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Distilling Design Theory and Methodologies for Additive Manufacturing from Case Studies

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Abstract

Additive manufacturing (AM) is a palette of digital fabrication tools that has quickly established itself as one of the key prototyping methods used during design development processes. Nevertheless, end-product applications of AM are rare and usually limited to high-end customised niches, such as medical implants or one-of-a-kind, expensive and high-performance objects (Anton et al., 2024; Attanasio, 2022; Madan et al., 2022; Prior, 2024; Reeves, 2013). The lack of more daily examples of successful AM end products despite a mature technology raises the question of whether there are no real niches for AM end products or if designers have not yet been able to identify and address them. I argue that a lack of suitable design theory and methodologies (DTMs) integrating a modern understanding of AM is at least partially responsible for the lack of progress. In this study, I analyse the current state of AM applications for end-product manufacturing and propose a bottom-up approach for creating AM DTMs from case studies to address the lack of available literature in the field.

1. Introduction

Additive manufacturing (AM) is not a novel set of technologies, but its design theory and methodologies (DTMs) are not yet up to pace with technological developments in the field (Killi, 2017). Taking the definition that design methodology 'is about how to design, more precisely, a design process model with logical consequential phases in which a design task is completed to develop product specifications' (Tomiyama et al., 2009), standard DTMs are challenged as end-product applications start to emerge from the original rapid prototyping purpose of AM (Yang & Zhao, 2015). This creates a need for a specific and updated theory and methodologies for this in-development environment.

Most academic literature in the field approaches the issue from a top-down perspective, reviewing methods (Yang & Zhao, 2015) or frameworks (Renjith et al., 2020), somehow dismissive of the massive volume of empirical experimentation delivered daily. Nevertheless, the majority of the available AM literature remains mainly divulgatory rather than academic in nature, as numerous volumes such as *Makers: The New Industrial Revolution* (Anderson, 2012), *Printing Things: Visions and Essentials for 3D printing* (Warnier et al., 2014), *Fabricated: The New World of 3D Printing* (Lipson & Kurman, 2013), *3D Printing for Artists, Designers and Makers* (Hoskins, 2018) and many others show. These volumes mostly showcase applications of the technology, sometimes exploring speculations on future possibilities without discussing theoretical aspects.

'By grouping records of individual design cases belonging to a specific product class and by extracting commonalities among them, we obtain "design methods"…' (Tomiyama et al., 2009). However, how does this process work? This paper discusses a constructive approach to generating DTMs in a bottom-up manner, using case studies as a starting point and aiming at generalising theory and methodologies for the field in a structured manner. I argue that Eisenhardt's (Eisenhardt, 1989) paper *Building Theories from Case Study Research*, with minor adjustments, can provide a suitable roadmap for this niche-oriented effort.

The results of this analysis will be discussed and placed in context within the existing literature, mainly represented by Killi's *Additive Manufacturing: Design, Methods and Processes* (Killi, 2017) and *Designing for Additive Manufacturing: Perspectives from Product Design* (Killi, 2013), which describe the adapt, integrate, compensate and elongate (AICE) approach for integrating AM and design practise.

2. End-Product-Oriented AM

AM's field of application evolution can be determined through the iterations of the most used technical names for it. Upon introduction, it was known as rapid prototyping, implying an evident scope. The second widely used nomenclature, rapid manufacturing, signalled a paradigm shift. This set of technologies can also be used to manufacture products instead of only helping in their development. However, this term was flawed. AM can certainly be fast as a method for prototyping compared with the available alternatives, but AM is certainly not as fast as a manufacturing machine compared with mass production methods. Thus, a third iteration was needed: AM, which gives a much better description of how the technology works, does not imply rapidness and opens the door to end-product applications (Gibson et al., 2020; Savini & Savini, 2015).[1]

Once the idea that AM could be used for end-product manufacturing settled in, different speculation lines on plausible futures took off. One line of thought focused on production flexibility, hypothesising an upcoming 'mass customisation' age (Reeves, 2014), while some analysts speculated on the democratisation of the design process that these new and disruptive production possibilities would bring (Kolarevic, 2015). Several authors pushed these concepts further by describing an upcoming utopia in which food, housing and customised objects of every kind would be supplied by AM on demand, locally produced in a sustainable manner, and optimising material use (Deighton, 2014; Lipson & Kurman, 2013). Different visions of this AM utopia usually come together under the umbrella concept of the so-called fourth—or new—industrial revolution (Anderson, 2012; Hopkinson et al., 2006).

