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ORIGINAL ARTICLE

Evaluating the suitability of niches for additive manufacturing production: proposal for a numeric evaluation tool

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Abstract
Additive manufacturing (AM) is a wide set of technologies that can be used for many different scopes. AM is now a well-integrated prototyping and development tool in most industrial endeavours, while proper end-product manufacturing has only seen very specific niche successes. Given the complexity of AM's matrix, which is full of discontinuities and non-trivial intercorrelations that play a relevant role in product design and development, it should not come as a surprise that not many end-product applications have succeeded in making use of it. This paper argues that understanding AM's complex matrix and correctly identifying suitable production niches for it are key elements of this issue, a topic for which existing literature and tools are scarce. The analysis of AM's status quo for end-product manufacturing and the review of existing approaches to integrate these technologies with product development are the basis used in this paper to propose a suitability assessment tool to fill this knowledge gap.

Keywords Additive manufacturing · Additive manufactured design · Additive manufactured production · 3D printing

1 Introduction

Additive manufacturing (AM) is an umbrella term for the wide set of technologies which can produce objects in an additive manner. The production flow that all technologies in this family share, where a 3D model becomes a real object without having to craft new tools to manufacture new designs, tends to blur the fact that the different manufacturing technologies involved are as different as the objects they can produce, though. The various uses that can be made of AM are also notoriously broad, from prototyping, to development, to end-product manufacturing. Despite being in the technology's umbrella name, the latter currently represents only 30.5% of AM's total output [1 p. 29]. Analysing the reasons for this and proposing a tool aimed at contributing to the development of this area are the subjects of this paper.

All emerging technologies experience Gartner's hype curve to some degree (Fig. 1) [2 p. 255. The starting overexcitement when the technology is introduced (peak of inflated expectations) is followed by the disillusion of meeting its limitations (trough of disillusionment). If things go well, the disillusion will be followed by a slow up-heading slope of learning how to correctly use it (slope of enlightenment), finally leading to a phase of broad successful results (plateau of productivity). This plateau usually finds itself below the starting peak of expectations but above the disillusion's low in terms of results. AM's hype curve has been unusually long, lasting several decades, and is arguably still far from reaching a proper plateau of productivity beyond very specific production niches [3].

This paper reviews the role of correctly identifying production niches as suitable for AM production in the delayed arrival of a wide plateau of productivity to the field. This review leads to the argument that the lack of tools for this purpose in the literature is a relevant part of the issue and, therefore, to the proposal of an assessment tool to address this knowledge gap. The proposed assessment tool is distilled from a set of case studies on end production AM, which has been well documented for several years and includes long-term market reaction and evolution. The analysis of the whole issue, as well as the proposed tool for addressing it, will be presented through Gartner's hype cycle.

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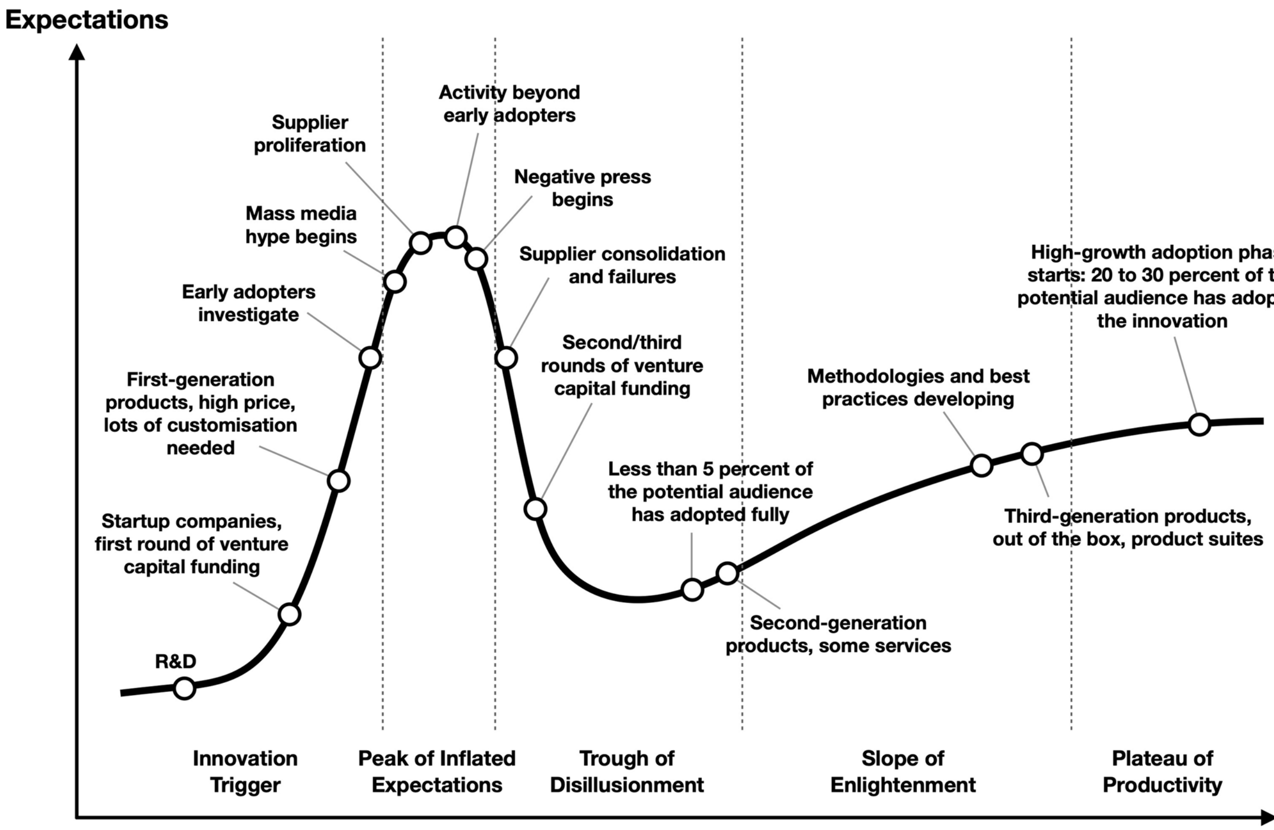

Fig. 1 Gartner's hype cycle. Adapted from [2. p. 255]

2 Additive manufactured products: the peak of inflated expectations

The evolution of what is considered a plausible use for additive manufacturing (AM) can be told through the different names this set of technologies has received. Originally, AM was known as rapid prototyping, clearly implying its expected scope. Despite all the hype surrounding AM and everything written describing an upcoming AM revolution in production [4–6], currently, most of AM's output does not come as end-products [1 p.29, 3].

