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Demystifying “absolute truths” of additive manufacturing

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ABSTRACT

The hype around additive manufacturing technologies suggests that any complex shaped structure can be fabricated regardless of the type of material used. Moreover, it is often suggested that additive manufacturing processes will certainly disrupt the supply chain logistics and that everyone will be able to print on the demand at the comfort of their home. In this viewpoint, we describe and demystify some of the common assumptions associated with these set of technologies. We also show that conventional manufacturing processes cannot be fully replaced by additive manufacturing technologies, but rather there is a need for a complementarity between well-consolidated manufacturing technologies and additive manufacturing. While some of the contents presented here are basic for specialists working in the manufacturing field, we expect that this viewpoint can aid researchers working on topics related to additive manufacturing, but with less focus on the manufacturing aspects, helping them understand the actual limitations and advantages associated to these technologies. The four key issues that are addressed in this viewpoint, and their consequences, also intend to shape and mold future entrepreneurial efforts on additive manufacturing, as well as define future impacts (environmental, logistics, commercial and disruptive) associated to additive manufacturing technologies.

1. Introduction

Additive manufacturing is one of the hottest topics nowadays. The hype around additive manufacturing is also perceived by society [1–4]. For example, key outlet journals often put out news on the “novel and advanced things” that are and will be enabled by additive manufacturing soon. Indeed, some of the proposed advances are true. Previously, it was (correctly) foreseen that 3D printers would be entering our homes and our lives easily [5]. The massive introduction of plastic 3D printers as an easy, low cost and accessible way to create small parts for day-to-day use was further evidenced during the peak of the covid-19 pandemic where these devices were used to create face shields for medical workers, but also for the general population [2]. As in all technologies, depending on the user, additive manufacturing can be also for less desirable applications, where the widespread of guns made using conventional 3D printers has been on the rise [6].

Despite the key importance of these technologies, we believe that some misconceptions must be addresses aiming at providing a clearer understanding on the impact, potential impacts, opportunities, and disadvantages associated with these additive manufacturing technologies.

In this viewpoint, we layout some key “absolute truths” and demystify them with scientific evidence of the large existing body of knowledge on additive manufacturing. These “absolute truths” are considered facts that are often observed in the literature dealing with additive manufacturing, but lack proper support from preexisting knowledge on multiple topics that are associated to manufacturing technologies (from more conventional and well-established processes to new ones). Four key issues are addressed in terms of the associated misconception, reality, and consequences. We believe that this work will be useful to create more awareness to researchers working on additive manufacturing with less connection to the processing side of these technologies, but also to society on the actual role of different additive manufacturing processes.

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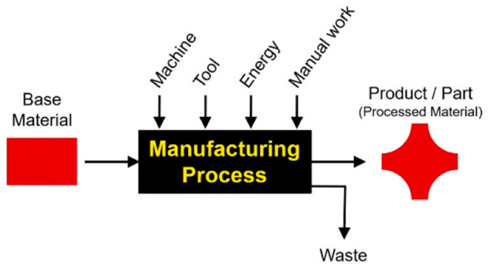


Fig. 1. The essence of a Manufacturing Process (MP): convert base materials into finished or semi-finished products or parts. The base material is processed, by means of machines, tools, and energy, until a set of properties and/or dimensions are obtained.

2. Additive manufacturing misconceptions, reality, and consequences

2.1. Key issue #1

The radical novelty and the essence of additive manufacturing.

2.1.1. Misconception

"Additive Manufacturing is something radically new; a revolutionary way to produce almost everything; an unparalleled technology; a new production philosophy".

