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Laurent Terrenoir, Laura Laguna Salvadó, Julie Lartigau, Arun Arjunan, Christophe Merlo. A maturity assessment model for metal additive manufacturing: additive manufacturing readiness levels. *International Journal of Production Research*, 2025, pp.1-18. <10.1080/00207543.2025.2571203>. <hal-05362815>

**HAL Id: hal-05362815**

**<https://hal.science/hal-05362815v1>**

Submitted on 3 Dec 2025

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**A maturity assessment model for metal additive manufacturing:  
Additive Manufacturing Readiness Levels**

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# **A maturity assessment model for metal additive manufacturing: Additive Manufacturing Readiness Levels**

Despite many promises, Metal Additive Manufacturing (MAM) adoption is still limited within industry. To effectively and successfully implement MAM, companies need to assess their maturity status quo, combined to the MAM technology maturity, at both organisational and operational levels. However, existing maturity models (MMs) are either only dedicated to just one of these levels or are not adapted to MAM. Thus, this paper proposes an original and tailored MM: the Additive Manufacturing Readiness Levels (AMRL), a multicriteria MM to evaluate the maturity of a MAM technology coupled with a use case, offering a context-aware approach that bridges technological capability and operational applicability. The model features 8 dimensions, divided on twenty-two sub-items to be assessed, referring to Industry 5.0 pillars including environmental and social considerations. To develop and validate the proposal, an iterative methodology is followed where the AMRL is applied to compare the maturity of three Directed Energy Deposition technologies coupled with nine use cases in the context of a French Technology Transfer Centre. Direct interviews with experts and measure of agreements granted validation. AMRL aims to contribute to the adoption of MAM by assisting decision makers. Future research could investigate its use on different industry sectors and decision configurations.

Keywords: maturity assessment, metal additive manufacturing, technology readiness level, adoption of AM, sustainable AM

## **1. Introduction**

Metal additive manufacturing (MAM) revenues, which currently stands at around 3 billion euros, are projected to grow steadily of approximately 26% over the next five years according to the 2025 AMPOWER report (Consultancy AMPOWER, 2025). To support its development and broader adoption at industrial level, policy makers encourage the developments of standards, qualification and certification processes, as well as sustainability evaluation frameworks. For instance, the European Commission, through the Horizon 2020, Horizon Europe and FP7 programs, from 2007 to 2023, financed

hundreds of research projects over a total of 887 million of euros to support the development of Additive Manufacturing<sup>1</sup> (AM). Recently, the European Commission shed the light on identifying the barriers and providing guidance for industry and small and medium enterprises (European Commission, 2020) as MAM show great positive potential for manufacturing companies to contribute to the transition to Industry 5.0 over the entire supply chain (Ford and Despeisse, 2016; Machado, Despeisse, *et al.*, 2019). For instance, it allows to reduce the consumption of critical raw materials (Chatterjee *et al.*, 2023), to relocate the production, and to be more responsive (Ivanov *et al.*, 2019; Kunovjanek and Reiner, 2020). Moreover, MAM appear to offer a means of enhancing the resilience, sustainability, and human-centricity dimensions, pillars of Industry 5.0 as stated by Ivanov (2023). Overall, MAM can support designing circular business models in metal processing industry, as it allows to extend product durability (Despeisse and Acerbi, 2022), to reduce wastes, and to favour the recyclability of parts (Devito *et al.*, 2024).

But despite their potential and the actions launched by policy makers to support their adoption, these processes are still not widely used on an industrial scale as it is still unclear when it is truly convenient to adopt AM (Jarrar *et al.*, 2023). In fact, the industrial development of these processes is hindered by the multitude of available technologies and materials, as well as the specificity of application cases (Dass and Moridi, 2019).

In literature, technology selection models have been developed either specifically for MAM or AM in general. Manco *et al.* (2019) analysed technology selection models for AM described in the literature and found that most models use production cost as the

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<sup>1</sup> [European Advanced Manufacturing Monitor](#)

primary criterion for technology selection (Achillas *et al.*, 2017; Baumers *et al.*, 2016). Other authors have based the choice of AM technology on energy consumption (Watson and Taminger, 2018) or multicriteria indicators such as a complexity index of the parts to be manufactured (depending on their geometry, number, variety, and the specificities of the manufacturing technology used) (Fera *et al.*, 2018). Moreover, decision support methods such as the Analytic Hierarchy Process (AHP) have been employed to rank the best AM technologies for manufacturing a given component. Mançanares *et al.* (2015) used AHP considering criteria such as production time, surface quality, accuracy, manufacturing cost, required post-processing operations, shock resistance, and flexural strength of the fabricated material. Zaman *et al.* (2018) developed a decision-making model using AHP to select a material and a MAM technology for a given use case based on criteria related to the material (mechanical characteristics, purchase cost, and environmental impact) and the machine (accuracy, manufacturing dimensions, achievable geometric complexity, productivity, and usage cost). These models provide technology selection frameworks based on a comprehensive understanding of the part specifications to be manufactured, i.e., the 'use case' to be implemented. But they lack to consider the maturity of the MAM process to be integrated, in the framework of Industry 5.0.

