A critique of solutions and research to the challenges of adopting metallic additive-layer manufacture in full-scale production.

Robert Bush[1†], Farid Dailami[1]

[1]*Bristol Robotics Lab, United Kingdom, BS16 1QY*

robert.bush@brl.ac.uk

Abstract

Manufacturing was a critical factor in determining the length and depth of the financial crisis of 2008. A larger manufacturing base enabled countries to grow cash reserves quickly and halt austerity years earlier. The UK's decline in manufacturing from the 1970s is the most severe of the G20 countries and the UK government, in an effort to reverse this decline, have pledged a focus on so-called Fourth Industrial Revolution (4IR) technologies. Additive–Layer Manufacturing (ALM) is core to 4IR and is predicted to offer a potential £72.1 billion boost to UK industry over the next decade. However, while the UK leads world-wide research in ALM, the adoption rate for using ALM in full-scale production is considerably lower than other countries with similar levels of ALM expertise (Germany, USA, South Korea, China, Italy). Metallic ALM offers enormous potential in full-scale production for reasons of cost, time and function. GE has already produced over 30,000 fuel nozzles, using metallic ALM, for its new GE9X engine. For Small & Medium Enterprises (SMEs) to benefit in a similar way, it is vital to reduce the complexities, cost and risks associated with this technology. There are some unique challenges which still need to be solved to give confidence to users of metallic ALM that it's ready for full-scale production. In this paper the reader will get a table summarising the challenges and current state-of-the-art solutions/research to these challenges. The authors offer their opinion on where gaps lie in current solutions/research and thus where new research activities are required. Our opinion is based on one authors experience of over 4 years intimate involvement within the metallic ALM industry.[†]

Keywords: Metallic Additive-Layer Manufacturing, Value Stream Map, Design, Build, Post-Processing, Test, Validation, Certification, Standardisation, Metal AM Challenges.

1. Introduction

1.1. Importance of Manufacturing

Globally, manufacturing contributes to OECD economies: 70% of exports [1], 77% of private R&D [2], 37% of productivity [1].

To create wealth and build an economy something needs to be created - whether it be music, film, commodity products, agriculture, mining or mass production - wealth only comes from creation. Services do not build an economy, they assist in distributing the wealth of the creators [3]. The figures in the list above underline the fact that manufacturing is *the* wealth-generating industry worldwide.

Attention towards manufacturing has increased as a result of the impact that bubbles in non-trade related sectors had on the severity and length of the financial crisis. Post-recession 2008, policy makers have investigated the causes and effects to learn from the mistakes made. Policy makers in Austria [4] found only one strong correlation which had an effect on the depth and length of the recession in each country. Countries which had a particularly high current account deficit *and* a low manufacturing base in their economy struggled to emerge from the recession. Greece and Spain took five years to emerge from the recession, compared to two years for Ireland and Lithuania. The critical difference between these countries was that the latter had a two times larger manufacturing base.[1] The larger manufacturing base enabled these countries to grow cash reserves quickly and halt austerity years earlier.

UK Manufacturing Since 1970 the UK's manufacturing sector has had the most severe decline in output as a % of GDP. In 2015 manufacturing output was 10% of GDP (from 28% in 1970) [8]. Of the G20 countries, the top three manufacturing output as a % of GDP are [8]: South Korea (29%), China (27%), Germany (23%).

Manufacturing is the main driver behind technological innovation and for the countries that develop and own these innovations, they have a strong position right at the start of the value chain. The learning for new products and process in the late innovation and pre-production phases creates spillover effects for other companies and subsequent innovations [4]. This promotes long-term sustained growth in output, employment and services which complement the manufacturing activity.

The UK government has realised the importance of manufacturing and in an attempt to revive the sector's growth, have pledged £121 million for "Made Smarter" - use of technologies specifically related to the 4IR [9].

2. Additive-Layer Manufacturing

There are four technology pillars to 4IR [10]: Artificial Intelligence (AI), Internet of Things (IoT), Robotics, ALM. The benefits with ALM read like an engineering wish list; the ability to produce unitised parts with complete design freedom, novel geometries and graded materials at both reduced cost (no tooling) and reduced waste (near net shape solution). Moreover this can be achieved with a high-degree of customisation at the point-of-use (local manufacture) with lead times far less than current methods. Plenty of real-world examples can be found in the existing literature ([11], [12]). One of the best examples is GE's new aero engine GE9X. Cobalt-Chrome fuel nozzles and Titanium Aluminide turbine blades are being manufactured on ALM machines (reducing fuel consumption by 10%). In October 2018, GE had manufactured over 30,000 fuel nozzles [13].