2.1.2. The reality

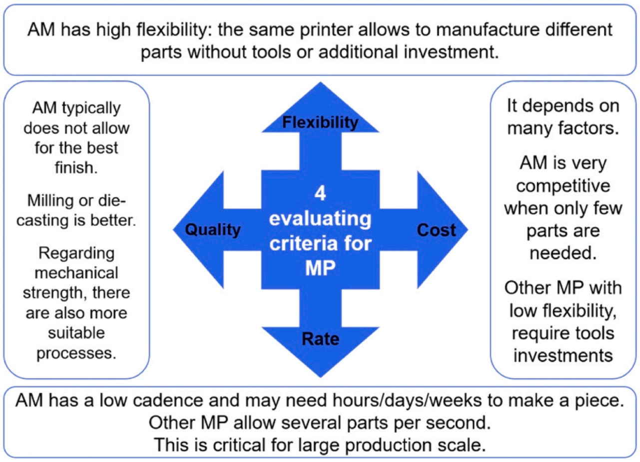
In its core, additive manufacturing technologies allow to convert *base materials* into finished or semi-finished *products* or parts [7,8]. This is nowhere different from conventional manufacturing technologies, as casting, forging, welding, or machining, where a certain base material experiences a predefined processing route(s) until a set of properties and/or dimensions are obtained. Therefore, additive manufacturing technologies, will process base materials (metals, ceramics, polymers or biological) to modify the geometry, dimensions, microstructure and resulting properties (refer to Fig. 1). With this in mind, additive manufacturing technologies can be considered as a set of Manufacturing Processes, framed in the scopes of hundreds more other manufacturing technologies [9]. As well established, all Manufacturing Processes can be grouped into one of four key fundamental categories: Moulding, Deformation, Substrative or Additive processes (refer to Fig. 2). Within these, additive manufacturing technologies are incorporated in the additive processes category.

Further highlighting that the additive manufacturing processes are not the start and end of the production cycle, we can evaluate what exists upstream (before) or downstream (after) of any additive manufacturing process. Before the start of any additive manufacturing processes, there is a need for a given number of other manufacturing processes to be used to obtain the starting base material, whether this is in the form of wire or powder, for example. In particular, the filaments for additive manufacturing of polymers are typically obtained by extrusion (a deformation process), while the wires for metal additive manufacturing are obtained by drawing and its powder counterparts are usually obtained via atomization methods. After the production of a part by additive manufacturing, there is usually a need for finishing operations, which can include cutting, machining, polishing, or drilling, for example.

2.1.3. Consequences

With this understanding of where additive manufacturing technologies fit in terms of process categorization, these technologies must be framed, analyzed, studied, and evaluated using the same already established criteria, approaches, and analysis tools used for other manufacturing processes. These include, quality, cost, production rate and flexibility (refer to Fig. 3).

To obtain a final product based on additive manufacturing technologies, there must be sequence of well-defined manufacturing process, where additive manufacturing is one element or node in the production chain as exemplified in Fig. 4. The impact of additive manufacturing can translate into the reduction of the number of necessary manufacturing steps within the whole production chain, as schematically shown in



AM has high flexibility: the same printer allows to manufacture different parts without tools or additional investment.

AM typically does not allow for the best finish.

Milling or die-casting is better.

Regarding mechanical strength, there are also more suitable processes.

It depends on many factors.

AM is very competitive when only few parts are needed.

Other MP with low flexibility, require tools investments

AM has a low cadence and may need hours/days/weeks to make a piece. Other MP allow several parts per second. This is critical for large production scale.

Fig. 3. The four evaluation criteria for Manufacturing Processes (MP) and how it evaluates Additive Manufacturing (AM): quality, cost, production rate and flexibility.