The concept of maturity highlights and quantifies the progress made by an organisation or an industrial system regarding a set of dimensions related to its economic and operational functions (Haug *et al.*, 2022). The integration of AM has been determined as a factor of organisational maturity in the context of Industry 4.0 through Maturity Models (MMs) as IMPULS and PWC (Bibby and Dehe, 2018). Several MMs address the maturity of companies and organizations within Industry 4.0 regarding the integration of innovative processes (Ansari *et al.*, 2023; Gökalp *et al.*, 2017; Lassnig *et al.*, 2018;

Machado, Winroth, *et al.*, 2019; Schumacher *et al.*, 2016) but non focuses on the maturity of the process itself. Acerbi *et al.* proposed a MM enhancing data-driven circular manufacturing, aiming at assessing the maturity of companies in exploiting data to use digital technologies and implement circular and sustainable strategies (Acerbi *et al.*, 2024). Regarding the adoption of technologies in the framework of Industry 5.0, the DREAMY framework has been designed to assess the maturity of companies in employing digital technologies (Carolis *et al.*, 2025). These relevant MM have set solid basis for the development of MM in the framework of Industry 5.0.

The maturity of a technology can be illustrated by its evolution through the technology life cycle, represented in Figure 1 (Reinhart and Schindler, 2012). The less mature a technology is, the greater the potential and risks associated with its integration.

**Figure 1 here**

Integrating immature technologies into a manufacturing process may entail various risks, including cost and time overruns, as well as a decline in process performance and product quality (Nolte, 2008). On the other side, incorporating significantly developed technologies (in decline) may prove disadvantageous.

Maturity assessment allows to identify barriers to target to develop the process. The maturity level of a technology in a specific process context is critical regarding its development and integration within this context (Rodríguez Salvador *et al.*, 2019).

Regarding MAM, a low maturity associated to a given technology can be an obstacle to the achievement of reliable performance and an impediment to its adoption by industry (Ford and Despeisse, 2016). Moreover, the various MAM processes exhibit varying levels of industrial maturity dictating their complexity of implementation (Ahn, 2021). Therefore, to help industrials selecting a MAM technology to integrate in their manufacturing process, the maturity of these processes must be considered. Thus, this

paper focuses on the research question:

**‘How to assess the maturity of metal additive manufacturing processes to support their industrial integration in the framework of Industry 5.0?’**

To answer it, the remainder of this paper is organised as follow. Section 2 deals with the limits and opportunities of existing maturity assessment models and their applications to AM and MAM in the research context. Section 3 describes the methodology used for the development of a specific MM. Section 4 presents the developed MM for MAM. The application, validation and the overall contribution of the proposed model are discussed in section 5. Finally, a conclusion and the perspectives of this work are presented in section 6.

## **2. Research context**

A model for assessing maturity can be described as a set of dimensions for measuring the level of maturity of an organisation's strategic and operational processes (Schumacher *et al.*, 2016). Various models have been developed in literature, some of them focused on manufacturing processes, or specifically designed to AM and MAM. They are explored in this section.

### ***2.1 Maturity models for manufacturing processes***

#### ***2.1.1 Technology Readiness Levels (TRL)***

The most well-known scale for evaluating the maturity level of technologies in both industry and literature is the TRL (US Government Accountability Office, 2016). This scale assesses the maturity of a technology on nine levels, from the initial research stages to its validation through successful industry use (Department of Defense of the United States of America, 2020). TRL assessment has been integrated in a comparison study

focused on MAM in the aerospace industry (Gradl *et al.*, 2022). The authors determined TRL up to 6 for Directed Energy Deposition (DED) technologies. The main obstacle to use TRL is that technological maturity is insufficient for evaluating the maturity of a manufacturing process (Olechowski *et al.*, 2020). Factors, such as material availability, manufacturing process development, and workforce skills, must also be considered (Department of Defense of the United States of America, 2020; Wu *et al.*, 2017). Moreover, it has been noted that TRLs are evaluated based on the evaluator's interpretation and the scope of the study, resulting in different evaluations for the same technology (Peters *et al.*, 2017).

### 2.1.2 *BIMATEM*

To address the need for expert input, a quantitative bibliographic assessment method called BIMATEM has been developed to determine a TRL from literature data (Lezama-Nicolás *et al.*, 2018). It correlates a technology's TRL to research papers and patents published. It has been used to assess the TRL of seven MAM technologies (Lezama-Nicolás *et al.*, 2018). This method seems limited for the precise definition of the maturity of a technology in relation to its use in a research laboratory or a company. This is due to the use of public data on a global scale, with sometimes long publication times.

### 2.1.3 *Manufacturing Readiness Levels (MRL)*

The Department of Defense (DoD) of the United States has developed the MRL scale for evaluating production system maturity in the context of their acquisitions or developments (Department of Defense of the United States of America, 2020). This scale consists of ten levels, aligned with the TRL. In comparison with TRL, it allows to assess not only the technology but the entire manufacturing process integrating the technology, leading to identification of gaps, associated risks, developmental opportunities, and

improved performance of production technologies and systems (Basu and Ghosh, 2017; Department of Defense of the United States of America, 2020; Sotirios, 2019). Additionally, the use of MRL scale evaluation is more precise as it is divided into nine items and twenty-three sub-items, each one evaluated on a scale of 1 to 10, based on specific questionnaires. The items include technology and industrial base, design, costs/financing, materials, performance and process control, quality, workforce, facilities and production management. The global MRL level, is calculated as the minimum maturity level assigned to each sub-item.