When the idea that AM could be used for more than prototyping, hopefully delivering consumer products, rapid prototyping was rebaptised as rapid manufacturing [7]. This name was flawed, though, since AM can be quick for prototyping purposes when compared with previous alternatives, but these technologies are — arguably in an intrinsic manner — slower than mass production methods when it comes to production. A third nomenclature iteration was required to reach AM, which correctly describes how the technology operates while leaving the door open for production purposes.[1]

A robust body of literature covers AM technologies from different perspectives. Anderson and Hopkinson et al. described the societal impacts of this upcoming revolution in *Makers, the New Industrial Revolution* and *Rapid Manufacturing: An Industrial Revolution for the Digital Age* [7, 8]. Gibson et al. provide an encyclopaedic compendium of these technologies' state of the art in *Additive Manufacturing Technologies* [9]. Bitonti describes AM methods and applications from a designer's perspective in *3D Printing Design: Additive Manufacturing and the Materials Revolution* [10]. Hoskins and Wernier et al., to mention two examples amongst many, provide beautiful portfolios of AM applied examples in arts, design, and the do-it-yourself environment

[1] Most people and many sources still call the whole set of AM technologies '3D printing' even though this term officially is only an alternative nomenclature for fused deposition modelling (FDM), a specific type of AM (ISO/ASTM 52900).

in *3D printing for Artists, Designers and Makers* and *Printing Things: Visions and Essentials for 3D Printing* [11, 12]. Killi contributed to the field from an academic perspective, introducing a product development approach for designers in *Designing for Additive Manufacturing: Perspectives from Product Design* and *Additive Manufacturing: Design, Methods, and Processes* [13, 14].

Despite mature technologies and the number of times the word ‘revolution’ appears in the titles of the previously mentioned volumes, actual AM end-products are still rare though. Beyond the medical applications, particularly when it comes to prostheses and customised aids, it is difficult to find fields where AM currently plays a relevant role in production or has noticeably changed the status quo. Some may argue that high-end products such as record-beating customised bicycles or rocket nozzles are good examples of the contrary [15, 16]. This paper argues instead that such high-end production niches, where the budget is not a constraint and a minimal efficiency increase can justify doubling the price tag, are irrelevant to the broad market and belong to a different analysis. This article wishes to discuss products which can affect the wide market landscape, if not becoming an alternative to mass production.

Most successful AM products in the wide market fulfil the following conditions: they are small, topologically complex, and require customisation. To this, we could add that their price must be relatively high [13 p. 76]. Hearing aids, dental implants, and medical prostheses in general are, therefore, excellent candidates to become AM products, and indeed, these product niches have been basically taken over by AM, or at least profoundly changed by it [17]. But is this the end? Is AM as a manufacturing tool to be relegated to medical applications and high-end products only? It is unlikely that experienced product designers truly believed some overhyped descriptions of an upcoming AM utopia, where everything could be delivered quickly, cheaply, customised, and locally produced, if not directly at home with just a click [6]. It is also unlikely that many economists thought that when the AM revolution ‘kicks in, it will eventually and inevitably reduce marginal costs to near zero, eliminate profit, and make property exchange in markets unnecessary for many (though not all) products’ [18 p. 78]. Those descriptions clearly belong to the peak of inflated expectations, while thinking that there is little more than medical implants as a market for AM products looks like the following trough of disillusionment in Gartner’s hype cycle. This valley of disillusionment is taking a great deal of time to overcome for a set of technologies which has been long enough in operation for key patents to have become public, though [19]. Is there no slope of enlightenment leading to a higher plateau of productivity ahead, or have we missed it? This paper argues that failing to correctly identify suitable niches for AM production is at least partially responsible for the lack of progress on this front. Let us, therefore, analyse the current situation to then propose a tool for evaluating the suitability of production niches for AM in the hope that this can contribute to the collective effort to change and enhance the production landscape through AM.

3 Additive manufacturing’s limitations: the trough of disillusionment

AM end-products have quickly grown as a market over the last decades. This market was practically non-existent in the early 2000s and developed exponentially to cross the 2.5 USD billion global revenue mark in 2022 [1 p. 162]. As previously said, the types of products behind those numbers have very little to do with an innovative design and production revolution, though, and a lot to do with very unsexy medical and dental prostheses. This paper does not wish to adhere to the snob indifference that some voices in the field give to such applications but rather to applaud their successes, learn from them, and try to find ways to achieve similar results in other production niches. In *Printing Utopia: The Domain of the 3D Printer in the Making of Commons-Based Futures*, Ibach comments that AM ‘is a tool, rather than an agent of the maker movement’, to then discuss how we could trigger a more profound revolution, aiming at ‘the utopian potential of the 3D printer within the discourse of commons-based future-making’ [20 p. 232]. On the contrary, this article wishes to contribute to the development of AM as a practical production tool in as many fields as possible, leaving the discussion of whether it has become a societal transformation agent for later. The abundance of such analysis, as well as the repetitive expectation that AM will be a silver bullet for societal crisis, be it COVID or the housing shortage [21, 22], can be read as a sign of the fact that we have been wandering in the AM trough of disillusionment for too long. Let us then have a look at the (often unspoken) limitations of AM, which brought us to AM’s trough of disillusionment.

AM is undoubtedly a catchy concept. Who could not be attracted to the idea that a single machine could produce everything, even itself? [23] When compared to traditional industrial moulding, AM is indeed a machine that can manufacture almost everything and belongs to a different category altogether. Yet, upon deeper inspection, production methods have been moving in this direction for a long time, creating a rather continuous spectrum of production flexibility. Automatised subtractive production methods, such as computer numerically controlled (CNC) machinery, are an excellent example of it and have been producing all sorts of different objects on demand for a long time. AM brings a higher degree of production flexibility than CNC, being in many cases the only solution for some complex topologies, yet even these wonder machines have many limitations. It is difficult to analyse AM as a whole in any regard given the large and continuously expanding array of technologies which fall under this umbrella category. Nevertheless, and without wasting time in describing all the types of AM machines in the market, hereafter a summary of the common elements which are usually experienced as limitations, shortcomings, and difficulties of AM as a family will be presented.[2]