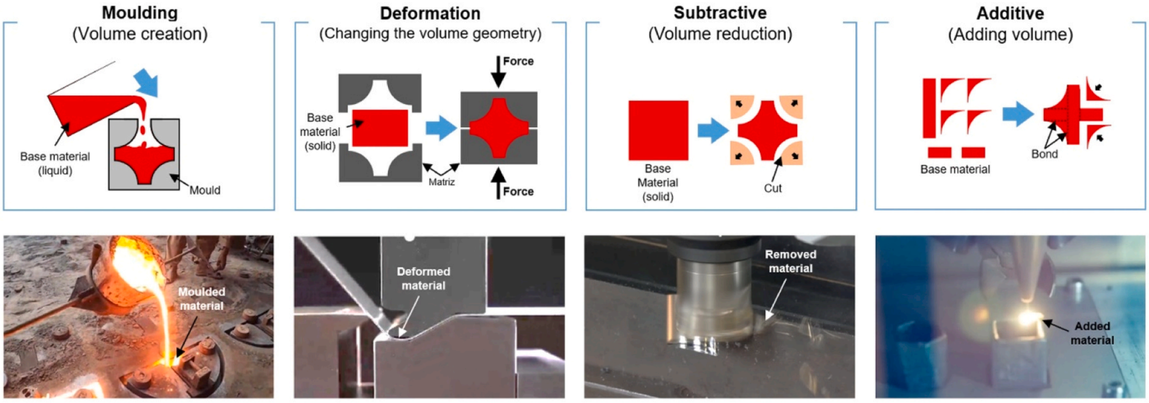


Fig. 2. The four key fundamental categories of Manufacturing Processes (MP): Moulding, Deformation, Substrative or Additive processes.

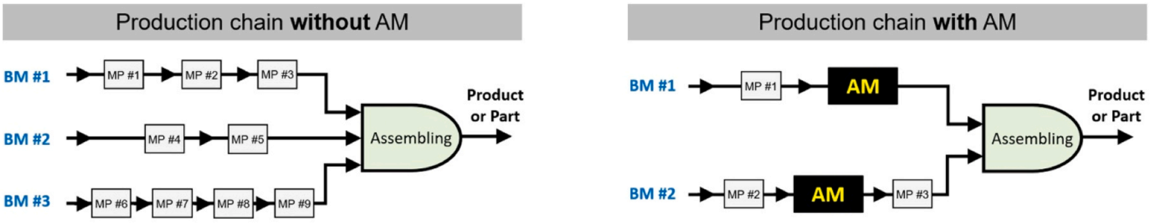


Fig. 4. The impact of Additive Manufacturing (AM) in the production chain: reduction of the number of necessary manufacturing processes (MP) and/or number of different Base Materials (BM).

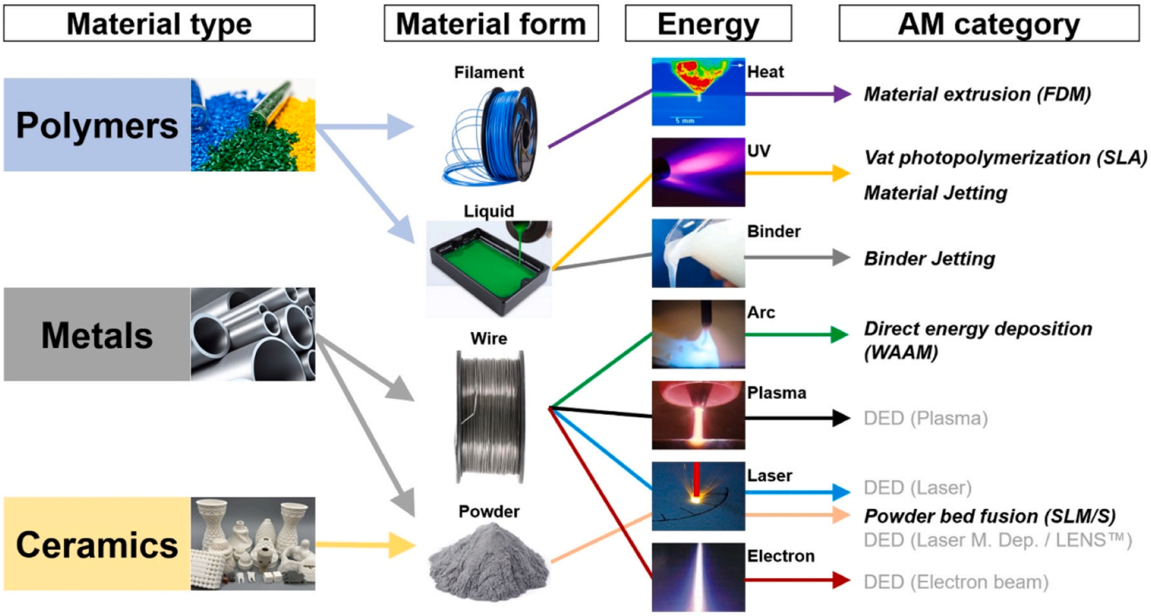


Fig. 5. The different additive manufacturing categories resulting from the combination of the different material type/form and different activation energy.