MRL has successfully been adapted to assess the maturity of hospital beds management system (Syamsuddin *et al.*, 2020), train wheel manufacturing process (Wiratmadja and Mufid, 2016) or human tissue bio-printing technologies (Wu *et al.*, 2017), for instance. Adapting the MRL requires significant adjustments as this MM has been initially developed within the specific DoD organizational context. Thus, the levels and items descriptions use a specific vocabulary, and acronyms related to DoD, which hardly fit with various applications context. Accordingly, Simpson (2020) argues that TRL and MRL, in their current forms, are not suitable for evaluating the maturity of MAM. TRL scale is too broad and imprecise, while MRL, despite being more precise, is too specific. Simpson suggests the development of a MM based on four criteria: machines, materials, design, and workforce.

#### *2.1.4 Maturity Assessment Model for Manufacturing Systems (MAMMS)*

The MAMMS model, constructed through consultation of a broad panel of experts, defines up to seventy-nine variables assessed on a five-point scale (Vivares *et al.*, 2018). These variables may be linked to the company's priorities, such as cost, quality, environmental protection, innovation spirit, or to the production levers, such as human

resources, production planning, technologies, and factories. Through maturity, employees evaluate the strengths and weaknesses of the company. They may also be related to the company's strategy. From the evaluations, a ranking of variables and an overall maturity score of the manufacturing system are computed. This model is **accurate** due to the detailed criteria. However, the significant resources (time and experts) required to implement it, appear to have hindered its adoption and usage.

### *2.1.5 Maturity model for Assessing Industry 4.0*

Schumacher *et al.* (2016) developed a model to assess the maturity of businesses regarding Industry 4.0. The model evaluates sixty-two criteria and allows the decision-maker to weight them. The model is clear and conceptual, based on both qualitative and quantitative analyses. It has been specifically designed for industrial businesses that manufacture their physical products for a particular group of clients. Therefore, it is not easily adaptable to other cases. This model has been used to determine the level of maturity of companies that have integrated MAM and to determine the relationship between their maturity, the development of knowledge about integrated MAM processes, and their performance.

Other maturity assessments models have been developed such as integration readiness levels (Sauser *et al.*, 2010) or design readiness levels (Revfi *et al.*, 2020) but as they have not been applied to MAM, neither AM nor other manufacturing processes, they are not detailed here.

## ***2.2 Maturity models designed for AM***

### *2.2.1 Additive Manufacturing Maturity Model (AMMM)*

Reboredo and Espadinha-Cruz (2024) recently developed a MM specifically designed to help organizations to assess their maturity level for integrating AM. The

AMMM integrates three perspectives. The organizational maturity evaluates the interest of AM regarding the global strategy of the organisation. The cultural maturity evaluates the skills and knowledge of both the employees and the organisation itself to be able to integrate and operate AM. The technological maturity evaluates the process adaptations to be made as well as the technical possibilities offered by AM. Each perspective is divided in dimensions and sub-dimensions. Each sub-dimension is evaluated on a Likert scale from one to five. Then, the scores for perspectives and dimensions are aggregated by calculating the average values. The main limitation raised by the authors about their model is the calculation method, which do not permit interpretability of the results and sometimes result in a lack of consistency and reliability of the results.

### *2.2.2 Fuzzy AMMM*

To improve the AMMM, Espadinha-Cruz and Reboredo (2025) developed the Fuzzy AMMM. Based on the original dimensions and scale, it combines quantitative and qualitative methods to establish dependencies between perspectives, dimensions and sub-dimensions. Pre-requisites were added to ensure that the final score calculated for each perspective are interpretable and overall consistent. The fuzzy AMMM has been applied in a firm from the automotive industry, which has been using AM for five years. Interviews were conducted based on a questionnaire of nineteen questions, with different members of the company. In the end, the results from the AMMM highlighted the need of developing employees' skills to improve the AM maturity of the company.

The AMMM and the Fuzzy AMMM are limited as they do not focus on the process to be integrated but rather on the organization. The technological perspective does not take into account the maturity of the process itself and neither the environmental dimension. Moreover, if the result obtained through AMMM allow to identify general

areas of improvement, they could not contribute to select a specific AM process for its integration.

### ***2.3 Gap identified and specifications of the needed maturity model***

In literature, the necessity to develop a maturity assessment model suitable for the MAM context has been highlighted (Fahimian et al., 2017; Olechowski et al., 2020) as the maturity level of a manufacturing process is a key element for its successful integration and industrial development (Rodríguez Salvador et al., 2019). Table 1 gives an overview of the main attempts to evaluate the maturity of AM processes discussed in this section.

#### **Table 1 here**

Overall, the TRL are not sufficient as they focus only on technology, and they do not consider the entirety of the process nor environmental and social dimensions. MRL and MAMMS on the other hand are more comprehensive but requires too many adaptations to be applied efficiently to AM. MRL for instance need to be adapted regarding the categories and the vocabulary of its items' scales. The models developed by Schumacher *et al.* (2016) and Espadinha-Cruz and Reboredo (2025) are focused on the organisational and company level. They include partially the aspect of process maturity but their assessment in the framework of these models has not been specifically tackled. Finally, in the context of Industry 5.0, such assessment should consider both technological (relative to the technical aspects of the technology and its related manufacturing process) and non-technological (relative to economic, environmental and social dimensions affected by the technology integration) criteria.

Therefore, this research aims to develop a comprehensive framework that integrates the Additive Manufacturing Readiness Levels (AMRL) to assess the maturity of MAM processes, drawing upon the strengths of existing models while addressing their weaknesses:

- Focused not only on the MAM technology but on the entire manufacturing process built around the considered technology from design to post-processing and including supply chain.
- Based on existing maturity scales such as TRL and MRL.
- Addressing the challenges of Industry 5.0, therefore considering non-technological aspects such as environmental and social dimensions.
- That allows self-assessment by industrials to support decision makers to compare and select MAM processes or to target development areas of an already integrated process.