On a more realistic plane, some researchers have started defining a roadmap aimed at better integrating AM into design and product development. However, most of these examples use AM as a prototyping tool rather than as an end-product manufacturing alternative (Capjon, 2004; Panda et al., 2023). Architecture stands out as a prolific field when looking for recent examples of the manufacturing-oriented use of AM. Numerous recent publications have explored the idea of using AM as a potential tool for building (Campos et al., 2020; Ibrahim et al., 2022; Puzatova et al., 2022; Salandin et al., 2022; Shen et al., 2022; Žujović et al., 2022). Some authors have even extended this analysis beyond planet Earth (Juračka et al., 2023; Korniejenko et al., 2022) or speculated on using AM to solve nothing less than housing crisis, emergency shelter need or construction sustainability (Flatt & Wangler, 2022; Gregory et al., 2016; Hager et al., 2016; Lojanica et al., 2018; Mahdi, 2021; Monroe, 2023; Sonwalkar, 2020; Tay et al., 2020; WASP, 2019). As much as I would like all these visions to become reality, in a world where prefabricated houses have been developed and optimised for centuries (Blasco & i Fausto, 2024), AM is unlikely to offer anything more practical, quicker or comparatively affordable. The potential advantages of AM in construction can eventually be derived from complex topologies, but elaborate architectonical shapes are not the priority and seldom overlap with the design of affordable or sustainable buildings. The repeated failure to understand this elementary fact, as consistently seen in the literature, is another example of the argument advanced in this paper: current DTMs for AM fail to understand AM's qualities, advantages and disadvantages, and this likely comes as a consequence of the usual top-down view rather than using a case-study-based bottom-up approach. Indeed, several case studies on AM construction can be found for 'first building of its kind' or 'experimental architecture' (Anton et al., 2024; Bhooshan et al., 2022; Salandin et al., 2022), but no concrete examples of successful affordable AM housing or AM being used to solve basic construction issues exist. Therefore, a bottom-up, case study-based approach could not produce DTMs with such fundamental misunderstandings.

In terms of applied reality and concrete attempts to develop functional DTMs for AM, current shortcomings of available software have been pointed out, for example, concerning the difficulties in dealing with irregular wall thicknesses (Bitonti, 2019, pp. 33-34).[2] According to my review, the most recent literature on my line of research was advanced by Killi and Kempton (Kempton, 2019; Killi, 2013, 2017), who identified numerous shortcomings of existing DTMs for AM. Killi's AICE approach, which will be discussed in detail in Section 7, is the most salient attempt to generate new DTMs for AM as a manufacturing tool. I will use the roadmap defined by this approach in my study.3

3. From Current Design Methodologies for AM to a Bottom-Up Approach

In *Rethink Assembly Design* (Becker et al., 2005, pp. 262-266), the following set of guidelines for AM design is advanced:

- Use the advantages that are included in [rapid manufacturing] RM processes.
- 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 using intelligent integration of functions.

These guidelines are still perfectly valid today, even though their concrete application is experience based. Only a user with previous experience in design for AM can know what the undefined advantages of RM, as mentioned in the first point, can be. The same can be said for how the 'intelligent integration of functions' can be achieved through AM.

Better-defined guidelines requiring less initial trial and error from newcomer users can and have been codified ever since. However, their approach remains classically top-down; from a set of guidelines, users should work their way down to the practicalities of specific cases, hopefully helping achieve a good result. Case studies are eventually included in this bulk of literature only as a verification test of the methodology after having explained it, such as the hosing cover example in Renjith et al.'s *A Design Framework for Additive Manufacturing: Integration of Additive Manufacturing Capabilities in the Early Design Process* (Renjith et al., 2020).