ALM in the UK ALM could contribute £72.1 billion to UK industry over the next decade, with £4.4 billion of savings passed on directly to the consumer. A 35% increase in customer satisfaction, 12.6 million tonnes CO_2 reduction in transport emissions by 2027 and a 7% reduction in non-fatal injuries during manufacturing rounds off the

[†]Throughout this report, the dagger symbol will reference the authors own work and experience. The author has worked on over 250 unique metal ALM components, led the post-processing technical side of over 50 New-Product Introduction projects, created a company-wide pFMEA, created or updated over 60 production processes, innovated a new finishing process and successfully completed four six-sigma green-belt level projects, all within metal ALM post-processing.

[1]Greece (-15% deficit of GDP, 8.5% manufacturing base), Spain (-9% deficit of GDP, 13% manufacturing base), Ireland (-7% deficit of GDP, 20% manufacturing base), Lithuania (-13% deficit of GDP, 16% manufacturing base). *Data from [5] [6] [7].*

'value at stake' [10]. The UK has world class ALM machine manufacturing capability, a well established national centre and is among the world leaders in research and innovation within high-performance applications (e.g. medical, aerospace). However, the UK is seeing significantly slower adoption and use of ALM than Germany, China, USA, South Korea and Italy. UK manufacturing companies view ALM as a somewhat immature technology which has benefits for prototyping but too many barriers to entry for full-scale production [10].

2.1. Metal ALM Challenge Areas

2.1.1. Cost The majority of machine sales in metal ALM have used a form of Powder Bed Fusion (PBF) technology where a laser or electron beam is used to melt layers of metal powder. New technologies from Desktop Metal, ExOne and XJET have yet to make an impact on market share [14]. This is unlikely to change in the next 10 years as aerospace, automotive, defence and medical companies have spent millions of pounds qualifying PBF machines and parts for production use in the coming years.

Figure 1 displays an overview of the Metal ALM process chain and highlights the recent shift in the balance of costs from the build process to post-processing. This is caused by a number of technological advancements in the build process and raw material bringing down associated costs. Depending on part complexity and quality requirements, post-processing can account for up to 65% of the parts cost† [15]. 40% of businesses are not considering adopting ALM for end-use production because of the cost [16] and to be financially viable in automotive applications, a cost reduction by a factor of ten is required†.

2.1.2. Design→Build→Process→Test†

Design The ALM journey starts with design. End-user requirements help determine which ALM materials to use and the product design specifications. To fully benefit from ALM, clean-sheet designs on a system-level must consider ALM from the outset. Once the physical parts are designed, pre-processing is required to define build layout, orientation, density and supports. The ALM machine parameters are selected, such as laser power, scan speed and scan strategy.

Build The core part of metal ALM is build. This entails data transfer to the ALM machine, before machine preparation and set-up such as cleaning, sieving, levelling, demagnetisation and pre-heating are carried out. The build process itself entails atmospheric control, laser scanning, powder recoating, z-axis control (layer thickness) and particulate filtering.

Process Post-Processing can encompass just three processes or more than 10 separate processes. Figure 2 displays the most common processes.

Test The ALM journey finishes with testing, validation and certification. There are currently no standards for metal ALM so this can be just 1 process and at other times, more than 10 separate processes (e.g. 3D scanning, X-Ray, dye pen, wall thickness, flow/leak test, hardness, porosity).

2.1.3. Input Variables The complexity of metal ALM is often overlooked, even by those with experience of metal ALM. There are over 65 Key Process Input Variable(s) (KPIVs) which interact and affect the parts final Key Process Output Variable(s) (KPOVs) (quality, cost, time, safety).

The main effects and interactions of these KPIVs on the KPOVs are still not fully understood and therefore process optimisation is an iterative, time consuming and costly process. The difference, however, between an optimised and non-optimised process has benefits in terms of cost (hundreds of pounds cheaper per part), lead time (days shorter), dimensional tolerance ($\pm 0.05mm$ instead of $\pm 0.5mm$), surface finish (0.2 Ra instead of 5 Ra) and defect rate (6210 Defective Parts Per Million (DPPM) instead of 187,670 DPPM). *These numbers have been generated as part of the authors work and experience† (see footnote on title page).*

2.1.4. Process Design Many processes used in design, post-process and testing have been taken from conventional manufacturing (e.g. CAD packages, EDM (electro-discharge machining), dye penetrant testing) and therefore optimisation is limited. Rather, what is needed, are processes designed for ALM which offer functionality to control the KPIVs and optimise the KPOVs.

3. Solutions to Solve ALM Challenges

Full-scale production in Metal ALM has been demonstrated by a select number of large multi-national companies that can afford the costs and manage the challenges associated, particularly those companies within the aerospace and automotive industries. However, for wide-scale adoption across the supply chain, especially SMEs, there are a substantial number of challenges within the areas described in Section 2.1. Table 1 will present the reader with an up-to-date list of some of the most important challenges within metal ALM right now. To stimulate further investigation by the reader, a selection of the leading research papers and commercial products, related to each challenge, will be referenced.