### **3. Research methodology**

This section aims to describe the methodology followed to develop and apply the AMRL considering the specifications defined previously. The methodology, as presented in Figure 2, is mainly adapted from the procedure model for developing MMs proposed by Becker, Knackstedt, and Pöppelbuß (2009). Based on the MMs developed for Industry 5.0 by Acerbi *et al.* (2024) and Carolis *et al.* (2025) the methodology followed is also informed from the sequential steps to develop a MM proposed by De Bruin *et al.* (2005). Other methods exist in literature for MMs development. The approach developed by Gokalp *et al.* (2017) is relevant when developing a MM to assess an organization or a company but it appears that Becker's methods is the most appropriate one when the MM is focused on the technology itself. This is why it has been chosen by the authors to develop their model.

**Figure 2 here**

### ***3.1 Problem identification and model conceptualization***

The first steps of the methodology, IDENTIFY and ASCERTAIN are consistent with the scope step of De Bruin's method. IDENTIFY refers to the literature review which results are detailed in section 2. A comprehensive literature review was performed using the Web of Science database and aimed to identify existing MMs and their limits regarding their application to MAM processes, considering their integration in an industrial production system. For the review to be the more comprehensive as possible, a structured search string has been used : (“maturity model” OR “maturity assessment” OR “maturity level” OR “readiness model” OR readiness assessment” OR “readiness level”) AND (“additive manufacturing” OR “3D printing” OR “AM” OR 3D-printing” or “rapid prototyping” or “manufacturing systems” or “manufacturing process”). Only papers in English, issued from a referenced journal or conference were selected. The resulting papers were then screened to identify if they meet one of the two inclusion criteria: i) the publication proposes a new MM designed specifically for manufacturing processes or considering additive manufacturing; ii) the publication applies an existing model to a use case in relation to additive manufacturing. From the screening, eleven relevant publications were selected and guided the state of the art presented above. **The relevance of the selected maturity models for AM was then assessed according to the following criteria:**

- **The focus of the model: does the MM assess the entire manufacturing process (process, supply chain, post-process), or only the organisational or strategical levels?**
- **Maturity levels and dimensions: is the model based on well-proven mechanics?**
- **Self-assessment: does it need to be manipulated by external expert?**

- Sustainability: does it address the environmental and/or social dimensions of Industry 5.0?

These criteria allowed to assess the models, as detailed in section 2.

Then, from the comprehensive literature review and the previous criteria, the gap and the specifications of the model to be built are identified (see section 2.3). Based on it, the second step, ASCERTAIN, defines the scope of the maturity assessment to fit with the specifications. The subject of the maturity assessment is accurately defined (either the complete product life cycle or the standalone technology or a compromise).

### ***3.2 Model development***

The DESIGN phase of the presented methodology fits with the step *Populate* of De Bruin's methodology. Based on the scope of the assessment and the specifications of the MM to be developed, it is necessary to define *what* is evaluated and *how* it is evaluated. *What* is evaluated is based in the scientific literature and will result in dimensions and items to assess (see section 4.2). *How* to evaluate them reflects in the maturity levels (see section 4.3), the procedure to conduct the assessment to enhance the assessment objectivity (see section 4.4.1), and the computation of the maturity score (see section 4.4.2).

### ***3.3 Model verification and validation***

The APPLY and VALIDATE stages of the presented methodology matches with De Bruin's test phase. The designed and populated model has been applied to the selection of a DED technology among the technologies at disposal on a specific technological platform considering their maturity. The validation of the model relies on a double iteration involving experts of the field. The first version of the model and the results of its application were presented to a panel of four experts. An interview was

conducted with each of the four experts. After a 20-minute presentation of the model and its application, a twenty-minutes discussion was lead with the expert about the model, its application and the obtain results. This first validation step, namely the verification, allows to identify weaknesses of the model to address them and to ensure that the model is suited to assist the industrial integration. Further details are reported in section 5.

Then a second validation iteration is defined, relying on agreement measurements between participants. At this stage the model has been provided to local experts to assess the maturity of the DED technologies in the framework of the use case. Their evaluation using the models were compared to assess the objectivity and the reliability of the model. The **Krippendorf's alpha** ( $\alpha_K$ ) has been chosen to measure agreement between participants as it is adapted to contexts with missing data which fit with the use case (Hayes and Krippendorff, 2007). The  $\alpha_K$  index is measured using IBM SPSS Statistics software and the KALPHA macro (Hayes and Krippendorff, 2007). The calculations to obtain  $\alpha_K$  are detailed in appendix 3.

The deployment and maintenance phase proposed by De Bruin have not been implemented so far. Through its future uses, the proposed MM will be maintained and improved over the years.

#### **4. Results: designed maturity model**

In this section, the Additive Manufacturing Readiness Level (AMRL) model, the MM for metal additive manufacturing processes, is presented, detailing its scope, its dimensions and the assessment procedure. The model validation is presented in section 5, also nurturing the discussion of the results obtained.

