Flaws as features: new perspectives for developing an additive manufacturing design language

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Abstract

In spite of some noteworthy niche-successes, many stakeholders would say that additive manufacturing (AM) has underperformed in relation to the early hype surrounding it (Wanke, 2019) or has lost its momentum (Killi & Morrison, 2020). The reasons for this underperformance are multiple: high costs per unit, unreliability when compared with established mass production methods and possibly a wrong understanding of the technology, amongst others.

In this paper I propose that the lack of analysis and the failure to grasp which are the real new possibilities at hand through AM are one of the main reasons behind the failed delivery of the 3D-printed utopia many announced at the beginning of the hype. In particular, I propose that the failure in developing a unique design language emerging from the actual properties of AM has stopped it from happening while trying to emulate mass production.

Manual and mass production are very well understood and established, to the point that they define our default tracks from conception to development to production. AM first entered the scene as a part of these tracks, being called "rapid prototyping" of an implicit mass production later down the line. Ever since, the new AM palette has struggled to define a space on its own as a method to deliver proper end products.

Some specific expensive niches were immediately successful in making use of 3D-printers, in what many expected to be no less than the start of the next industrial revolution (D'Aveni, 2013). Yet outside these niches AM is starting to resemble nuclear fusion, a promised all-success which somehow never arrives.

Every material combined with a production method will have qualities, properties, and limitations. Artisans have explored metal, clay, glass, and wood for millennia and developed design languages not only suited but emerging from them. Similarly, smart additive manufacturers should reflect both on the possibilities and flaws of the tools at their hands, developing a new, unique design language emanating from their materiality. Within this matrix, AM's "flaws" (filamented textures, rough and dusty surfaces, chaotic extrusion...) are possibly the most neglected aspects, still understood as elements to be ashamed of rather than creative possibilities.

Within this paper I analyse some notorious flaws of the AM palette and propose new perspectives to integrate them as possible features and advantages in this yet to be properly developed design language.

Author keywords

Additive manufacturing; 3D print; AM; crafts; AM limitations; design language; innovation.

Additive manufacturing limitations

Step 1: buy a 3D printer
Step 2: print a 3D printer
Step 3: return the 3D printer

Popular meme text

This meme would make perfect sense if 3D printers were the almighty machines which some utopian visions would like us to believe are our near future. *"The smell of freshly baked whole wheat blueberry muffins wafts from the kitchen food printer. The cartridges to make these organic, low sugar muffins were marketed..."* (Lipson & Kurman, 2013).

In reality we are not only very far away from such a thing. Arguably, we will never have similar Star Trek technology in our kitchens.[1][2]

"Additive manufacturing" is an unusually self-explanatory name, but it wasn't the first baptism attempt for the technology. "3D printing" is catchy and intriguing but confuses more than clarifies regarding the method. "Rapid prototyping" clearly defines the proposed function without dealing with the technology itself. AM is a paradigm shift in relation to these iterations in terms of clarifying its goal (not only prototypes) and by describing how it works (by adding material). As opposed to casting, carving and material removal techniques, AM works in a step-by-step increasing manner, making non-microscopic layers or filament traces unavoidable almost by definition (Wanke, 2019).

Smooth surfaces have always been a proxy for craftsmanship and quality. Mass production democratised smooth

1 As far-fetched as it may seem, this is no strawman of some AM enthusiasts' line of argumentation. In 2014 Horizon, the EU research & innovation magazine, published an article called "What does the future hold for 3D printing?" quoting Marcel Slot stating that "the ultimate goal of 3D printing is a Star Trek-style replicator. Deighton, B. (2014). What does the future hold for 3D printing? *Horizon, the EU research & innovation magazine*. Retrieved 22.12.2022, from https://ec.europa.eu/research-and-innovation/en/horizon-magazine/what-does-future-hold-3d-printing

2 For a realistic overview of the 3D printed food landscape see Killi, S., & Morrison, A. (2020). Could the food market pull 3D printing appetites further? In (pp. 197-203). https://doi.org/10.1201/9780367823085-36

finishes, a parameter which otherwise required high skills and time dedication. Just imagine how devoted and skilled would you need to be to produce a smooth piece of wooden furniture with crude 18th century tooling, where even sandpaper would have been time saving science fiction.