- Speed: It is somehow ironic to acknowledge that slow production velocity is a characteristic of AM despite initially having been called rapid prototyping/manufacturing. Technology keeps improving, and AM production is, in general, quicker than it was decades ago. Sometimes the improvement comes in a disruptive manner; the way the 'continuous liquid interphase production' (CLIP) technology claimed to have increased production speed by an order of magnitude in relation to all existing stereolithography (SLA) AM machines when it was introduced [25]. Nevertheless, producing objects additively will almost intrinsically be slower than injection moulding, sheet bending, extruding, and basically every standard mass production tool.
- Energy use: Almost as a corollary from the previous point, longer production times usually imply more energy investment per part than traditional methods. Production flexibility and the possibility to manufacture very complex topologies come with a higher energy demand per part downside [26 p. 3].
- Accuracy and reliability: Accuracy changes widely from one AM technology to another. FDM concrete for construction and desktop FDM machines are in different orders of magnitude in their respective accuracies, and different technologies in the same size range can vary notoriously. Nevertheless, accuracy and reliability are often an issue for AM when simply attempting to replace traditional production methods. Filamented FDM surfaces, layered structures in most cases, and different structural and rheological results derived from part orientation during manufacturing make the whole production and certification process less straightforward than designers, engineers, and AM enthusiasts could wish for [14, 27].
- Size: AM machines come in all sizes, ranging from units designed to manufacture microscopic objects to facilities which can produce actual bridges in sections, yet they do not cover that range continuously. Whereas building a two-storey house and a skyscraper with concrete moulding involves the same building materials (and quite often even the same machinery and support structures), each order of magnitude in terms of volume in AM has led to a different engineering solution. Furthermore, certain technologies disappear or begin at dimensional thresholds. For instance, there is no SLA machine with a larger output volume than a couple of cubic metres, and it is unlikely such a thing will become a reality any time soon because it would not make sense from an engineering point of view [28 p. 114]. Further complicating matters, some AM machines operate with production blocks, which have fixed costs almost independently of the fraction of the volume being used by the produced object, transforming a continuous variable into a discrete one in practical terms. Maximum possible size is a design issue for all production methods, but given the peculiarities of AM machines, for AM design projects this must be taken into account earlier in the process, and the decisions related to it will have profound, lasting consequences for the whole project. Switching AM machine because a minor update in the design implies it does not fit in the production chamber anymore usually alters the budget, the palette of materials, and many other aspects in discontinuous and counterintuitive manners, often risking the project's viability [14].
- Materials: Unlike common knowledge, AM machines have a wide range of possible materials beyond plastic polymers. There are AM units designed for many sorts of clay, glass, metal, and even biological materials. Nevertheless, the different AM technologies tend to be suitable only for some of those families, if not only one specific material [1 p.88–117, 29]. Furthermore, AM materials and procedures have very different properties and qualities. It is currently difficult, or at least more expensive, to find food-safe materials for SLA, while it is also challenging to avoid rough surfaces with synthetic laser sintering (SLS). Much research is being devoted precisely to these issues, and some previous hurdles have been cleared. Nevertheless, the palette of AM methods and their respective materials and properties is highly discontinuous, with wild price variations correlated to minor adjustments in non-trivial manners.
- Price: As stated several times before, AM is an umbrella term for many different technologies and materials with a similarly wide price range. Still, finding examples of single objects that will be cheaper when produced through AM rather than with traditional mass production methods is challenging. The comparative advantages for AM emerge when a design cannot be manufactured with other methods due to its complex topology or personalisation degree or when the production range does not allow for

[2] For a description of the different available AM technologies there is a large body of literature available, for instance *Digital Manufacturing: Design, Methods, and Processes*, *Additive Manufacturing Technologies*, and *Comparison and Analysis of Different 3D Printing Techniques*, to mention just a few [9, 13, 24].

the high initialisation costs associated with mass production. As opposed to the utopic vision of AM, most of the time, every analysis will quickly show that in the absence of very specific advantages, AM is more expensive than the alternatives when it comes to production [1 p.93]. This should not come as a surprise if we have already seen that AM is usually slower than mass production and requires more energy.

- Sustainability: This is a contested topic in AM, to say the least. While some will argue that material optimisation, decentralised production, and customisation possibilities automatically make AM more sustainable than the alternatives [30], the reality is far more complex. Holistic comparative analyses of the sustainability of AM are arduous to make, and when done for case studies that cover all relevant aspects, they tend to give a similar or higher footprint for AM than for mass production [26]. Attempts to create a general model for the sustainability evaluation of AM projects usually conclude that the analysis must be case-by-case, bringing us back to the beginning [31]. More than a shortcoming, assessing the sustainability of AM technologies is a very complex issue. According to this paper's review, the most effective currently available approaches for this purpose come in the form of guidelines and checklists, like the one presented in *Additive Manufacturing From the Sustainability Perspective: Proposal for a Self-assessment Tool* [32].
- 3D modelling: The final element in this list is one that usually gets to be forgotten when thinking about the costs related to AM, namely the 3D modelling for it. While it is true that AM avoids almost entirely the initialisation costs of mass production since it does not require new moulds or similar, crafting a 3D model can be a very demanding effort, depending on the design. There are intelligent tools and methods to decrease the required effort for customising AM products, but they are often non-trivial or carry design implications. If such elements are forgotten, we may end up with a production process requiring as much time and effort as using simpler technologies to do the job. This has been pointed out by Kempton in *Take Cover: Case Study in Artisan Telephone Covers for DDM* and Killi in *Additive Manufacturing: Design, Methods and Processes* [13, 33]. Their analyses say that AM's production sweet spot, all relevant aspects taken into account, does not start from produced unit number one but finds itself somewhere between the low numbers that traditional craftsmanship allows and the large numbers that mass production can deliver.

It goes almost without saying that AM also possesses innovative and disruptive advantages compared to traditional manufacturing techniques, such as flexibility, decentralised production, complex topologies, and customisation possibilities [4–7, 34–36]. The point of the previous list is to have a clear look at the downsides, which tend to be often neglected, if not entirely forgotten, by AM enthusiasts. AM's advantages are the centre and focus of most publications on AM; therefore, for this paper's purposes, it is not necessary to review them again.

It is also worth mentioning that some limitations can be understood as qualities and used as positive design features, as pointed out in *Flaws as Features: New Perspectives for Developing an Additive Manufacturing Design Language* [37]. Despite AM not being a new set of technologies, design methodologies for it have not yet developed to fully utilise its unique qualities the way this has occurred for traditional manufacturing methods, less embraced its flaws as valuable features.

