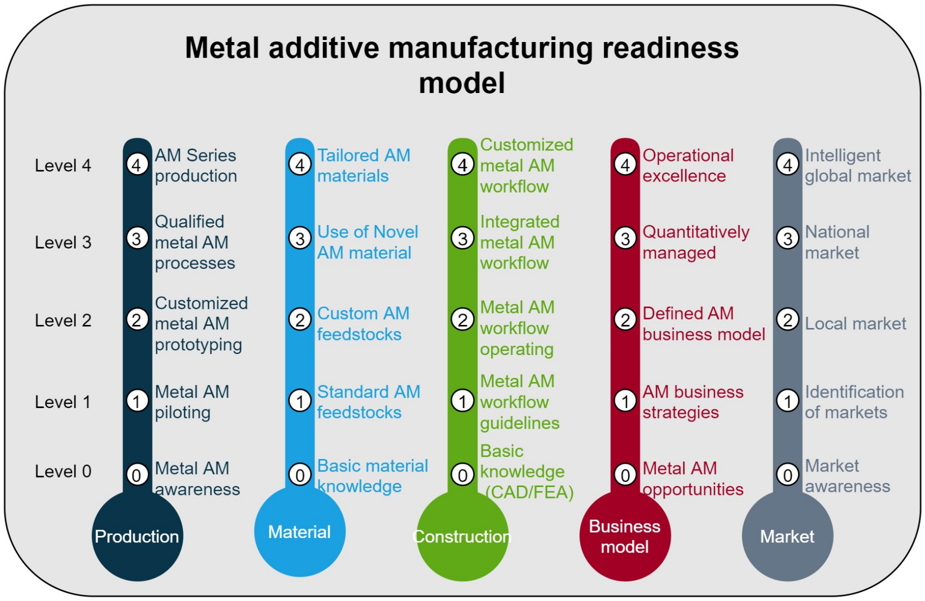

Fig. 2: MAM readiness model

the technology and the minimum requirement for considering MAM implementation. The subsequent levels gradually build towards the final level, which is a fully optimized industrialized implementation.

The readiness model is specifically tailored to MAM technology and the company's needs. Under normal circumstances, the companies should be on the same level in the different pillars to ensure successful implementation. Level 1 is the lowest level for actual implementation, and level 4 is fully integrated MAM implementation. The first step for the company is to identify its current position on the scale. Then, depending on the goal and ambition, they should analyze what they want to achieve with the technology and choose their path on the model in their planning phase. For most, the adoption should be gradual, starting with pilot projects. Then, depending on the success rate and experience, further adoption and climbing the scale are achievable. SMEs' limited resources often hinder them from specializing in all MAM fields. In most cases, SMEs require outsourcing various services (e.g., printer technology, material, design, etc.). Thus, staying on different levels is more applicable for companies pursuing MAM adoption success.

V. Insight from the Kolarctic manufacturing industry

An explorative qualitative research approach was used to explore the potential impact of MAM and to obtain a deeper understanding of the state-of-art from a company perspective. In total, 11 in-depth interviews were conducted with the industries in the Kolarctic regions. The Kolarctic region consists of the circumpolar regions of Norway, Sweden, Finland, and Russia. The Kolarctic region was chosen as a representative area. To our knowledge, no commercialized MAM solutions have successfully been implemented in the region and it is of interest to see how the technology can affect and change the production processes as well as determine the limiting factors hindering a wide-spread MAM adoption. The region also acts as an excellent representation due to the limited awareness of the technology and being an area financially very risky [55].

TABLE I: Production pillar

Pillar	*Definitions*
0	Awareness of MAM techniques (BJ, PBF, MJ, etc). General knowledge of advantages/disadvantages.
1	MAM piloting. Testing MAM production before more widespread adoption.
2	Customized MAM processes (prototyping).
3	MAM operating at a certain standard during sustained commercial manufacturing.
4	Mass customization. An advanced system combining the low cost of mass production with the flexibility of individual customization.

TABLE II: Material pillar

Pillar	*Definitions*
0	Basic material knowledge.
1	General material knowledge of various materials that can be used in MAM processes (powders, wires).
2	Custom MAM materials. More detailed knowledge of material properties, and understanding of how material properties can be affected. (e.g., production, process variations, post-processing).
3	Advanced material knowledge: Understanding which materials to use for which processes, and how to alter material properties.
4	Tailored AM materials. Understanding how the material can be tailored to the print, and printer technology (e.g. what material should be used and under what circumstance and environment).

TABLE III: Construction pillar

Pillar	*Definitions*
0	Basic knowledge of the MAM workflow and elements within. Should be familiar with computer-aided design (CAD) and finite element analysis (FEA).
1	MAM workflow guidelines. At this level, the firm understands the steps required for constructing MAM products.
2	MAM workflow operation. At this level, the steps are understood, but can also be operated by personnel without assistance.
3	Integrated MAM workflow. At this level, the firm is able to recognize product improvement opportunities based on printing technology such as redesigning for improved functionality, waste reduction, and potentially faster lead times.
4	Customized MAM workflow: Optimized MAM workflow. All the steps are operated and understood by the operators. They can easily design, produce, and deliver MAM parts.