#### ***4.1 Scope of the model***

The second step of the methodology presented in Figure 2 consists in identifying and defining the scope of the assessment. To meet the requirements (see Section 2.4) the scope of the MM is based on a couple that links a MAM technology to an application case: Technology Use Case Couples (TUCC). The TUCCs need to be defined before each application of the model, in accordance with the specific context of the study. Defining and identifying the TUCC to be assessed enables our model to adjust to the assessment requirements, depending on the application context. The TUCC concept also guarantees that our evaluation is not exclusively concentrated on the technology but rather looks at the whole use case. Therefore, each assessment from the proposed model will rely on specific TUCCs, which allow for a more accurate evaluation, in adequation with its context. For instance, considering Directed Energy Deposition processes, a TUCC should specify the technology (defined by energy source and material form) coupled to a use case including the main MAM application cases - as defined by Ford and Despeisse (2016): new part, repair and functionalisation - and, non-exhaustively, the material and the part geometry.

#### ***4.2 Dimensions and items of the developed maturity model***

The proposed MM has been developed from the MRL. The MRL assessment items and levels have been modified to: (i) align with the distinct features of the MAM, (ii) encompass non-technological aspects (economic, environmental and social) as well as technical ones, and (iii) be pertinent to the evaluation of TUCCs. The items and sub items of the proposed model are presented hereunder.

Eight items and twenty-two sub-items have been determined as illustrated in Figure 3. Most of these items and sub-items come from the original MRL. They have been adapted to the context of MAM. On Figure 3, the sub-items marked with an asterisk

(\*), are the one that have been added, mainly to complete the non-technological dimensions. Overall, the items and subitems from the MRL and the new ones have been reorganised to propose a clear categorisation featuring technological and non-technological aspects.

### Figure 3 here

The list of items presented is a result from various iterations of model validation.

They are defined as follow:

- **A. Industrial technology:** determines whether the technology considered is ready for industrial-scale development of the TUCC. The maturity of the manufacturing technology at the heart of TUCC, i.e., the MAM process itself, is evaluated (A.1). Its availability and the gathered knowledge in the industry (A.2) as well as its ability to be integrated into the manufacturing process (A.3) are also assessed.
- **B. Design:** relates to the design phase in the MAM production chain. MAM enables novel approaches to production and design. This criterion considers the aspects of industrialization (B.1) and the guarantee to produce and manufacture various geometries (B.2).
- **C. Materials:** measures the maturity of knowledge of the studied input materials in the TUCC (C.1), as well as the readiness of the supply chain for these materials (C.2).
- **D. Process:** encompasses the evaluation of process modelling (D.1), control of process performance (D.2), and quality control of produced parts (D.3).
- **E. Handling:** assesses the maturity of equipment needed to control hazards and risks arising from the operation of the TUCC within its

immediate environment (E.1) and equipment required for the functioning of the entire production line (E.2).

- **F. Costs:** includes the modelling of the production cost of the TUCC (F.1), its analysis (F.2) and the design of the organisation's budget strategy for implementing the TUCC from its development to its integration into full production (F.3).
- **G. Environment:** considers the environmental impact of the TUCC, including environmental impact modelling (G.1), analysis (G.2), and the sustainability strategy of the organization for implementing the TUCC from its development to full-scale production integration (G.3).
- **H. Social:** addresses the social dimension, including: the skills necessary for the development and implementation of TUCC in the production line (H.1), the consideration of operator drudgery (H.2), the modelling of the social impact of TUCC in terms of life cycle (H.3) and production management (H.4).

The sub-items are detailed in appendix 1. For instance, sub-item D.1, modelling and simulation, is explained as follows:

- D.1 reflects the level of maturity achieved in the modelling and simulation of the physical phenomena involved in the manufacturing process. According to the TUCC, the models make it possible to predict the behaviour of the MAM process and its results, both qualitatively and quantitatively. Is the process modelled for just a part of the TUCC (like a bead) or in its globality? Is the model only theoretical or validated through prototypes manufactured? Are there models develop for managing industrial production

### ***4.3 Maturity scale of the model***

A readiness scale has been designed based on TRL and MRL, specifically adapted to MAM. Table 2 presents the Additive Manufacturing Readiness Levels (AMRL). The AMRL is defined between 1 and 10. Each score corresponds to a level of maturity that demonstrates the evolution of the TUCC, from its initial research and development phases to being fully operational in industry.

**Table 2 here**

Industrial production at low and full-scale capacity allows for differentiation between production line operation during testing and startup phases (low capacity) and its operation at the desired maximum production level once the line is ready (full capacity). We do not use terms such as small, medium, and large-scale production here, as the MAM is not meant to produce large series like those made using conventional manufacturing methods.

An adapted version of the AMRL scale is developed for each sub-item to assess it. These specific scales are provided in appendix 2. The example for the sub-item D.1, modelling and simulation (in D, process) is given in Table 3.

**Table 3 here**

### ***4.4 Assessment method***

Each sub-item of each TUCC must be assessed. The evaluator has to choose and justify the level on its specific scale (see appendix 2) using proofs such as: state of the art, scientific literature, standards, projects reports, patents, prototypes parts, or industrial expertise (i.e. interviews with experts).

#### 4.4.1 Items score

The AMRL allow the assessor to study the maturity of each sub-item in particular. Aggregating the maturity score at the item level enables visualisation and comparison of differences between items. The AMRL consider the maturity score of an item as a mean of its subitems. Thus, the items are representative of the whole of their sub-items. For example, the score for item A is the average of the scores for sub-items A.1, A.2, and A.3, with each sub-item having equal weight. This calculating method provides a general overview, which is useful either to target the lowest mature items or to compare MAM processes between each other for each item. But this method lack interpretability. In some situations, the aggregated score can smooth out the sub-items score or hide a singular sub-item score. For instance, the item C can result in a score of 5 with C.1 equal to 0 and C.2 equal to 10 and vice-versa. This extreme example illustrates the limits of this aggregation method applied to the items level. In case of issues with the aggregate scores, the scores of the sub-items must be referred to.