AM has dramatically increased its quality, yet its filamented, hairy, support-structure scarred, layered roughness will remain one of its characteristics. No foreseeable technological development could provide casting or extruded-like surfaces and even if this occurred such technology would unlikely become a common, mainstream or desktop tool. No matter how optimistically utopian our 3D printed near future gets to be described in the opening chapter of "Fabricated: the new world of 3D printing" (Lipson & Kurman, 2013), AM's ugly duckling is here to stay. But is it truly ugly or have we failed to identify its species?

Material aesthetics in crafts

> *"By chance, a piece of titanium in the firm's material sample pile caught the team's eye. On an uncharacteristically overcast Los Angeles day the metal square was nailed to a telephone pole in the office parking lot; it went golden in the grey light and the team was smitten."*
>
> Guggenheim's Museum blog (Mendelsohn, 2017)

Aesthetics in crafts emerge from their materiality. Bilbao's Guggenheim architectural concept asked for an innovative curvy solution at large scale, but once titanium was serendipitously selected as the quotation tells, the novel material changed the original design as well. Material, shape, size, and light reflections became an inseparable entity.

Artists and craftsmen have gotten their hands dirty with the mediums at their disposal. Centuries of crafty experimentation have left us with virtuoso techniques which embrace their materiality. Being born with crafty techniques already established as "tradition", we may miss the fact that the different mediums and their belonging aesthetics may be very different, even contradictory, from one another. There is certainly no absolute good/bad in arts, but in art school the different techniques must be learned and more often than not will be criticised as poor. Even more interestingly, similar criteria could lead to "good oil" and "bad watercolour" technique evaluation. A classic critique almost every fresh art student will suffer comes from not deploying watercolour's fuzziness. There are plenty of counterexamples, yet classic academic watercolour technique is about learning to use its watery mess for the appropriate purpose. Wash, blending, backrun, tilting and almost every other watercolour technique makes reference to a somewhat chaotic possibility of the medium (Van Leuven, 2017). We learn these elements as academic craftsmanship and therefore will likely fail to realise that this is a fine example of using what could be considered a flaw (the messiness of watercolours) as a high-quality feature instead. We don't see a chaotic blend of uncontrolled, overlapping, dripping, watery blueish waves on paper. On the contrary, we enjoy a beautiful depiction of a cloudy sky, masterly achieved in three skilled strokes, some paper tilting and a sponge intervention.

Similarly, every other traditional crafting technique emerges from its materiality, developing an aesthetic on the way. Weavers, painters, sculpturers, potters and photographers have a language of their own. One of the latest additions to the family are the digital artists, who have seen their medium emerge and grow in a single lifetime. Yet even within this brief episode different schools and aesthetics were born and became aesthetically appreciated on their own. Early digital visuals were constrained by heavy pixelation, very limited colour palettes and short memory availability. Only 20 years later these technical limitations were a thing of the past yet "pixel art" became a thing, an established style, which some creators voluntarily use as an expressive tool, similar to the recent revival of stop motion animation (Costa, 2014).

Computer adventure games were very popular in the 90s and made extensive use of pixel art aesthetics (they didn't have any other choice). Ron Gilbert, the creator behind the popular "Monkey Island" game series, made phenomenal use of the comedic possibilities of clumsy pixelated imagery and animations. In the following decades his creations achieved cult status, which motivated him to create a new episode to his pirate saga. "Return to Monkey Island" became one of the most anticipated releases of 2022, yet Gilbert didn't deliver a nostalgic pixel art product, crafting a modern, smooth, cartoon-looking environment instead. Fans were divided about it, to put it mildly (Troughton, 2022). Pixelated, 256-colour graphics had become something emotional to defend, in a similar reactionary manner to Star Wars fans demanding unspoiled analogue versions of their childhood movies instead of the "digitally enhanced" versions George Lucas produced for the 25th anniversary re-release, a discussion which reached a religious tone (Lyden, 2012).