TABLE IV: Business model pillar

Pillar	*Definitions*
0	MAM opportunities. The firm should be aware of the business opportunities MAM can offer (reduced lead time, reduced waste, cost-effectiveness)
1	MAM business strategies. At this level, the firm understands how MAM can affect its existing business model (will MAM redefine or streamline its existing production? in-house vs outsourcing, cost analysis for MAM, etc).
2	Defined MAM business model. At this level, the business model should be defined based on knowledge developed in the first pillars. The business model should also be redefined accounting for changes in supply routes.
3	Quantitatively managed. At this level, the firm has established quantitative objectives for quality and process performance and uses them as criteria for managing projects.
4	Optimized - Operational excellence, a fully redefined business model optimized for customers. At this level, the firm continuously adopts and improves according to changes in technology, market, and customers' needs. Often utilizing continuous improvement strategies such as lean, six sigma, and scientific management.

TABLE V: Market pillar

Pillar	*Definitions*
0	Market awareness. Obvious industry trends, emerging trends, relationships between elements in the market, and how to create new markets and customers.
1	Identification of market. General understanding of the MAM market and potential markets applicable for the firms products.
2	Local market should be established applicable for the industry sector. Market analysis should have been conducted, and customers be onboard.
3	National market. A network should exist at this stage.
4	Intelligent global market. The firm should have a full overview of the MAM market. They should know exactly where the potential is and utilize it. Firms should be active globally, deliver to a global network, and participate in global AM networks.

A. *Sampling procedure*

The sampling procedure used was criterion sampling. We sought interview objects that either had prior experience or minimally had a basic understanding of the MAM technology, as well as ties to the Kolarctic regions. Thus, two criteria were defined for the selection of the interview objects.

1) Industries of companies with ties to the Kolarctic region.
2) Industries or companies with prior ties or minimally a basic understanding of the AM technology.

The sample was homogeneous in terms of choosing participants that face similar challenges while adopting new technological innovations. The purpose was to gain as much insight as possible related to the adoption challenges of MAM within the Kolarctic.

B. *Interview procedure*

The interviews were semi-structured and the questions were divided into three categories. Generic questions about the company, company-centered questions related to their adoption of MAM, and questions related to the general outlook of MAM. The interviews included eight SMEs, two business associations, and one large enterprise. The interviews lasted about one hour and were carried out digitally and face-to-face. The interviews were held by different persons in Norway, Sweden, Finland, and Russia. Prior to the data processing, all identifying information was removed. The interviews were carried out in collaboration with the "From idea to printing of metal product" (I2P) project under the Kolarctic CBC programme.

C. *Data analysis*

This study utilized qualitative content analysis in order to identify common themes from the interviews. The first step following the interviews included reading and familiarizing ourselves to the data. This was followed by coding of the data which was used to identify themes over the various interviews.

The two categories relevant for the data analysis was:

- Drivers for implementation.
- Barriers and challenges for adopting MAM within the companies.

D. *Result data*

The results indicate how the industry perceives MAM both within their operations, and in their respective industries and markets. All together four themes for drivers were identified. Technological opportunities, environmental opportunities, economical potential and strategic benefits such as shortening of supply chains, building larger networks and new markets. Six themes for barriers were identified. Lacking competence, deficient awareness of opportunities (both within companies and among customers), financial challenges related to high costs of adoption, an unfamiliar market, technological barriers related to the maturity of MAM, and finally organizational culture. Companies seem resistant to change. As an example, one participant mentioned that traditional industries have challenges to adopt new operating culture.

E. Discussion

All subjects show a general understanding of MAM and can understand the technology's potential. However, the MAM technique is currently out of reach for most companies. There is a common consensus that the lack of awareness, competence, and the market is a key challenge hindering further adoption. Additionally, barriers such as high costs, technology immaturity, high uncertainty, and difficulties in changing organizational culture are also highlighted. Even with the ambition and will to adapt, businesses lack the tools to effectively benefit from MAM.

VI. Conclusion and further work

MAM is undoubtedly an important technology with profound business potential, especially for SMEs with the increased global competition and the need to stay up to date with innovations. MAM has significantly grown the recent years and is not expected to slow down. Despite MAM's growth and apparent advantages, it is still difficult for SMEs to benefit from the technology entirely. Therefore, this paper's focus has been on understanding the potential value proposition of MAM for SMEs and identifying the challenges that lie in the implementation of MAM for SMEs.

Throughout the literature, the benefits of MAM remain clear, but despite significant effort through years of work, MAM remains unexploited for most SMEs. Most research investigating MAM implementation has not explicitly targeted SMEs. Moreover, the MAM implementation procedures will differ in SMEs compared to LEs due to their limited resources, lack of technological expertise, and supply chain position.

The authors presented the results of an interview survey with the Kolarctic regions to gain further insight into how MAM could affect SMEs. Based on the insight from these interviews and the reviewed literature, the author presents a framework for a MAM readiness model to guide SMEs toward implementing MAM into their operations. The model is composed of five pillars (production, material, construction, business model, and market) and five levels. Each level in the readiness model currently defines an essential subset of the organizations' processes.

At the current stage, the different pillars in the readiness model are still at a general level, and further detail still needs to be added to each level. Each level on the readiness model should be measurable and have specific and generic goals associated with each predefined process area. The representation should provide a path of improvement from level 1 to level 4, with each level encompassing specific goals that need completion before advancing.

Acknowledgment

This paper and research is co-funded by the Kolarctic CBC Programme in collaboration with the project I2P (From idea to printing of metal products).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 825196.

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