#### 4.4.2 Global AMRL score

The AMRL evaluates the maturity of a TUCC on a one to ten scale for each item. Sometimes, for comparing different TUCC at a global level, it is useful to translate these maturity levels into a unique aggregated maturity score above all items. To do so, the authors deemed necessary to attribute various importance to the items according to the context of the evaluation, either to evaluate the impact of the items or to deliberately disregard one or several items. This ensures that the model can be easily applied within different contexts and thus its flexibility. So, if necessary, for the calculation of the TUCC's global AMRL score, items are weighted. Their importance is assessed on a scale ranging from 1 (indifferent) to 4 (necessary). For each item, a weight  $p_i$  is applied to item  $i$ , whose maturity,  $amrl_i$ , has been calculated based on the evaluation carried out. The

final maturity score for each TUCC is calculated based on the scores of each item  $i$  according to equation (2.1):

$$AMRL = \frac{\sum_{i=1}^n amrl_i \times p_i}{\sum_{i=1}^n p_i} \quad (2.1)$$

Note that equal weight may be assigned to all items, resulting in the AMRL score being the average of the criteria scores.

Using weights is only one possible way of obtaining a global score. This method may introduce biases, which is why it is only an optional stage. As previously stated, the global score isn't mandatory, it depends on the purpose of the assessment. Other approaches from decision support science as analytical hierarchy process could be investigated to aggregate the results of the AMRL as well as a collaborative approach, which could be the purpose of future research.

## **5. Discussion, model application and validation**

The AMRL model has been applied and validated based on a specific case study. The results, as well as risen limits and perspectives are presented in this section.

### ***5.1 Case study***

The AMRL is applied to the selection of a Directed Energy Deposition (DED) process for a research project among different technologies at disposal on a specific technology transfer centre. DED is defined by the ISO standard - ISO/ASTM 52900:2021 (ISO/ASTM 52900:2021(E), 2021) as a process in which focused thermal energy is used to fuse materials, here metallic, by melting them during deposition. They are typically categorized based on the type of energy source used (laser, electron beam, and electric arc) and the form of the filler material (powder and wire). These technologies can be used for various purpose: manufacturing large-sized parts, repairing, or functionalizing (Ahn,

2021). For the case study, the selection of the DED process to be used relies on its maturity.

Figure 4 shows the actions and their actors for selecting a TUC using the AMRL model, which is then followed step by step. The authors act as the assessor.

**Figure 4 here**

#### *5.1.1 TUCCs considered*

The first step is the TUCCs definition. The DED technologies considered here are laser metal deposition – wire (LDM-W), laser metal deposition – powder (LMD-P) and wire arc additive manufacturing (WAAM). Nine use cases are considered defined by the application type (new part manufacturing, repair and functionalisation) and the material (titanium, stainless steel and aluminum). A total of twenty-seven TUCCs were defined, as presented in Table 4. These application cases allow us to differentiate the use cases according to the manufacturing surface (substrate, functional part or defective part). The material has been included in the TUCC because the observed developments are not uniform depending on the material used.

**Table 4 here**

#### *5.1.2 Global AMRL score calculation: weights definition*

For this specific application of the AMRL, to easily compare the TUCCs to each other, a global AMRL score has been calculated. To aggregate the maturity score, the items were weighted. The weights have been determined by the same assessor, the authors, according to the context and objectives of the project for which a DED technology must be chosen.

The Criteria A, C, D, F, G and H are considered the most important items, with a weighting coefficient of 4, as technological maturity (item A) and manufacturing process

maturity (item D) are the focus of our work. It was also very important to consider the sustainability dimensions (items F, G and H). Finally, as material is part of the TUCC (item C), it was also important to differentiate the maturity of TUCCs in this respect.

Item E (equipment) is weighted with a coefficient of 3. This is because the selection of the TUCC is centred on the manufacturing stage itself rather than on its production environment and the equipment to be used in the production line. However, as this item is still related to the others (such as item H), it remains at level 3. Finally, item B is weighted with a coefficient of 2, which corresponds to "not very important". In fact, design maturity is less important in the specific selection context.

### *5.1.3 Maturity scores obtained*

The authors gathered the necessary knowledge about the DED processes at the platform to be able to assess each sub-item of each TUCC. To do so the authors, who acted as the assessor, used the technical and scientific documentation from the platform. If information was lacking for a specific sub-item of a TUCC, the process engineer in charge of the process related to the TUCC was asked about directly. Table 4 synthetises the readiness scores of each sub-criterion for each TUCC. The scores have been determined based on the equipment of the technology transfer centre, its associated manufactured parts and prototypes as well as the documented research (research papers, for instance).

For example, the assessment of the sub-item D.1 (according to Table 4) for the TUCC [LMD-W ; New part ; Titanium], and for the TUCC [LMD-P ; New part ; Titanium] is set to 4. For both technologies, research programs have been led on the platform to model the impact of process parameters on the geometrical quality of the manufactured beads (Cazaubon et al., 2021; Milhomme et al., 2021) . But these models just focus on specific process parameters for bead manufacturing. The next step for improving maturity of this sub-item would be the extension of the model to thick parts

manufacturing or more complex geometries before being able to model a complete prototype.