If you are a watercolour aficionado, pixel art connoisseur or Star Wars fan, the previous, crude descriptions of these aesthetics in terms of materiality and limitations almost certainly provoked an emotional reaction in you. This story and analysis are therefore not only about materials and aesthetics but also about the emotions they induce. We will come back to this topic later.

From prototypes to end-products

> *"A prototype is always more expensive than anything."*
>
> Wes Anderson (Anderson, 2009)

As previously mentioned, 3D printers were firstly known as "rapid prototyping" machines, and in many environments they are still called that way. This is a very senseful name since in most product development processes AM plays its most relevant role at the prototyping phase.

The answer to the question why didn't we start crafting end-products immediately when AM manufacturing technologies became available could require a whole book on its own. The factors which played (and still play) a role range from industrial patents, to technological limitations, to production economics, to plain cultural biases and tradition-based resistance to update our production methods (Killi, 2017). For the purpose of this paper economics, tradition and cultural biases are the most relevant parts of the matrix to analyse.

Regarding economics, in high-end projects where there are no budget constraints, quite often AM can provide unbeatable solutions. Boutique clients looking for an extra 0,1% efficiency regardless of the price tag are good AM customers. Accordingly, new generation rocket nozzles and customised, record-beating bicycles are now mostly produced through AM (Attanasio, 2022). These high-end, flagship projects can certainly make the AM community proud, yet such successes don't move us towards a democratic, accessible AM utopia at all. They will remain luxury niches and as much as they are inspiring, they are of little interest for the purpose of this paper. Let us have a look at the accessible budget area instead.

Wherever a mass production effort can be implemented and makes economic sense, unless currently unforeseeable technological jumps occur in the AM methods, almost by definition mass production will be more efficient than AM. AM enthusiasts may react to this with counterarguments such as less transport costs and fewer CO2 emissions if locally 3D printed, less material waste due to topology optimisation and more efficiency due to customisation. These arguments can be perfectly valid within specific, well-defined niches. Such niches have a "sweet spot" which differs from the numbers of traditional mass production and are far less common than AM supporters -including myself- would like to admit. Furthermore, the idealised vision of a locally produced, efficient and tailored part tends to forget the time, effort and amount of iterations usually required to produce a successful 3D model (Killi, 2017).

Once a suitable niche is identified, namely, when there is need for customised parts in a middle-range production volume where the price of the part allows for the development process, then AM makes perfect sense as end-product. This has already happened in objects which are small, expensive, and benefit from customisation, such as hearing aids (Killi, 2013). Beyond these very narrow spaces AM still struggles to establish itself though.

The previous analysis regards mostly industrial production. What happens at the other end of the spectrum instead? Could the crafts not be interested in AM as well?

Machine-made crafts

"The greatest dilemma faced by the modern artisan-craftsman is the machine. Is it a friendly tool or an enemy replacing work of the human hand?"

Richard Sennett (Sennett, 2008)

In his extensive crafts' analysis, Sennett reflects on the introduction of machine production. The cold, mass-produced perfection, opposes handwork's irregular but warm soul. He quotes an Encyclopaedia article on glassblowing: *"imperfect, handmade glass has virtues: these are irregularity, distinctiveness, and what the writer refers to vaguely as character"* (Sennett, 2008).