4 Navigating additive manufacturing's complex matrix: stagnation in the trough of disillusionment

The previous section reviewed the downsides, limitations, shortcomings, and difficulties which are somehow intrinsic to current AM technologies (as well as their envisionable subsequent iterations). These complications, intertwined uniquely with AM's advantages and potentials, create a very particular and difficult-to-navigate production matrix. This paper argues that the complexity and discontinuity of this multidimensional chart at the intersection between design, engineering, and technology are at least partially responsible for the long stagnation we can appreciate in the field beyond the already mentioned, very circumscribed successful niches.

There have been several attempts to address the issue of how to navigate this complex matrix, though. For instance, in *Rethink Assembly Design*, Becker et al. provided a set of guidelines which should help designers in this effort [38]. The guideline includes advice such as:

- Use the advantages that are included in RM processes.[3]
- Do not build the same parts designed for conventional manufacturing processes.
- Do not consider traditional mechanical design principles.
- Reduce the number of parts in the assembly by intelligent integration of functions.

These advices make perfect sense and are still perfectly valid today. Nevertheless, they require previous experience and knowledge from the user. What are the advantages of

[3] Note the use of rapid manufacturing (RM) nomenclature.

AM? How should the designs for AM be different from the traditional ones? Which mechanical principles should be used when standard ones are discarded? How does one achieve intelligent integration of functions through AM's characteristics? And above all, how do these abstract guidelines relate in practical terms with reality? For instance, which real-life AM unit is the appropriate one for delivering the mentioned AM advantage, given a particular design decision? Experienced AM designers have answers to these questions. Still, when asked how they gained their knowledge, they usually conclude it was through practical experience, trial and error, and learning from failures rather than by reading textbooks on the topic.

A better, holistic approach in the field is the AICE workflow introduced by Killi in *Design for Additive Manufacturing: Perspectives From Product Design* and *Additive Manufacturing: Design, Methods, and Processes* [13, 14]. The AICE approach, further commented on by Kempton in *Unpacking Making: A Product Design Critique on Emergent Uses of Additive Manufacturing*, proposes an iterative approach to the whole design process for AM, from early design to post-production possibilities [39]. The AICE acronym stands for adapt, integrate, compensate, and elongate.

- Adapt: Presents suggestions on how creative, analytical, operational, and other methods could be adapted to additive manufacturing, not only as means of production, but also as a facilitator throughout the whole development process.
- Integrate: Presents suggestions on how the engineering and production process should/could be integrated into the design process, giving instant and constant feedback to the developing of the shape.
- Compensate: Moderator step that addresses questions such as how deficiencies in the process could be compensated, balanced, and restructured.
- Elongate: Addresses the lean possibilities in AM, with redesign as a continuous process, whether custom-made or during cocreation.

Both Killi and Becker deeply discuss the object to be produced and how to successfully bring it from conception to reality through AM. There is, though, little discussion in both of them on whether a specific design is suitable for AM to begin with. This may seem trivial, but given the previously described complexity of AM's matrix, deciding whether a concept can be developed through AM with comparative advantages is challenging to foresee. Killi's primary case study on customised AM, a patient-customised assistance tool for hip surgery, is an excellent example of this. His experience in the field led him to identify such an artefact as ideal for production through AM. When trying to implement the project, though, practicalities such as the powdery result and clearance tolerances became difficult obstacles, and despite partial success the design did not go beyond early tests. Killi comments that better integration in the early development of what was learned during the production attempts could have made the design a success, hence the development of AICE as a self-verifying, iterative approach.

However, tools to identify such production niches are lacking, and this paper argues that this has contributed greatly to the field's stagnation. Before presenting a proposal for an evaluation tool to fill this gap, let us examine a set of unusual case studies that were pivotal in its development.

5 Musical instruments case study: a second-generation successful AM niche

The maker movement has embraced AM technologies as a powerful crafting tool, and at this point, very creative experiments, uses, and results can be seen in every imaginable field [8, 11, 12, 40]. Without dismissing this community's value, few of these applications have developed beyond the case studies or do-it-yourself realm and into proper production, with an ecosystem of clients and a documented product evolution. Some may argue that this is precisely the point and goal of the makers' movement: disrupting design and production conventions, if not capitalism altogether [18]. This paper argues instead, on a similar line with Killi and Russo, that there is space and potential, and maybe even a need, for a different scale of production through AM between the crafts and the industry. Killi calls this in-between production space neo-craftsmanship, and Russo names it hyper-handicrafts [14 p. 62, 36 p. 149]. One successful example of such an AM in-between production success comes from the unexpected musical instrument-making field.

In 2014, Savan and Simian presented early results on experimentation with AM technologies to reproduce the cornett, a renaissance wind musical instrument, for research purposes [41]. These early experiments organically developed into a production niche that has become a significant world player within the community of the cornett players. The evolving results of this project have been reported at different stages by the researchers and the media, as well as producing a cascade of spin-off projects and innovation in the musical research environment in general [42–49].

A more comprehensive overview of the long-term results of the experiments done with AM in the musical field was presented by Simian in *3D-Printed Musical Instruments: Lessons Learned from Five Case Studies* [50]. This article discussed five musical instruments produced through AM: cornetts, shakuhachis, fagottinis, ukuleles, and slide pipes (Fig. 2). All five projects had different scopes and triggered very different degrees of attention from their respective

Fig. 2 Clockwise from top left, 3 AM cornetts, an AM shakuhachi, an AM ukulele, and an AM fagottino alongside the original. AM models and photos by Ricardo Simian

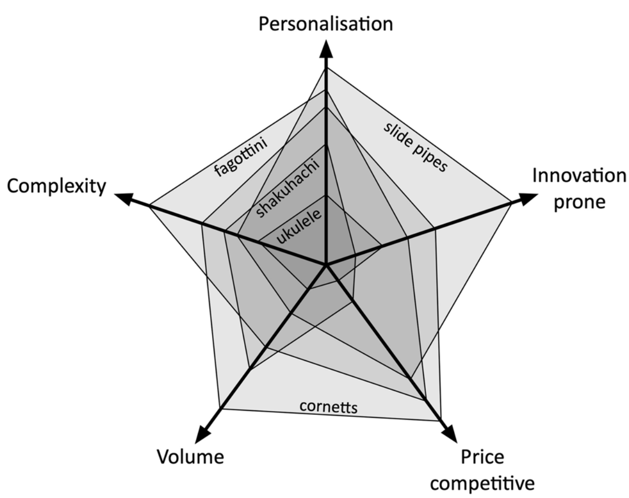

Fig. 3 Star map evaluation for the five case studies. Diagram by Ricardo Simian, from [50]

musical communities. Accordingly, they developed into widely different types of production, ranging from one-of-a-kind objects to proper neocraft production niches. The surprisingly constant long-term demand for some of these instruments is even starting to resemble the 'long tail' market envisioned by Anderson in *The Long Tail: Why the Future of Business is Selling Less of More* [51].