Based on the calculation detailed in the previous section, results are presented in Table 5. The results indicate global AMRL score ranging from 1.9 to 4, meaning the evaluated TUCCs are still in the research and development phase within the studied context and according to the defined criteria weighting, which is not surprising given the context of a technological Research and Development platform.

**Table 5 here**

The manufacturing of a new part in stainless steel using WAAM-CMT is the most mature TUCC (closest to AMRL 4) in our application and has been chosen to develop a research project.

## ***5.2 Verification and validation***

As detailed in the methodology section, two validation iterations were carried out, the verification and the validation. The model and its application, as presented in the previous sections, take into account the adjustments from the first validation iteration.

### ***5.2.1 Verification***

Interviews were conducted with four experts with more than five years of experience in the field of MAM. Their profiles are detailed in table 6.

**Table 6 here**

The experts agreed that compared to existing models as presented in the **theoretical background** section:

- The presented model was specifically designed for MAM and suited to assess their maturity, which was a need for both industrialists and academics. In comparison with MRL and MAMMS, the AMRL maturity

scales suits the challenges of MAM addressing all aspects influenced by the integration of such technologies.

- The model itself was appropriate to assess the maturity of MAM technologies, overcoming common bias in such models, as subjectivity of the assessor. In comparison to the TRL, the AMRL gives a more detailed insight of the process maturity and less subjective as it is more guided.
- The AMRL allows to identify specific improvements through the maturity scores of each item at a process level (operational). This is an evolution from the models developed by Schumacher (2016), Espadinha-Cruz *et al.* (2023) and Reboredo and Espadinha-Cruz (2024) where the maturity is assessed at company level and thus only allow to identify improvements at strategic levels.

They also identified a few limitations that were eventually tackled by the update of the model, which version is presented above, in the following ways:

- The sub-items and their respective rating scales were enriched with more details to ensure the comprehension of the assessor and ensure the less subjectivity possible. For instance, some items shared the same generic scale which has been modified to specifically fit to each sub-item.
- The TUCC were also specified: material was added as a variable to the original TUCC, which only included the technology associated with the use case. In addition, the definition of the TUCC evaluation scope has been considered.
- The possibility of weighting the items to obtain an aggregated maturity score has been added.

### 5.2.2 Validation:

The second validation iteration involved six experts, which profiles vary from technical MAM platform manager to MAM process engineer, as detailed in Table 6, with various level of knowledge about the TUCCs. They were asked to assess some TUCCs from the case study using the AMRL through direct interviews. The measurement of participant agreement allows to determinate the objectivity and reliability of the developed model. Six TUCCs were assessed by six different participants, with two TUCCs per participant (i.e., twelve assessments) among the 27 TUCCs defined. These assessments were compared at sub-item level between each other's, thanks to reliability measure. For the three ratings obtained for each of the six selected TUCCs (two ratings as part of the validation plus our rating detailed in section 5). The measure is done through the KALPHA macro, run for seven observers, one hundred and thirty-two units (twenty-two criteria for six TUCCs) and an ordinal level of measurement (as detailed in Appendix 3). The result obtained is  $\alpha_K=0.66$  which is close to the consensus value of 0.67. Moreover, if the global assessment of all TUCCs assessed by each participant may show some low variations, the overall ranking of the TUCCs according to their maturity does not differ. This level of agreement shows that:

- The AMRL is reliable because it allows TUCCs to be assessed without considering the subjectivity of the assessor, which had been identified as a major problem in the literature.
- The specific vocabulary, regarding MAM, and the detailed assessment scales are accurate enough to guide different individuals to a similar assessment of TUCCs.

Thus, the AMRL provides a substantial added value in comparison to existing models when it comes to the maturity assessment of additive manufacturing regarding, technical, economic, environmental and social aspects.

### ***5.3 Contribution to knowledge, to practice and managerial implications***

The proposed AMRL is a step to overcome the gap in the adoption of MAM technologies in the manufacturing industry. This tool intends to facilitate the assessment of the maturity of the targeted MAM technology within the specific production system context, at both technological and organisational dimensions, in the framework of Industry 5.0. Already existing models focus on specific aspects, either just the organisational or technological one. They are often tailored to single elements rather than on the entire process. Moreover, the sustainability implications of introducing such a technology in an existing industrial system is not systematically targeted, as they do not always consider both environmental and human dimensions. Moreover, none of them addresses the technological specificity of MAM technological context. Thus, the AMRL allows an objective assessment of the maturity status of a MAM technology within a specific manufacturing production context, providing decision makers indicators to compare and select MAM technologies, and identifying challenges and gap to improve within their additive manufacturing process. This research brought various theoretical contributions:

- A comprehensive literature review about MMs for additive manufacturing technologies and companies.
- The development of the technology-use case couples (TUCC) as subject of the MM, which allows the assessment to be context aware.

- The definition of eight items and twenty-two sub-items covering the entirety of the MAM production process as well as environmental and social aspects.
- The definition of ten maturity levels for MAM inspired by the MRL and their declination for each of the twenty-two sub-items.

Regarding the practical and managerial implications, the AMRL offers several opportunities for supporting adoption of MAM in industry. The AMRL can help companies to evaluate and select the best fitted MAM technology regarding their production context thanks to maturity. Moreover, the maturity assessment through AMRL also provides a comprehensive vision of an existing MAM process, identifying less matures dimensions, on which to prioritize future actions and developments. Specifically, this research work can help practitioners in various ways:

- Assisting the product industrialisation process involving MAM technologies: the AMRL could be integrated in a decision support system where MAM maturity should be considered.
- Identifying maturity “hot spots”: the AMRL item and sub-item evaluation highlights the dimensions where development efforts are needed to increase the overall maturity. At long term, the AMRL evaluation could be part of a continuous improvement management process.
- Adopting and implementing MAM at his full potential: as performances of MAM relies to its implementation, the AMRL can provide a roadmap for a successful integration.