Yet, as we have seen before, AM is certainly not a good example of mass-produced perfection. Firstly, AM's output does not come in mass volumes. Secondly, irregularities, layers, filaments and support-structure scars are quite a quintessential trademark of it. [3] Could AM be too irregular to be accepted as a valid industrial end-product and at the same time too precise to be discarded as a legit craft? Looking at both ends of current market's spectrum -crafts and industrial production- it would seem this is the case. Yet I would like to argue this should not necessarily be AM's future, appreciated only by techy makers and figurine collectors. The fact that we have insofar failed to accept and embrace AM's character does not mean that it doesn't have one.

At BIT's 2018 World Congress of Smart Materials, Dr. Brando Okolo reported that one of the early concerns regarding the 3D printed PEEK prothesis they were producing was to reduce the surface roughness. Their parts were manufactured with top-quality, extremely fine filaments, yet the results were nowhere near the smoothness of standard casted pieces. It was only after a surgeon asked them not to polish them because a rougher surface increases biological adhesion, that they realised this was a feature rather than a flaw (Philipp et al., 2018). This possible advantage has been previously mentioned (Reeves, 2013) and is now being integrated as one parameter to manage in order to optimise prothesis tolerance and adhesion (Shilov et al., 2022). Similar analysis have been carried out, for instance, aiming at make smart use of SLS' natural porosity to develop sound-absorbing objects (Zieliński et al., 2022).

Figures 1 and 2 show a simple earring design oriented in slightly different angles on an FDM printer. [4] The different orientations result in different surface patterns. If consciously used as an aesthetic element, the ugly duckling output of the cheapest desktop 3D printer may turn to have a character. Furthermore, in this case a "silky" a character that could not be produced either by hand or through mass production.

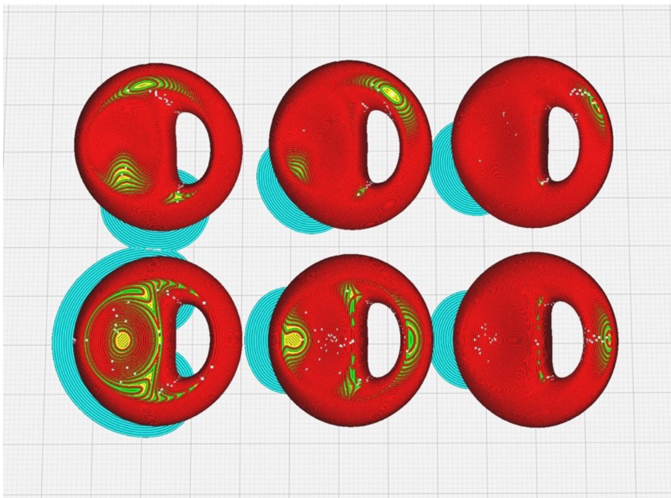

Figure 1. Simple earring with different orientations at the printing bed.
Design and photo: Ricardo Simian, 2022

The ceramics department has been more open to embrace the new materiality which 3D printers can offer. Maybe because each clay 3D print ends up being truly unique no matter how reliable your materials and hardware are? Extruding ceramics almost looks like a living process, where minuscule bubbles and irregularities in the mix can lead to notoriously divergent results, if you manage to get to the end of the print at all. Plenty of artsy examples on this regard can be found on Pinterest and similar platforms. It seems like clay artists have less of an issue in accepting this machine as an extension of their hand instead of a replacement.

3 In his 2018 book Stephen Hoskins dedicates a full chapter to AM crafts and craftspeople, yet without mentioning a single time flaws, irregularities, imperfections nor shortcomings of the technology. On the contrary, the whole analysis focuses on case studies where AM methods are used to produce complex designs, suited only to CAD modelling and high-end design boutiques. Hoskins, S. (2018). *3D printing for artists, designers and makers* (2nd ed.). Bloomsbury.