Fig. 4. Nonetheless, it should be emphasized that such additive manufacturing process(es) will be a node within the production chain and not the chain itself.

2.2. Key issue #2 – the omnipotence and unlimited character of additive manufacturing

2.2.1. Misconception

3D-printing offers unlimited options for complex designs. Thus, it has the potential to produce any desired geometry. It will substitute traditional manufacturing processes, who are unable to have the freedom of design typical of additive manufacturing technologies.

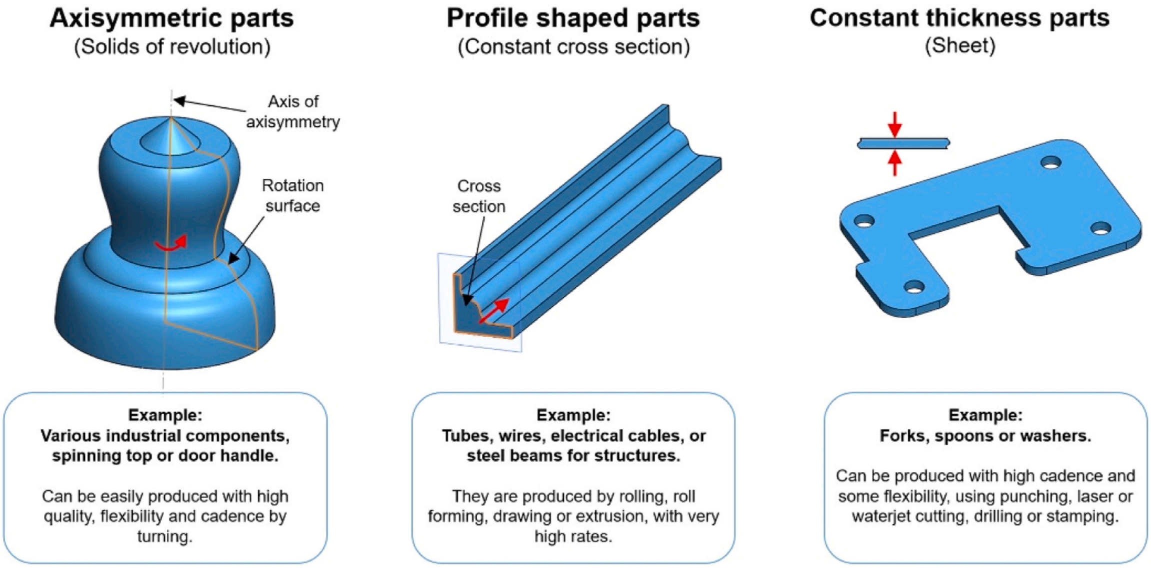
2.2.2. The reality

In theory, the above point is correct. However, like any other manufacturing process, additive manufacturing technologies are bound by physical, chemical and/or mechanical phenomena, as well as the printed material properties. In fact, additive manufacturing technologies involve different material bonding phenomena (chemical reactions, melting and solidification and sintering, for example); using different types of materials (polymers, ceramics, metals); that are presented in different forms (filament, wire, powder, or liquid); and use different activation energy sources (heat, laser or ultraviolet radiation, electric arc, plasma, electron beam, for example). The combination of those variables results in different additive manufacturing technologies, as schematic represented in Fig. 5. All of this is bounded by the laws of nature, imposing considerable limits to the additive manufacturing.

One prime example, concerns powder-based additive manufacturing methods, where the resolution of the produced parts is limited by the size of the heat source and/or dimensions of the selected powders. To achieve increased resolutions, one could: i) reduce the heat source size. However, there are scaling laws that cannot be ignored and such reduction may deem impracticable to process the material(s); ii) reduce the size of the feedstock materials. This option which brings increased costs to the material, more material waste, but also increases health and safety issues to workers since sub-micron sized particles are being now being processed.