The disparities in the commercial results between the different instruments called for an explanation, which the article attempts to provide through a multi-axis map for each of them. This evaluation map covers the niches' technical, economic, and cultural aspects through five axes: complexity, personalisation, innovation prone, price competitive, and production volume (Fig. 3). Complexity and personalisation for AM designs have been analysed in the previous sections and many other sources. The price competitiveness of an AM design is a highly niche-specific analysis, but it is easy to perform, and its results are relatively straightforward. Production volume speaks of a particular instrument's market demand, which, surprisingly enough, can vary enormously between different instruments. As argued in the paper, suitable AM niches are neither very exclusive ones nor mass-production spaces but rather in-between numbers around the hundredths to low thousands, which perfectly coincides with the 200- to 1050-unit 'sweet spot' figure identified by Killi's customised cell phone cover case study [13 p.17]. The fifth axis in this analysis, namely 'innovation prone', may be the most unusual element to consider in such a mapping. The logic behind it is that the subjective openness to innovation shown by the performer's communities for each instrument will play a pivotal role in whether an AM version of their instrument will be accepted and adopted or not. The evaluation of the five instruments through this five-axe map provided the following result:

Taking into account both the area covered by each instrument and that to define a suitable niche, no axis can have a meagre value, the evaluation results corresponded — according to the article — to the real-life performance of the different instruments in their market spaces. The long-tailed performance that the cornetts have enjoyed for 10 years shows that this unusual AM market space was not a short-lived hype, making it an excellent example of what Gartner's hype cycle calls 'second generation product' since it was developed several decades after AM technologies were introduced and expanding into a field which was not initially foreseen for these machines. The analysis presented in *3D Printed Musical Instruments…* concludes that the cultural aspects covered by this evaluation model are crucial for seeing whether a production niche (defined by both a product and its environment) is suitable for AM production. Let us now have a look at a proposal to generalise this evaluation framework, aimed at assessing the suitability of production niches for AM production in the early development phases of a project.

6 Critical and comparative advantage parameters: measuring the way out of the trough of disillusionment

The previous analysis mapping was tailored to the musical instruments' environment. This paper introduces a generalised assessment tool for the suitability of AM products and production niches, based on the same approach but integrating the AM shortcomings mentioned in Sect. 3. Reflection on the musical instruments evaluation tool and AM's limitations led to the conclusion that the relevant parameters to be assessed fall into two categories: critical and comparative advantages. Critical elements are the ones which must be fulfilled by a niche to be suitable for AM. The comparative advantages are, instead, aspects that can give an upper hand or an edge to the project thanks to AM, but the absence of these cherry-on-the-cake elements does not necessarily jeopardise the niche's suitability.

6.1 Critical parameters

According to this paper, the critical parameters for a product niche to be suitable for AM production are sweet spot, size suitability, material suitability, and innovation proneness.

- Sweet spot: Evaluation of whether the design finds itself in a production sweet spot, meaning that the projected volume of sales, combined with the production costs and price per unit, makes sense or is advantageous when compared to the alternatives. This parameter is a composed analysis in itself, integrating several factors, but it is a standard market analysis and can, therefore, be taken as a whole.
- Size suitability: Evaluation of the suitability of the design's projected size in relation to the volumetric cut-off production limits of existing AM units.
- Material suitability: Analysis of whether the materials related to the AM machines being considered suit the project's functional, engineering, and aesthetical criteria.[4]
- Innovation proneness: Assessment of the openness to innovation within the product's niche users, this being a rather cultural aspect.

Critical parameters must be cleared by the project for it to be viable and a high evaluation in one (or more) of them does not compensate for a very poor evaluation in another. For instance, if a project requires a food-safe result, it does not matter how competitive the price can be and how well-tailored AM machines are for the design if no certified food-safe material is available. Similarly, experience shows that in specific environments, cultural and aesthetic elements have the upper hand when deciding on a product, as opposed to purely economic ones. If this were not the case, plastic imitations of wood would have overtaken entire market niches a long time ago, while most users usually prefer natural wood, even for many objects that will never be touched or observed closely. Innovation proneness of the market niche is, therefore, a crucial element to be assessed when it comes to customer acceptance, as Raymond Loewy pointed out in his MAYA (most advanced yet acceptable) concept [52 p.162]. Loewy's intuition regarding the interconnection between the appreciated novelty and typicality of a design and its market appeal has been tested and arguably verified by Hekkert et al. in *Most Advanced, Yet Acceptable: Typicality and Novelty as Joint Predictors of Aesthetic Preference in Industrial Design* [53].[5] AM products must not necessarily be novel, though. This will depend both on the traditionally produced alternatives and the look of the achieved AM product.

Different market niches and their respective customers can be surprisingly different regarding their acceptance of novelty and their need for typicality (sometimes labelled 'authenticity'), even against their own economic interests. This may seem unlikely at first, but entire global markets, such as the wine industry, are based on highly specific typicality values, despite solid empiric evidence that not even experts in the field can differentiate red wine from white one under blind test conditions [55]. Similar tests

[4] The aesthetical criteria of a project comprise all elements which define the look and feel of the objects involved. If, for instance, the colour and the surface texture are a crucial element of a design, then the material palette and the production process for it must be defined accordingly. As we have already seen, in the case of AM, a preconditioned set of materials precludes or enables specific types of technology, often in discontinuous and counterintuitive manners.

[5] The present paper refers to MAYA as the novelty versus appeal analysis as described by Hekkert et al., not to the study of disruptive and shocking aesthetics pushed to the limit for marketing purposes, as discussed by Mayer [54].

provided concordant results for violin experts attempting to distinguish old violins from modern ones [56, 57]. If this is the case, then why do people spend orders of magnitude more money for old violins or wine from Bordeaux rather than acquiring much cheaper but similarly functional alternatives? This is a question for a different research, and studies of the kind which Hekkert et al. made would likely help elucidate the mechanisms behind these choices. While wine and violin experts place themselves at the upper end of the need-for-typicality spectrum, on the other end, we can find examples such as sports professionals, who tend to immediately integrate any innovation which leads to a performance advantage, almost independently from aesthetics or typicality. The analysis of the musical instrument niches showed that their customers were in neither extreme, and differently open or reactive to innovation. The evaluation concluded that this element was relevant to the commercial output. Therefore, the customer's openness to innovation must be accepted as an intrinsic part of the analysed market niche, to be necessarily verified whenever attempting to assess whether it will be suitable for AM production or not.