4 FDM stands for "fused deposition modelling", the AM method where material is extruded through a nozzle. This technique encompasses a large range of applications, from small plastic desktop printers to large concrete-pouring machines and is one of the most widespread AM methods. Savini, A., & Savini, G. G. (2015, 18-19 Aug. 2015). A short history of 3D printing, a technological revolution just started. 2015 ICOHTEC/IEEE International History of High-Technologies and their Socio-Cultural Contexts Conference (HISTELCON)

Figure 2. FDM earring printed in different orientations.
Design, 3D print, and photos: Ricardo Simian, 2022

Figure 3 shows a 3D printed clay cup alongside the original 3D model. The modelled overhanging circular rings of the 3D model become irregular blobs and waves in reality, producing a semi-regular, not entirely predictable pattern. Through this production methods, can't we aim to enter the realm of the character-producing irregularities and distinctiveness which the Encyclopaedia praises on traditional glass blowing?

Jibbe van Schie's project "Woven translations" (Figure 4) interlaces ceramics and textile tradition through a self-assembled, multicolour clay 3D printer. *"My ceramic printer makes use of a process similar to the way tapestries are woven. Every colour is present at all times yet an image is created by bringing one of the colours to the surface"* (Van Schie, 2022).

Gartner's hype cycle explains that every emerging technology will experience an early peak of inflated expectations, a trough of disillusionment and a slope of enlightenment before reaching a plateau of productivity (Steinert & Leifer, 2010). AM has followed a very messy hype cycle and different actors will passionately argue that we find ourselves in entirely different points of the curve right now. I would argue that different niches have experienced almost independent curves, each field learning on its own time what must be learned to reach a plateau of productivity. Many fields, including AM crafts in general,

Figure 3. 3D printed clay cup with semi-regular patterns alongside the 3D model which was fed into the printed. Design, 3D print, and photos: Ricardo Simian, 2022

Figure 4. Woven translations designs by Jibbe van Schie.
Design, 3D print, and photos: Jibbe van Schie, 2022

have certainly not yet achieved that goal, otherwise the crafts market would look different today. Embracing the materiality which naturally comes out of 3D printers and developing aesthetic values may well be an important part of this long, raising slope of enlightenment.

The provided examples regard FDM-made objects, yet the analysis of the flaws and possible uses of them as advantages is not only limited to this technique. As previously mentioned, SLS provides rough and layered surfaces by nature, while SLA for most models require support structures which must be removed, leaving scars behind.[5]

It could be easy, and tempting, to reduce the mentioned shortcomings of AM to FDM only, or to wish that future developments will make them disappear altogether. SLS, SLA and all other AM methods have their unique finishing trademarks, which makes them inherently different from traditional mass-produced objects. It is true that AM's quality has increased since its origins, yet within any foreseeable development the basic elements of it -be it extruded textures, layers, or granular-sprayed surface roughness- are here to stay. Further research and analysis are required to discuss all of AM's existing techniques to the depth provided for FDM within this paper.

Additive manufacturing as an artistic tool

> *"I am not looking for the perfect print, actually, when the print is done I am not that interested in it anymore."*
>
> Sigrid Espelien (Espelien, 2022)

Norwegian clay artist Sigrid Espelien, currently PhD fellow at the Oslo National Academy of the Arts, goes beyond the use of AM as a method for artistic production to elevating the printing process into an artistic ceremony. *"Sometimes I think about it like watching a fire, because you don't know... when you are always printing new files you don't know how the printer will move and this collaboration with the machine -because you have to work together- becomes a very intimate process"* (Espelien, 2022).

In a techy field, where speed and efficiency are taken for granted as goals, Espelien's appreciation of the slowness of the 3D printing process is refreshing. Who could have thought that the romanticized vision of the artistic craftsman blowing glass, weaving on a loom or turning ceramics could be applied to the interaction with a 3D printer. *"It feels like a very sacred moment, or that I am actually finding a way to get closer to*

5 SLS stands for "selective laser sintering", a layer-by-layer, powder-based AM method. SLA is the abbreviation of "stereolithography", also a layer-by-layer process using photochemical reactions to solidify liquid resins. Ibid.