Fig. 6. An example of a product (metallic threaded screw) that no variant of additive manufacturing can produce as well as a mechanical lathe since the beginning of the 20th century, in terms of production rate, quality, cost and mechanical resistance.

It must be noticed that some basic products, such as metallic threaded screws, are produced faster and better using a simple mechanical lathe from the beginning of the 20th century than with any current



Example:
Various industrial components, spinning top or door handle.

Can be easily produced with high quality, flexibility and cadence by turning.

Example:
Tubes, wires, electrical cables, or steel beams for structures.

They are produced by rolling, roll forming, drawing or extrusion, with very high rates.

Example:
Forks, spoons or washers.

Can be produced with high cadence and some flexibility, using punching, laser or waterjet cutting, drilling or stamping.

Fig. 7. Example of some part geometries for which additive manufacturing typically offers no advantages.

additive manufacturing technology (refer to Fig. 6). In fact, there is no additive manufacturing technology allowing the production of a screw with the quality, cost, cadence, and mechanical resistance obtained by the lathe or the thread rolling. Other specific products geometries also can be produced with much advantage using traditional manufacturing processes instead of additive manufacturing (refer to Fig. 7).

Several theoretical works on additive manufacturing predict the ability to create truly customized parts. Often, focus is preferentially placed on customization of mechanical properties, with different degrees of variability. However, these approaches fail in considering how to achieve, in practice, these graded (mechanical) properties. Any thermophysical property is dictated by a material microstructure. Let us consider a simple case where we have two materials (A and B) which have highly distinct properties (material A – with high strength and high density; material B – with low strength and low density). One can hypothesize that by mixing A and B in different volume fractions can have a balance on the properties of each material weighted by the respective volume fraction. This is used for example in predicting the mechanical response of composite materials [10]. While for polymers the previous approach can be successfully used often, the same is not true for most of the metallic systems used for additive manufacturing. This can be ascertained to multiple causes including: i) lack of solubility of one material into the other, promoting the formation of secondary (and often undesired phases) which have a mechanical behaviour quite different from the starting base materials; ii) existence of non-equilibrium solidification conditions (in fusion-based additive manufacturing) with the existence of off-equilibrium microstructures as well as the existing of segregation which can locally change the material behaviour.

Given that metallic materials are the go-to options for structural components, and therefore the most sought for industrial applications, it is not perceivable in the near future a full control of the mechanical response of additively manufactured parts only considering chemistry/microstructure. It should be emphasized that there are ways to mitigate this lack of full control by modifying the structure of the component itself, if this is compatible with the targeted geometrical features of the produced component. In summary, the conditions that such materials can be processed are also tight. Therefore, the multimaterial combination (with quite different properties) to produce complex and multicomponent products is often impossible.

2.2.3. *Consequences*

Additive manufacturing technologies are not the solution for all engineering problems, and it is not a technological panacea for the production industry. Let us consider one commonly used product: a mobile phone. With its current design configuration, it is impossible to create such a product by additive manufacturing, even if one used different additive technologies. Therefore, one can/may want to rethink the product design criteria, moving away from the traditional and well-established concepts.

For example, nowadays, product design methodologies should also consider the materials compatibility for manufacturing and expand this approach to encompass additive manufacturing technologies. Due to the previously described issues related to the mixing and lack of compatibility that often occur during metal additive manufacturing, one could consider a new product design philosophy. Perhaps, it is time to rethink the product design criteria, out of traditional product design concepts (for example design for production, assembly, maintenance or environment). The product design for additive manufacturing should consider the material compatibility for manufacturing according to a design for Maximum Material Compatibility (DMMC) and Design for Minimum Material Diversity (DMMD). The aim is to design a part, select different alloys and determine the suitable composition mixes that can translate in actual tunable and easily predictable properties (these being mechanical or functional).