Finally, concerning the sweet spot analysis, deciding whether a product is in a plausible market price range goes beyond simply being cheaper than any alternative. Some products define their own niche by offering features that no alternative has, such as the previously mentioned customised AM hearing aids. This product, similar to some AM medical prostheses, simply has no competitor in the market in terms of features. Nevertheless, they still have to be offered at an acquirable price in order to become a viable market product rather than a one-of-a-kind or museum object. Analysing whether a product inhabits a market sweet spot is, therefore, a necessary assessment even for designs that are qualitatively far beyond the traditional alternatives, something which can quickly happen with AM designs given their intrinsic topological flexibility and freedom.

6.2 Comparative advantages

The comparative advantages of the parameters identified in this analysis are complexity, customisation, decentralised production, optimisation, and sustainability.

- Complexity: Topological complexity of the design in terms of giving AM an advantage over traditional manufacturing.
- Customisation: Assessment of whether the design can be customised through AM and whether this is a product-enhancing feature or a customer need.
- Decentralised production: Analysis of whether AM possibilities for decentralised production models give an advantage compared to traditional manufacturing techniques.[6]
- Optimisation: Assessment of whether the design can optimise traditional manufacturing techniques through AM.[7]
- Sustainability: Evaluation of possible sustainability advantages through AM's production matrix.

Comparative advantage parameters are a plus when evaluating a production niche, but they are not intrinsically essential to define a suitable AM spot. It does not matter how advantageous a design can become through customisation if the price is not competitive unless the price is not a limitation in the project and high performance is the only goal, like in the previously mentioned record-breaking bicycle. If we find ourselves in such a project, though, where the budget is not a constraint, then we do not need a niche suitability analysis to begin with. For the rest of the projects that experience real-world constraints, we can continue with this evaluation tool. As mentioned before, 'price competitive' does not necessarily mean cheaper. Sometimes, customers do decide to pay more for a product with better features. Still, the price must be competitive, meaning in a similar ballpark, and therefore accessible for the same customer niche.

Needless to say, comparative advantages can also become critical parameters through different mechanisms. For example, suppose a project is subjected to sustainability regulations. In that case, according to the law's definition, sustainability will be a critical parameter for that assessment, requiring an adjusted version of this evaluation tool.

This paper argues that mixing parameters from the critical category with the comparative advantages is a typical mistake in the AM literature. Indeed, as far as the literature review presented in the previous sections shows, they are always presented side by side when talking about AM's characteristics. A project's lack of comparative advantages is not a limitation for an AM design to succeed. Therefore, they should belong to a separate part of the assessment than the critical parameters. If an AM design can be cheaper to produce than the traditional manufacturing alternatives, it will tend to become successful even if it is not personalised, does not optimise any aspect, or is equally (un)sustainable. This is unlikely to happen due to the already mentioned AM's shortcomings, though, and indeed, the market review done for this paper delivered no counterexample. Still, such a thing is theoretically plausible and future AM technologies could eventually allow for it. In any case, given how much AM technologies have already matured, it would be unwise

[6] See for instance Montero et al.'s article on decentralised production models through AM [58].

[7] For instance reducing assembly parts as mentioned by Becker [38].

to count on upcoming technological advances to change the status quo.

7 Proposal for a numeric evaluation tool: instruments for a slope of enlightenment

The previously mentioned parameters produce two mapping sets, one for the critical elements and one for the comparative advantages, as shown in Fig. 4.

Object-oriented product metrics is a field to which a lot of research has been devoted to, yet general frameworks have struggled to emerge [59, 60]. Given their practicality and the possibility to empirically test them, numeric evaluation models are particularly powerful. This is a solid motivation to propose a numeric evaluation tool in this paper instead of the visual-only star map used in *3D-Printed Musical Instruments…* [50].

The numerical evaluation tool required to assess the critical parameters would need to be such that a low evaluation in only one of them brings the whole compound coefficient down since no critical element can be missed for a successful result. This can be achieved using individual evaluation coefficients between 0 and 1 for the different parameters and multiplying them together. A single '0' evaluation will bring the whole multiplication to 0, even if all other coefficients are 1. This formula is extreme in making single low evaluation coefficients clearly present in the compound result, but this is precisely what is needed when critical elements must be individually cleared. Therefore, the evaluation scale of the multiplication result will have to be adjusted accordingly and made non-linear. Nevertheless, this method will ensure that all critical hurdles have been cleared.

The numerical evaluation tool for assessing the comparative advantage parameters must instead only aggregate the individual evaluation coefficients since the lack of a specific advantage does not hinder the presence or validity of another. This can be achieved by simply adding together the individual evaluation coefficients.

To make a numeric assessment through the individuated critical and comparative advantages axes, it is therefore proposed to assign a coefficient between 0 and 1 for each parameter, according to the following reference goalposts:

- 0: The parameter is clearly not fulfilled or is not a feature of the project.
- 0.25: The parameter is mostly not fulfilled or is present but does not play a relevant role in the project.
- 0.5: The parameter is barely fulfilled or is present but not as a remarkable feature in the project.
- 0.75: The parameter is mostly fulfilled or plays a relevant role in the project.
- 1: The parameter is undoubtedly fulfilled or is a crucial element in the project.

Of course, if the evaluator considers it suitable, more nuanced figures between the provided goalposts can be used.

Let us now apply this evaluation system to the previously mentioned musical instruments case study. Of the five different cases, one was one-of-a-kind project (the slide pipes), and one was intended to be a research-only endeavour (the fagottini). These two projects were, therefore, never meant to potentially become commercially successful and it does not make sense to analyse their respective niches from that perspective. The remaining three projects (cornetts, shakuhachis, and ukuleles) were meant to eventually become commercially successful, but as explained in the article, this was not the