Figure 5. Photogrammetry from Bjørvika's Palèhaven shopwreck archeological excavation site, 3D printed in clay with the permission from the Norwegian Maritime Museum (detail). 3D print and photo: Sigrid Espelien, 2019

the landscape... because I can see it from the inside... I'm also thinking about how can I share this experience with people, the printing in itself, because is something that people feel distant from" (Espelien, 2022). Figure 5 shows a detail from one of Espelien's artistic readings of a landscape through AM.

This emotional appreciation and understanding of the printing process brings us back to the aesthetics question posed before. Once an object, and the production process behind it, are experienced as emotional, the discussion regarding its validity ends. The questions emerging from the artistic evaluation of an object or action may lead to a different, and endless, rabbit hole, but they shift the whole debate to a different dimension, away from the technical and ethical complaints aimed at AM as a production method listed before.

The archetypical debate on tradition vs innovation, man vs machine -of which 3D printers seemed to be doomed to become yet another iteration- entirely dissolves if AM becomes tradition. Clay turning was once a technological innovation, as opposed to the traditional approach for vase production by rolling a "clay rope" (Sennett, 2008). Clay 3D printing, and FDM 3D printing methods in general, brings us back to a filament/rope deposition method. Could this be treasured as a return to an ancient tradition? Maybe yes, but only if the crudeness of FDM's production methods is not only acknowledged but also emotionally embraced, as Espelien proposes.

Conclusions

Much attention has been given within the AM community to the technical improvements achieved, each of which moves us closer to the 3D print utopia, where high-quality mass production has become a daily, possibly even home-desktop reality. This is very understandable for an emerging technology struggling to define a niche for itself. Even more, it is the least we should expect from a set of technologies which have been introduced to the public as nothing less than the next industrial revolution.

Failure to deliver this dreamt utopia must not be necessarily understood as going back to the drawing board and restarting from scratch though. All the contrary.

In a recent conference at Stanford University Peter Thiel pessimistically stated "they promised us flying cars, and all we got was 140 characters". The backlash didn't wait, arguing that indeed we didn't get flying cars but we have now things like the internet and smartphones instead, and when offered the choice between those most people would choose our pocket-sized supercomputers before heavy hardware constantly speeding over our heads (Pooley & Tupy, 2022).

Similarly, 3D printers will likely never be the magical, multi-purpose, home sci-fi machines which would solve all our needs. Actually, if we think better of it, even if such machine could be produced the annoyance of having to shop products would only be replaced with the annoyance of having to shop printing cartridges and printing files. Plus dealing with the maintenance of the machine. Not a great step forward I would say. Independently from that, we didn't get such machines, but we got a new way of producing things, with an entirely new set of proprieties, pros and cons. We can either complain about them not being what we dreamt of, or we can start making wise use of them as they are.

One of the main focuses in the AM environment are developments in delivered quality, meaning machines are getting better in producing what customers would like to receive and we appreciate every improvement. This fact alone shows that there are evident issues and flaws in current AM. I propose shifting the attention from the ideal quality customers would like to see -which has been shaped after mass-production standards and aesthetics- to the qualities that AM spontaneously provides instead, developing new design paradigms from them.

One key element of making good use of the new available possibilities regards developing an idiomatic aesthetic which emerges from the technical possibilities of the technology, embracing its flaws as an intrinsic part of it. Once this process takes place flaws can become possibilities, features, or even character.

A further step on this line goes directly into artistic territory, when the production process itself acquires a value which goes beyond the industrial link between idea and finished object.

Further technological developments may arrive in the AM world, and they will be certainly welcome. In the meantime, there is space for further applications of the tools we have at hand today, something that is more likely to happen if we understand them precisely in that manner: tools in our hands.

Acknowledgments

Thanks to everyone at AHO for the comments, contributions and technical assistance to this document as well as the practical research behind it.

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