In a sense, the paradigm of conventional printers can be used for a better understanding of such an approach: in a paper printer, with only three colors, Red (R), Green (G) and Blue (B) one can create an infinite number of other colors. The same principle can now be extended for any material group. However, in this case, we will have a multidimensional matrix, since multiple other features must be considered. Needless to say, that by increasing the matrix dimensions one can get very narrow operating ranges. Thus, there must be a critical balance between allowing for a vast range of materials to be processed, while at the same time different microstructure/properties relationships are considered to enable full control of properties in additively manufactured parts. We hypothesize that with the use of artificial intelligence methods such approach can be drastically reduce the need for an outdated trial and error methodology, leading to materials saving while increasing the applicability of additive manufacturing technologies.

2.3. *Key issue #3 – impact on supply chains*

2.3.1. *Misconception*

Typically, production and consumption of a given production are

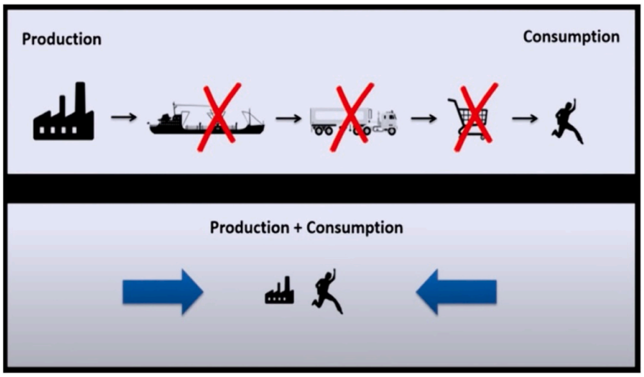


Fig. 8. Comparison of a supply chain without (top) and with (bottom) additive manufacturing according to [11].

separated, and this requires long supply chains. The advent of additive manufacturing allows to significantly shorter the supply chain, putting production and consumption much closer to each other. The production of the desired part(s) occurs right where one needs the product to be (or nearby). Product transportation is no longer required, or is significantly reduced, since the product can be fabricated by the end-user or in its facilities.

2.3.2. *The reality*

according to the Greek philosopher Parmenides of Elea (530 to 460 BC), *Ex nihilo nihil fit*, which means "nothing comes from nothing". This means that any product, regardless of its nature or function, is composed of one or more materials. From nothing, nothing can be produced. Therefore, while the product may not require transportation, the base material will need to be obtained. In fact, there is a need to process raw materials until the base material needed for additive manufacturing is obtained. As detailed before, additive manufacturing can process or transform base materials but does not necessarily create them.

2.3.3. *Consequences*

A supply chain is needed to produce and transport raw materials from the extraction place to the 3D printer place (refer to Fig. 8). It is not clear that major gains in terms of energetic efficiency can be gained from the implementation of additive manufacturing-based supply chains. However, production and lead times can be significantly reduced either considering industrial applications or day-to-day usage by the general population. Two key advantages that can arise from the use of additive manufacturing, especially when performed in-house (i.e., where the produced part will be primarily used) are: i) transportation can be significantly easier, as instead of transporting large complex shaped structures, one can fabricate them in-loco and then assemble them ready for use; ii) as a consequence of the previous advantage, the need of packaging, especially, plastics and hard-to-recycle materials is significantly decreased, which decreases the carbon-footprint associated to the produced part.

However, the raw material that is converted into scrap and waste is also transported and is produced at home, instead in a factory. At the end, only the place of the manufacturing process change: from the factory to home, but the manufacturing chain is still there from the material extraction to the product (refer to Fig. 9).

2.4. *Key issue #4 – the democratization of additive manufacturing*

2.4.1. *Misconception*

Additive manufacturing is like a plug and play process that allows anyone to fabricate their own products in an easy and expedite way. Basically, a 3D printer is like another home appliance.

2.4.2. *The reality*

The above misconception is overall true for some polymer-based additive manufacturing. However, when it comes to additive manufacturing of ceramic and metallic materials the scenario substantially changes. Here, it is not enough just "turn on the equipment and start printing". There is a need for a critical understanding of the process fundamentals and how these can be used to: i) create defect-free parts; ii) control the microstructure and therefore the response of the fabricated parts.