Few analyses in this field have placed case studies in the foreground. One such example is *Take Cover: Case Study in Artisan Telephone Covers for DDM* by Killi and Kempton (Kempton & Killi, 2014). Nevertheless, generalising knowledge from such niche cases is challenging. How could the shortcomings encountered in using SLA (stereolithography, a photochemical-based type of AM) for cell phone covers be of use for producing hearing aids with the same technology, for instance? This is likely the reason for the lack of advancement in this endeavour. Nonetheless, I argue that this effort is necessary for the field's progress to move from utopic speculation to more and better results in reality. In particular, I assert that integrating a better understanding of the role that specific application niches play in the design and production matrix should be a fundamental topic at the forefront rather than an anecdote at the end of the development process, which is the way it tends to happen when we approach DTMs for AM in a top-down manner. I identify this aspect as a relevant research gap that must be addressed.

4. 'Building Theories from Case Study Research' by Eisenhardt

> Traditionally, authors have developed theory by combining observation from previous literature, common sense, and experience. However, the tie to actual data has often been tenuous. Yet, as Glaser and Strauss argue, it is the intimate connection with empirical reality that permits the development of a testable, relevant, and valid theory. (Eisenhardt, 1989)

Eisenhardt proposed a roadmap for building theory from case study research, addressing a gap in the literature and research practice. For this purpose, she defines a process in eight steps: getting started, selecting cases, crafting instruments and protocols, entering the field, analysing data, shaping hypotheses, enfolding literature and reaching closure. According to her analysis, 'Theory developed from case study research is likely to have important strengths like novelty, testability and empirical validity, which arise from the intimate linkage with empirical evidence'. This is something we would certainly like to achieve in the design-for-AM field.

The relationship between theory and methodology is a complex issue that is openly debated between different schools of thought. In design, theory and methodologies are notoriously intertwined, often even referred to as a single 'field of design theory and methodology' (Tomiyama et al., 2009). In the present analysis, I refer to the symbiotic understanding of the relationship between theory and methodology described by Chan and Clarke in *Rethinking the Connection Between Theory and Methodology: A Question of Mutual Affordances* (Chan & Clarke, 2019). In this understanding of mutual and reciprocal affordance, I propose that Eisenhardt's eight-step roadmap for distilling theory from case studies, with some minor adjustments, can be suitable for building design theory and methodologies within the AM field. This approach aligns with the 'grouping records of individual design cases belonging to a specific product class and by extracting commonalities among them' process described by Tomiyama.