## **6. Conclusion**

This article presents the Additive Manufacturing Readiness Levels: a maturity model developed to support the adoption of metal additive manufacturing by industry. In

the literature, no existing MM addressed specifically MAM at both organisational and technical level, considering its specific adoption context and the Industry 5.0 dimensions. Thus, this research proposes an original and tailored MM for MAM offering a context-aware approach that bridges technological capability and operational applicability. It focuses on the process itself rather than on the organisation or the company as existing MMs (Reboredo and Espadinha-Cruz, 2024; Schumacher et al., 2016). It has been developed following MM development approaches from information technology field and design research methodology. The main theoretical contributions are:

- A comprehensive literature review on AM maturity assessment.
- The definition of the concept of technology use case couples (TUCC) as the subject of the assessment.
- The AMRL MM designed with eight dimensions and twenty-to sub-items, with their specific maturity scales on a one to ten levels. The MM feature economic, environmental and social dimensions at technical and organisational scale, through the entire supply chain from design to manufacturing, considering materials, handlings, process modelling and the production line.

The AMRL provide several opportunities at the practical and managerial level:

- Assisting the selection of MAM technology in industrialisation stage.
- Developing continuous improvement of MAM production systems.
- Improve the performances of MAM.

The AMRL has been validated through its application in the context of a specific technology transfer centre. It allowed to select a MAM DED technology coupled to a material and a use case according to its maturity. Twenty-seven alternatives were assessed and final maturity scores from 1.9 to 4.0 (on a 0 to 10 scale) were obtained. Measures of

agreement between experts using the model, combined with direct interviews pointed out the reliability and the suitability of the proposed model.

Some limitations have been identified, which have enabled to outline prospects to be investigated in future work:

- For the TUCCs considered in the use case, the model is appropriate. The TUC definition stage of the model needs to be tested in other use cases. Moreover, the extension of the model to other AM than MAM should be studied.
- For some sub-items, the line between one maturity level to another can be thin, as reported by the participants to the validation. Thus, the development of more tangible elements for the assessment, like a detailed questionnaire for each sub-item which could determine the maturity level by answering yes/no questions, would simplify the assessment.
- As the validation stage allowed to confirm the results obtained through the model, a systematic validation step could be added to the AMRL. Multiple assessors could evaluate the TUC considered. This collaborative assessment could facilitate discussion and reaching a consensus, ultimately yielding a single consolidated assessment.
- The validation only focuses on one use case. In the future, the model should be used in various context and the analysis of the experience of the assessor and the reliability of the results could lead to identify more improvements prospects. As stated in Section 3, the deployment and maintenance of the AMRL will rely on these future applications and feedback.

- The aggregated maturity score through weighting needs to be investigated and compared to other aggregation methods (individual and collaboratives). This aggregation method has been chosen among other ones. In literature, the original MRL, as developed by DoD, uses the minimum score of the sub-items assessed as the score of the item. Schumacher *et al.* (2016), and Reboredo and Espadinha-Cruz (2024) in the AMM, use the mean aggregation. Espadinha-Cruz and Reboredo (2025) developed a fuzzy calculation of the aggregation score based on the mapping of dimensions and sub-dimensions of their model. Using fuzzy aggregation in the AMRL could be considered in future work, which could then allow to integrate the AMRL in the AMMM.

Overall, the main perspectives of the presented work are:

- The improvement of the maturity score aggregation method and the development of questionnaires to support the assessment.
- The deployment of the proposed AMRL, which ultimately will contribute to its maintenance.
- Its integration into decision support system such as the AMMM.

Finally, by extending the application of AMRL to various AM processes (e.g. material jetting, material extrusion, sheet lamination, binder jetting, powder bed fusion and vat photopolymerization) and materials (concrete, polymers or ceramics), its aim is to contribute to the integration and adoption of AM in industry considering its impact on the whole supply chain.

### **Acknowledgment**

This research was conducted with support from ESTIA, France, the University of Wolverhampton, UK, and financial support from CAPB (Communauté d'Agglomération Pays-

Basque). This research project was undertaken with the assistance of resources and services from the ADDIMADOUR platform, Additive Manufacturing Solutions.

The authors report there are no competing interests to declare.

### **Data availability statement**

The data that support the findings of this study are available from the corresponding author, L. Terrenoir, upon reasonable request.

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Table 1. Synthesis of the literature review on maturity assessment models for additive manufacturing.

Table 2. AMRL scale.

Table 3. Specific AMRL scale for sub-item D.1.

Table 4. Assessment for each sub-item of each TUCC.

Table 5. Results of the AMRL for DED process selection.

Table 6. Profiles of the experts interviewed for both validation iteration

Figure 1. Technologies life cycle adapted from (Ernst, 1997; Reinhart and Schindler, 2010)(Ernst, 1997; Reinhart and Schindler, 2010).

Figure 2. Methodology for developing the maturity assessment model.

Figure 3. Items and sub-items to be assessed in the proposed maturity assessment model for MAM.

Figure 4. Steps, resources and actors for DED process selection using the AMRL.