Moreover, the complexity of metal and ceramic 3D printers is significantly higher than conventional polymer-oriented printers. The solidification, and eventually multimaterial mixing, when it comes to metals or ceramics, often brings potential defects that may require specific knowledge to user to avoid defects and poor performance. This requires knowledge of electrical, mechanical and materials engineering to overcome process-related problems associated with such complex equipment. Regarding environmental impact, although some authors have highlighted benefits compared to conventional manufacturing processes [12], the fact remains that there is still a significant impact, primarily due to the electric energy used, as shown by an exergy analysis [13].

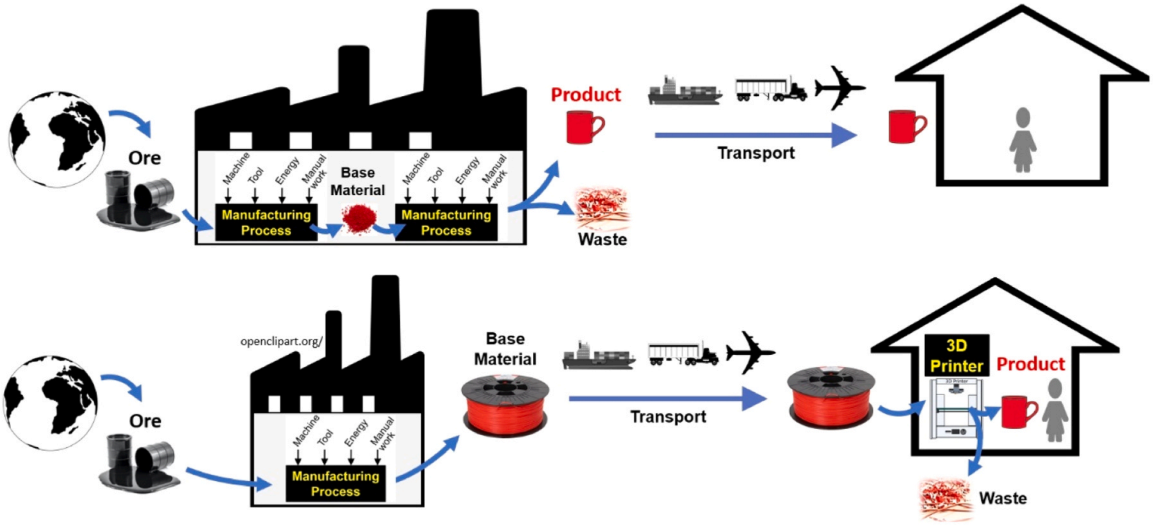


Fig. 9. Actual supply chain without additive manufacturing (top) vs with additive manufacturing (bottom).

2.4.3. Consequences

There is an obvious need to increase the literacy associated to additive manufacturing technologies, especially when it comes to processing metals and ceramics. Therefore, a multidisciplinary approach encompassing the fields of mechanical, electrical and materials engineering is fundamental to make the most use of the amazing features enabled by additive manufacturing. This literacy increase must also be oriented towards industry to train workers on the use and potential applications associated with these technologies.

3. Conclusions and final remarks

In this viewpoint, some common misconceptions associated to additive manufacturing technologies were detailed and demystified. By focusing on four key issues typically associated to additive manufacturing (#1 “additive manufacturing is a set of novel manufacturing processes”; #2 “additive manufacturing can print any geometry and any material”; #3 “supply chains can be circumvented with additive manufacturing”; and #4 “anyone will be able to use additive manufacturing”), we detailed the reality associated to those issues and their consequences and impacts at multiple levels. It can be perceived that additive manufacturing has multiple tremendous advantages but will likely be a niche market when compared to conventional and well-established manufacturing technologies. Nonetheless, the impact and outreach of additive manufacturing is tremendous and will certainly be around in the future decades.

Processing-related issues in additive manufacturing can often be circumvented by using knowledge associated with already well-established manufacturing processes. Thus, the fundamentals associated to additive manufacturing technologies, must always circle back to conventional manufacturing processes due to decades of knowledge that already exist. This can aid in improving process control and properties control and should be considered at all levels.

Author contributions

Both authors contributed to the study conception and design, as well as paper writing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.cirpj.2024.07.008.

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