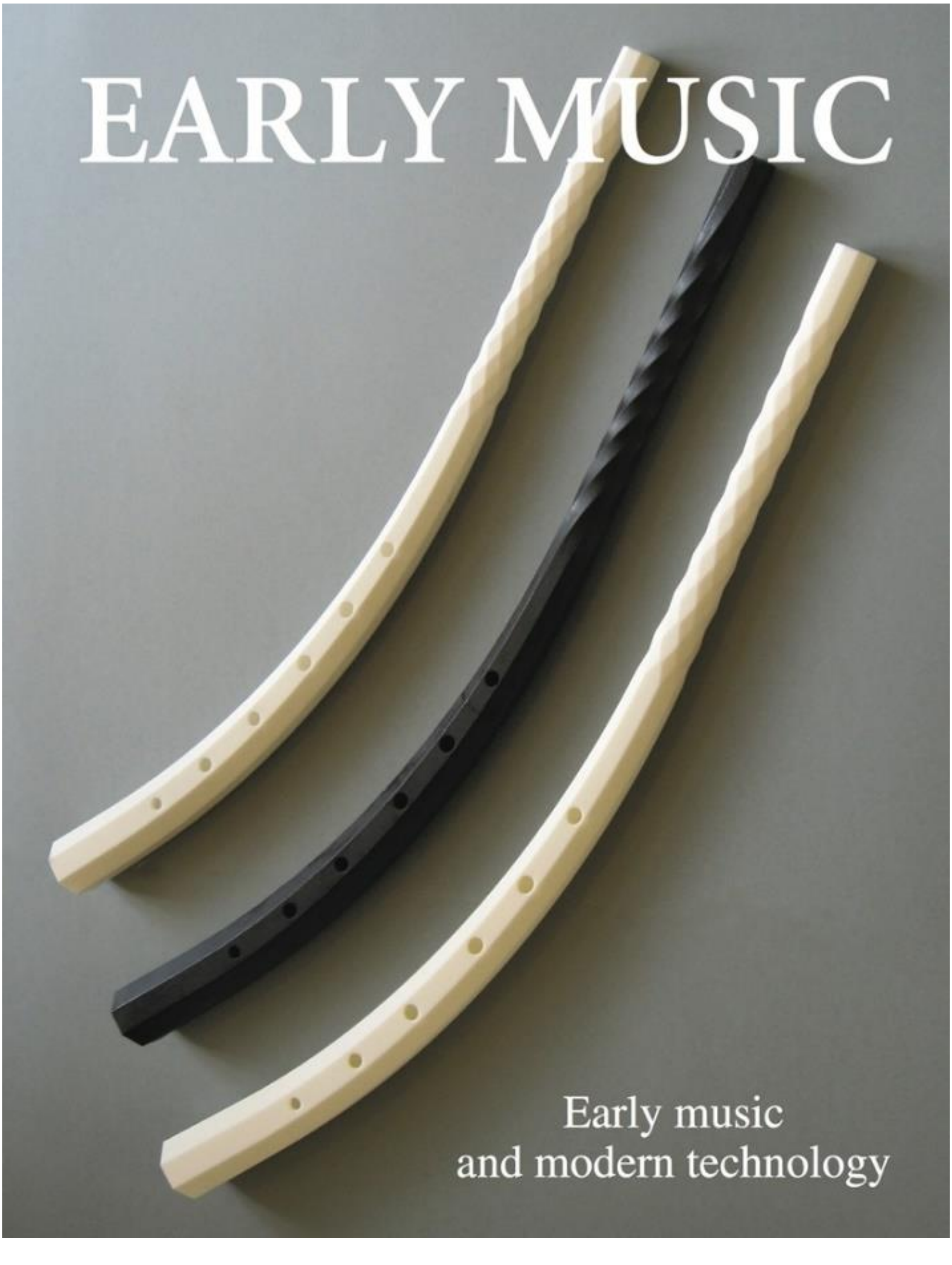
The sixth step mentioned by Eisenhardt (shaping hypotheses) requires special attention in my analysis. As I do not aim to build theory only but also methods, I propose focusing not only on how hypotheses explain or refute the data but also on how design methodologies repeat observed successes and avoid failures. Therefore, I rename this step 'shaping hypotheses and methodologies'.

5. Selected Case Studies in End-product AM

The case studies selected for my analysis belong to a particular niche: musical instruments produced through AM. This unusual application of AM technologies lies at the intersection of many different areas, including culture, tradition, acoustics, museology, pedagogy, crafts, industry, ergonomics and design. Early reports on the progress of the experimentation and plausible future scenarios for AM musical instruments were provided in a paper co-authored with Jamie Savan titled *CAD Modelling and 3D Printing for Musical Instrument Research: The Renaissance Cornett as a Case Study* (Savan & Simian, 2014) and in Howe et al.'s (Howe et al., 2014) *Digital Evaluation and Replication of Period Wind Instruments: The Role of Micro-Computed Tomography and Additive Manufacturing* (Figure 1). A deeper analysis of the business scenario for musical instruments was presented by Berlin et al. (Berlin et al., 2016) in the master's thesis *Musikinstrumente Aus dem 3D-Drucker*. Further developments in the area were discussed in an article co-authored with Stefan Verdegem called *Adding a New Dimension to Woodwind Instrument Making, With a Little Help from Our (Tech) Friends* (Verdegem & Simian, 2022). I recently presented a more expansive dataset of case studies, including long-term developments, in *3D-Printed Musical Instruments: Lessons Learned from Five Case Studies* (Simian, 2023).