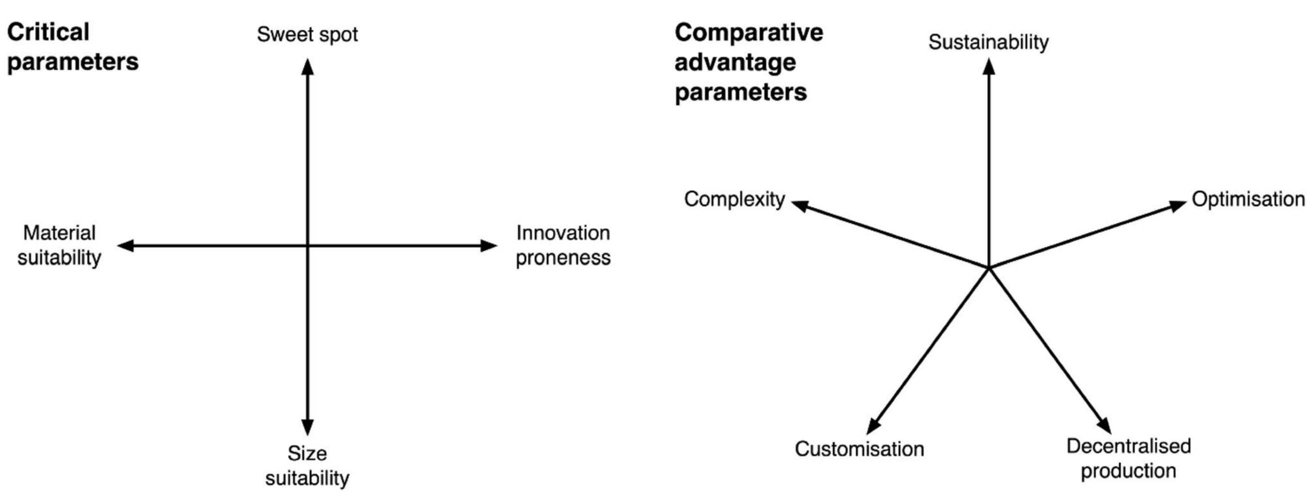

Fig. 4 Four-axe evaluation map for critical parameters (left) and five-axe evaluation map for comparative advantage parameters (right). Diagrams by Ricardo Simian

case. By applying the proposed numeric assessment tool to these three cases, the results shown in Table 1 are obtained.

Let us now use these results to calibrate the evaluation scale of the resulting aggregate coefficients based on the real-life performance of these three cases as AM production niches, as reported in *3D Printed Musical Instruments…* [50].

Analysing the aggregate results for the critical parameters, which according to the formula can be between 0 and 1, the following evaluation scale seems to suit what can be observed in the real-life results presented in *3D Printed Musical Instruments…* [50]:

- 0 to 0.19: The analysed niche is not suitable for AM production.
- 0.2 to 0.29: The analysed niche is potentially suitable for AM production.
- 0.3 to 0.39: The analysed niche is suitable for AM production.
- 0.4 to 1: The analysed niche is highly suitable for AM production.

Analysing the aggregate results for the comparative advantages instead, which according to the formula can be between 0 and 5, the following evaluation scale seems to be reasonable:

- 0 to 0.99: The analysed niche does not make use of AM's innovative features.
- 1 to 1.99: The analysed niche makes little use of AM's innovative features.
- 2 to 2.99: The analysed niche makes use of AM's innovative features.
- 3 to 3.99: The analysed niche makes good use of AM's innovative features.
- 4 to 5: The analysed niche makes full use of AM's innovative features.

Table 1 Evaluation chart for cornetts, shakuhachis, and ukuleles

	Cornett	Shakuhachi	Ukulele
Sweet spot	1.00	0.75	0.25
Material suitability	0.75	0.50	0.75
Size suitability	1.00	1.00	1.00
Innovation proneness	0.75	0.75	0.75
Aggregate coefficient critical parameters	**0.56**	**0.28**	**0.14**
Sustainability	0.00	0.00	0.00
Optimisation	0.50	0.25	0.75
Decentralised production	0.50	0.50	0.50
Customisation	1.00	0.75	0.50
Complexity	0.75	0.50	1.00
Aggregate coefficient comparative advantages	**2.75**	**2.00**	**2.75**

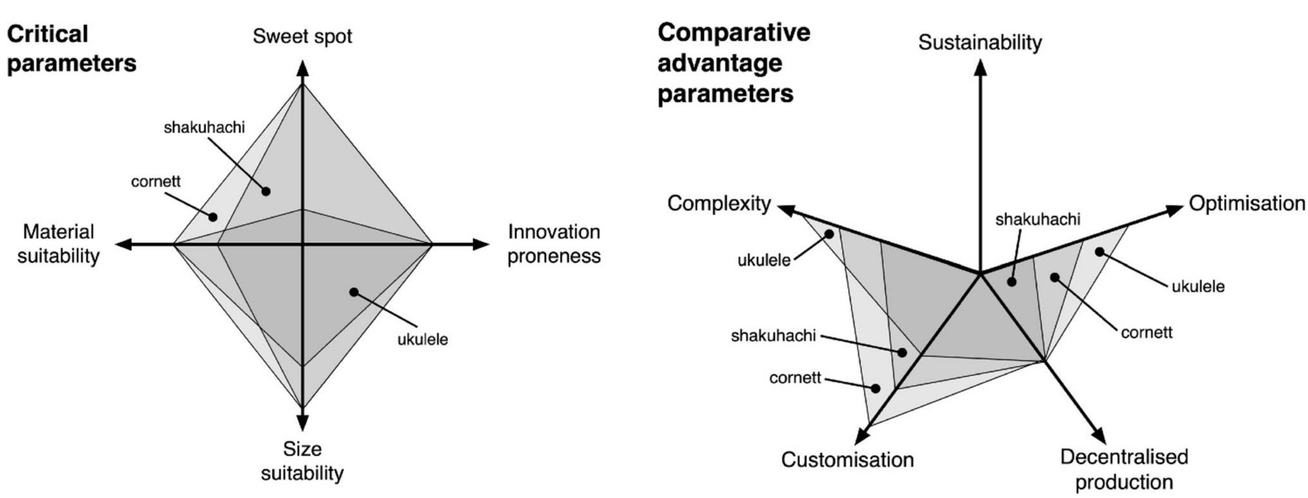

Fig. 5 Four-axe map for the critical parameters (left) and five-axe map for the comparative advantage parameters for cornetts, shakuhachis, and ukuleles. Diagram by Ricardo Simian

8 Applying and testing the tool: building a plateau of productivity

The proposed evaluation tool delivers not only a numeric evaluation and its corresponding assessment but also the four- and five-axe visual mappings described in Fig. 4. By using the evaluation coefficients from Fig. 5 to generate such mappings, we obtain the following visual evaluations for the three musical instruments as AM production niches (Fig. 5):

Combining the critical and comparative advantage assessments described in the previous section, the tool delivers composed evaluations such as 'the niche is not suitable for AM production despite making good use of AM's innovative features'. In the case of the three analysed musical instruments, these compound assessments read as follows:

- The cornetts are a highly suitable niche for AM production that makes use of AM's innovative features.
- The shakuhachis are potentially a suitable niche for AM production that makes use of AM's innovative features.
- The ukuleles are not a suitable niche for AM production despite making use of AM's innovative features.