Figure 1

Early Music Journal's cover, volume 42 (2014), featuring 3 AM cornetts. Design and photo by Ricardo Simian.



3D Music Instruments was the start-up I founded to examine the applications of 3D modelling and AM in developing and producing musical instruments. During its existence, 3D Music Instruments gathered a large volume of case studies and won the Purmundus Challenge Design Award for AM in 2018 (Manglani, 2018).[3] Following Eisenhardt's advice ('…while there is no ideal number of cases, a number between 4 and 10 cases usually works well') from the available case studies, I selected the following nine musical instruments for the purposes of the current analysis (Eisenhardt, 1989):

- Renaissance cornett: Development and production of the whole array of instruments belonging to the Renaissance cornett family.[4]
- Perfetto: Revisited the modern iteration of the Renaissance cornett in an attempt to enhance its possibilities through AM.
- Ukulele: Development and production of AM ukuleles integrating new design features through AM (Figure 2).
- Slide pipe consort: A custom set of instruments developed for composer Jasper Vanpaemel's composition 'XYZ', which premiered at the Concertgebouw in 2019 (Simian, 2019).
- Fagottini and tenoroons: A set of replicas of museum instruments belonging to the now-forgotten instrument family of the fagottini and tenoroons as part of a series of research projects conducted by the Schola Cantorum Basiliensis in 2017–2023 (Simian, 2025).
- Cornelele: Hybrid novel instrument integrating a ukulele and a cornetto into a single body (Figure 4).
- Slide trumpet: Development and production of mediaeval and renaissance slide trumpets, which are transition instruments between the natural trumpet and the early trombone.
- Renaissance shawm: Development and production of Renaissance shawms, double-reed instruments that would later evolve into the oboe.
- Shakuhachi: Development and production of the shakuhachi, a traditional Japanese flute.

Figure 2

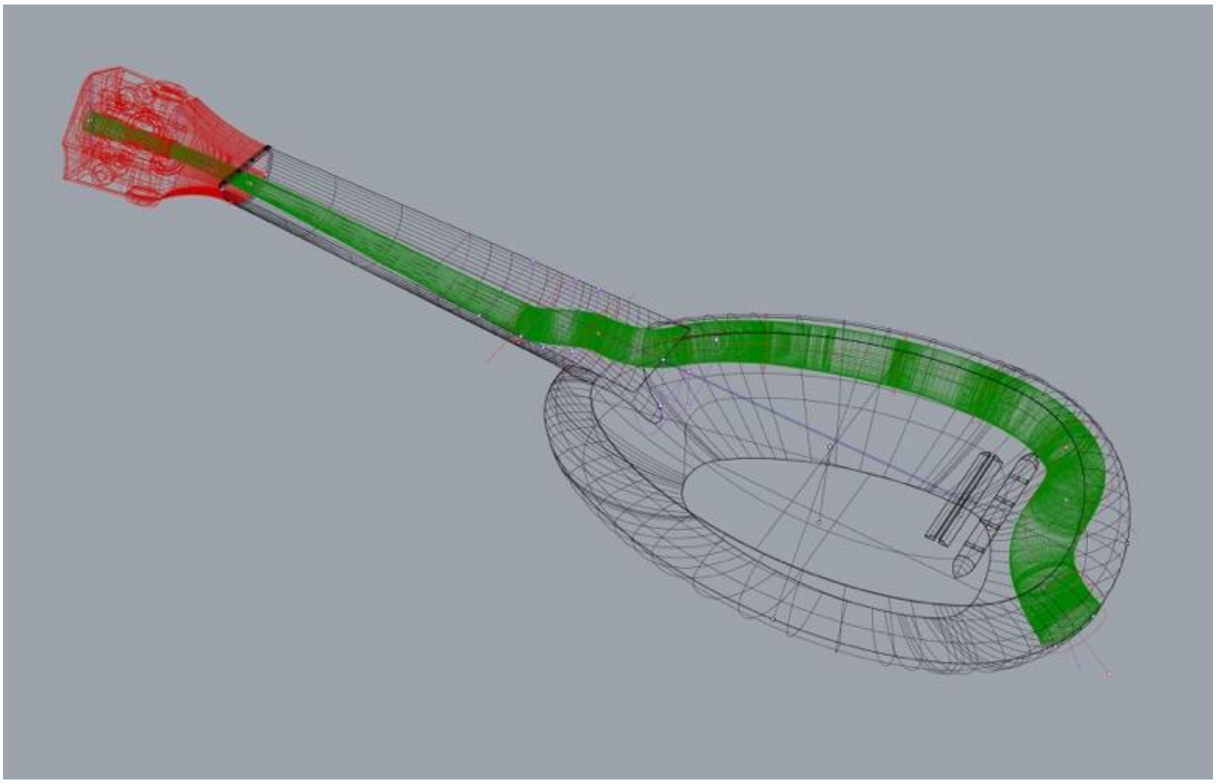
AM ukulele. Design and photo by Ricardo Simian.

Figure 3

Historical fagottino (wood) alongside its AM replica (white Nylon PA12). 3D model and photo by Ricardo Simian.

Figure 4

3D model of the cornelele showing the cornett's inner bore inside a ukulele body. 3D model and image by Ricardo Simian.



These case studies led to notoriously different outcomes in terms of further development and production demand. Although some of them, such as the cornelele, never had potential customers and were intended only to be an experiment to test the limits of the technical possibilities, the cornett, ukulele, slide trumpet, shakuhachi and shawm are instruments in use with active performing communities (Simian, 2023). This potential customer base could have demanded further production of the resulting instruments, but this effectively occurred for only some of them. The matrix of elements that led to these divergent results is complex and involves tradition, culture, marketing, production prices and specific established production alternatives for each. I observe that this niche/market analysis has been neglected in most AM DTMs. Furthermore, I argue that this is a crucial element when trying to understand why there is a large gap between the all-encompassing predicted 'fourth industrial revolution', which many argued was the future of AM (D'Aveni, 2015; Deighton, 2014; Hopkinson et al., 2006), and the very circumscribed successes we have seen in reality thus far (Wanke, 2019).

I expect that the theory and methodologies distilled from these case studies will:

- Shed light on the reasons behind the divergent results regarding market niche suitability.
- Provide insight into the analysis of when and where AM provides comparative advantages instead of simply telling what can be technically produced through AM.
- Help to individuate novel suitable niches for AM that have not been discovered insofar.

6. Distilling DTMs from Case Studies

Having defined the research question and the case studies to be used, we then addressed the first two points in Eisenhardt's roadmap (getting started and selecting cases). Let us now examine the application of the following six steps in the proposed DTM building process:

- Crafting instruments and protocols: This step focuses on data collection. For our case studies, a suitable set of qualitative and quantitative parameters and indicators is defined.
- Entering the field: In this step, we are expected to overlap data collection with analysis, eventually revealing the need to adjust the collection phase and reiterate it.
- Analysing data: Within-case and cross-case analyses are conducted in this step. The differences and agreements between the different case studies, as well as the successes and failures, are revealed.
- Shaping theory and methodologies: Through an iterative tabulation of the evidence for each construct, we search for causal evidence between the DTMs used and the observed relationships in the data.
- Enfolding literature: Similar and conflicting literature is compared to help develop internal validity and sharpen concepts.
- Reaching closure: In Eisenhardt's words, the process ends 'when marginal improvement becomes small'.

This sequence of steps, which uses selected data from the abovementioned nine case studies, is the thread that I used in the article *Evaluating the Suitability of Niches for Additive Manufacturing Production: Proposal for a Numeric Evaluation Tool* (Simian, 2024), published by the International Journal of Advanced Manufacturing Technologies. This paper represented the first application of the research approach to develop DTMs for AM described in this text, and it aimed at better understanding how different production niches work for AM as an end-product manufacturing tool. The argument presented was built upon the analysis and comparison of different AM case studies from the musical instrument realm, delivering a numeric evaluation tool.