Since the assessment scales have been tuned to accommodate the existing data on the performance of the musical instruments, this evaluation is little more than the translation of existing information into a different format. Nevertheless, the fact that using the evaluation scales and the defined formulas consistently for the three cases produced different compound results which can be fitted to a reasonable evaluation guideline shows that the evaluation tool is at least potentially sound. Let us now test this evaluation tool with a different, external case study to see if it keeps delivering a reality-matching assessment. For this purpose, Adidas' AM sneaker, an emblematic endeavour in the AM production field [61], seems reasonably suitable for the task.

Adidas launched a partially AM-produced shoe called Futurecraft 4D in 2017 featuring user-customised midsoles (Fig. 6). A key element of this design was the use of CLIP technology, which allows for many types of polymers while increasing production speed notoriously in relation to previous SLA units. The first 5000-unit limited edition sold out but did not become a permanent member of Adidas' shop [62]. After Futurecraft 4D, several iterations of the project have been launched, starting with Alphaedge 4D in 2018 (Fig. 6) and arriving at the currently available version, called 4DFWD [63]. All versions after the original 4D have dropped the design's midsole customisation element, which is a pity since it was a flagship attempt to push AM production into mass-customisation territory.

Adidas's shop offers a broad palette of models and prices. Within those options, the 4DFWD models cost

Fig. 6 Adidas Futurecraft 4D (left) and Adidas Alphaedge 4D (right). Photo by Ricardo Simian

roughly 50 to 100% more than similar models with standard midsoles. The design is not customised but advertises a better performance through its midsole's complex topology, which could not be produced with standard manufacturing methods. If this were truly the case, all Olympic athletes would be running on such shoes almost regardless of the price tag, though.

Finding a suitable material for this design was a difficult task, according to Carbon itself:

Carbon's EPU 41 was the only printable material that came close to the requirements for this application. When launching the collaboration our teams realized that in order to make the shoe of the future, we needed to take what was already an incredible material and push the boundaries even further. [64].

As mentioned before, sports professionals are not primarily interested in the looks of their gear as long as it performs, but average Adidas customers are very worried about aesthetics instead, particularly when investing more than usual for an item, which is the customer segment 4DFWD is aiming at. Colour palette limitations, as well as other aesthetic design constraints imposed on the project by choosing CLIP AM, are, therefore, an additional hurdle in this case.

Regarding size suitability for the project, Carbon's AM units are perfectly suitable for shoe midsoles. They better be since they were developed for this scope thanks to a USD 200 million investment by no other than Adidas [65].

Assessing these elements through the evaluation tool, the results shown in Table 2 can be obtained:

These results can be read as 'Adidas 4DFWD is potentially a suitable niche for AM production despite making little use of AM's innovative features'. In the following years, we shall see whether Adidas has found a sound niche through a product that the proposed evaluation tool qualifies within the risk

Table 2 Evaluation chart for Adidas 4DFWD

	Adidas 4DFWD
Sweet spot	0.50
Material suitability	0.75
Size suitability	1
Innovation proneness	0.75
Aggregate coefficient critical parameters	**0.28**
Sustainability	0.25
Optimisation	0.5
Decentralised production	0
Customisation	0
Complexity	1
Aggregate coefficient comparative advantages	**1.75**

zone. It must also be noted that a giant such as Adidas may as well support sidekick projects within its portfolio with interests beyond purely economic ones, something a small company could not allow itself. Adidas' strategic planning and finances are not public to scrutinise in this regard.

It is self-evident that retrodictions, such as those presented here for the musical instruments and Adidas 4DFWD, are less potent than predictions when putting a hypothesis to the test. Nevertheless, at least it can be said that the evaluation tool's results are nuanced in matching the real-life performance of these designs as commercial endeavours. Likewise, for Adidas' 4D designs, the evaluation tool places them in the risky zone between unsuitable and suitable, which perfectly coincides with the continuous reworks and relaunches of the project. Furthermore, given the empirical nature of this evaluation tool, the correct procedure to correct or improve it is to first put it to the test retroactively, then fine-tune it to better fit real-world market reactions and results by using more data, and then make verifiable predictions.

This paper proposes that this evaluation tool, or a fine-tuned version of it (eventually integrating more parameters), would be fundamental to identify suitable niches for AM production better, to avoid or correct projects which may superficially look attractive but are not viable, as well as also identifying potential niches which have remained unobserved. Needless to say, more work is needed to fine-tune the evaluation scales and to make verifiable suitability predictions through it to test its validity, solidity, and reliability.

9 Conclusions

AM's characteristics, possibilities, and limitations create a complex production matrix, wildly discontinuous in nature, where adjustments in one parameter may imply major changes in others, often in counterintuitive manners. Production niches that intend to use AM for end-product purposes, and their related designs, find themselves at the non-trivial intersection between engineering, AM expertise, marketing, design, and niche-specific knowledge. Successfully navigating such cross-field environments, and finding solutions for them in the discontinuous AM landscape, is not a trivial task; and therefore, it should not come as a surprise that we have mostly seen very niche-specific successes in such attempts.

Correctly identifying which production niches are suitable for AM production is a central part of this topic, but there is a lack of tools in the literature to make such assessments. Starting from a set of case studies conducted for over a decade in some cases, this paper proposes a suitability assessment tool for production niches. This tool aims to verify whether AM can be successfully used in them and see if it carries comparative advantages to traditional manufacturing methods. It can be used to iteratively review and adjust designs and projects to bring them to a feasible AM production track. The main aim of this assessment tool is to help avoid unsuitable production niches for AM at early development stages, as well as eventually correct designs and projects in an iterative manner, bringing them back to a functional AM track if possible. Finally, it is also expected that this tool will help find possible AM production niches which have not been identified as such, therefore contributing to the development of a proper AM plateau of productivity, something which, despite matured technologies, the field is yet to see broadly.

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Data availability Not applicable.

Code availability Not applicable.

Declarations

Conflict of interest The author declares being the founder and director of 3D Music Instruments, a startup at the core of the research made on AM musical instruments which was used as a fundamental source for this paper.

Ethics approval This research did not require ethics committee or IRB approval. This research did not involve the use of personal data, fieldwork, or experiments involving human or animal participants, or work with children, vulnerable individuals, or clinical populations.

Consent to participate Not applicable.

Consent for publication Not applicable.

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