7. Contribution of the Resulting Methodologies to Existing Literature

The 'enfolding literature' step in the proposed roadmap addresses the comparison between similar and conflicting literature. As explained in the introduction, while numerous top-down sources can be found, there is a lack of literature addressing DTMs for AM from a bottom-up perspective.

The most relevant exception to this is represented by Killi's (Killi, 2013, 2017) AICE approach and further commented on by Kempton (Kempton, 2019). This sketch of a method is conceived as a holistic approach to integrating design, engineering and production when using AM. The four letters of the acronym stand for adapt, integrate, compensate and elongate.

- Adapt: Presents suggestions on how creative, analytical, operational and other methods could be adapted to AM, not only as a means of production but also as a facilitator through the entire development process.
- Integrate: Presents suggestions on how the engineering and production process should/could be integrated into the design process, providing instant and constant feedback on the development of the shape.
- Compensate: The moderator step addresses questions such as how deficiencies in the process could be compensated, balanced and restructured.
- Elongate: This addresses the lean possibilities in AM, with redesign as a continuous process, whether it is custom-made or during co-creation.

AICE approaches the entire development, production and even post-production possibilities, such as emerging developments and unexpected spin-offs, holistically and iteratively. The element that is less present in this matrix is the starting niche analysis, which is the richest aspect of the nine case studies selected for analysis. Therefore, I expect a contribution to the existing literature to emerge at this point.

The first example of such a result is the previously mentioned article titled *Evaluating the Suitability of Niches for Additive Manufacturing Production: Proposal for a Numeric Evaluation Tool* (Simian, 2024), which contributes to the niche analysis quadrant. This contribution is in the form of a numeric evaluation tool for AM niches, a complete novelty in the field, according to my literature review. Based on this success, I believe that further analysis of applied AM case studies and their data, following the process described in this paper, could and should deliver novel insights into the field and motivate updated and enhanced DTMs for AM.

8. Conclusion

Design for AM aimed at end-product development and production is not a novel field. Nevertheless, it can be argued that it has taken longer than usual for it to reach a plateau of productivity in its hype cycle, stalling in a peak of inflated expectations (Steinert & Leifer, 2010). The lack of suitable DTMs for this purpose has also played a role, as traditional design approaches have been developed for traditional production methods, which are very well developed and understood but have an entirely different matrix of possibilities and limitations.

Attempts to create DTMs for AM have mostly used a top-down approach, leading to general guidelines requiring previous user experience. Case studies have been integrated into this literature only as verification examples at the end of the argumentation. This paper proposes a process to address the lack of DTMs for AM and the lack of bottom-up analysis in the field by distilling methodologies from selected case studies. The roadmap for this endeavour uses an adapted version of Eisenhardt's *Building Theory from Case Study Research* as the backbone (Eisenhardt, 1989).

The resulting DTMs are expected to contribute to the existing efforts in the field, mainly represented by Killi's (Killi, 2013, 2017) AICE approach, and to set a model for further development of DTMs for AM using the voluminous available data in the form of case studies.

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CONFLICT OF INTEREST
The author declares being the founder and director of 3D Music Instruments, the start-up at the core of the case studies advanced in this paper as material for distilling DTMs for AM.

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[1] Independent from these iterations, the most used term for AM in everyday language, 3D printing, will likely remain in use interchangeably with AM, despite being technically incorrect as it corresponds to the name given in a patent to a specific technology within a whole palette of options comprised under AM ISO/ASTM 52900.

[2] These shortcomings of existing tools are to be expected as they were developed for traditional production methods with specific possibilities and limitations.

[3] Some of these case studies are the source material of the article '3D-printed musical instruments…'. (Simian, 2023).

[4] Not to be confused with the cornet with one 't', which is a modern brass instrument closely related to the trumpet.