An analysis of Table 1 is provided in the "Impact" (the positive effects and consequences of solving or reducing some of the negative aspects of the challenge) and "Interaction" (the extent of a challenges interactions and inter-dependencies across all four value streams) columns. A critical review of the solutions/research is provided in the "Gap?" column; where if a gap is highlighted, it is the authors opinion that the current solutions/research activities are not sufficient or timely and new activities are required. The author stresses that Table 1 is designed to provoke and stimulate further investigation by the reader in their area of expertise.

4. Conclusion

Manufacturing is an industry which generates wealth and economic security. In the following decades, metal ALM will be a key growth area within manufacturing. Some challenges are preventing the adoption of metal ALM for full-scale production. The author highlights three core areas and two unique challenges within each area that require accelerated development or a shift in research strategy to successfully solve the challenges:

(1) Hardware
  - (a) Automated removal of supports
  - (b) Powder removal and surface finishing of internal channels

(2) Software
  - (a) In-situ build monitoring and closed-loop feedback of melt-pool and layer defects
  - (b) Optimisation of post-processing strategy (incl. fixtures) at design stage

(3) Standardisation
  - (a) Robust and reliable support strategies
  - (b) Parameter sets by build requirement (quality, build time, material, geometry)

The author recommends that readers use Table 1 as a resource to provoke further research in targeted areas. The author and corresponding research lab have used Table 1 to commence their own work, using robotics, in solving one of the aforementioned challenges.

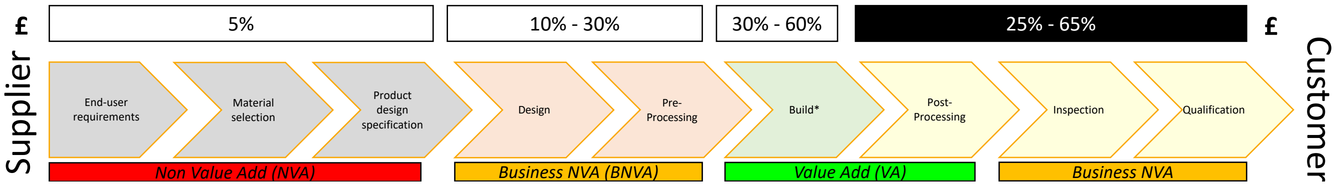

FIGURE 1. Metal PBF value stream map showing value added processes and cost-breakdown by process. Cost figures from [15] and †.

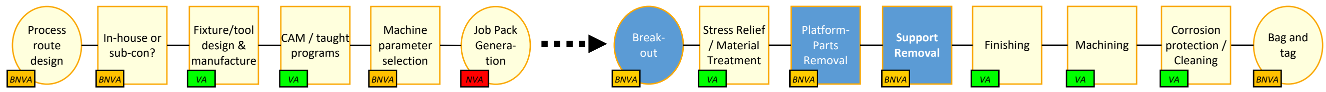

FIGURE 2. Post-Processing process map. Shaded blue are processes which do not add value to the final part but are always required when using Metal PBF†.

References

[1] OECD-STAN, "Structural analysis database," 1995-2005. [Online]. Available: http://www.oecd.org/industry/ind/stanstructuralanalysisdatabase.htm

[2] OECD-ANBERD, "Analytical business enterprise research and development database," 2008. [Online]. Available: http://www.oecd.org/sti/inno/anberdanalyticalbusinessenterpriseresearchanddevelopmentdatabase.htm

[3] M. Burton, "Progress in digital manufacturing: The uk national perspective," Digitalising Manufacturing Made Smarter conference, October 2018, presentation.

[4] K. Aiginger, "Industrial policy for a sustainable growth plan," Austrian Institute of Economic Research (WIFO), Working Paper 469, 2014.

[5] OECD, "Current account balance," 2008a. [Online]. Available: https://data.oecd.org/trade/current-account-balance.htm

[6] ——, "Gross domestic product (gdp)," 2008b. [Online]. Available: https://data.oecd.org/gdp/gross-domestic-product-gdp.htm

[7] WorldBank, "Manufacturing, value added (% of gdp)," 2008. [Online]. Available: https://data.worldbank.org/indicator/nv.ind.manf.zs

[8] C. Rhodes, "Manufacturing: International comparisons," House Of Commons, Briefing Paper 05809, January 2018.

[9] P. Hammond, *Budget 2018*. OGL, October 2018, no. HC 1629, ch. 4, p. 56.

[10] J. Maier, "Made smarter," Siemens UK, Review, 2017.

[11] ATI, "Insight: Additive manufacturing - applications in aerospace," Aerospace Technology Institute, Insight Report 08, September 2018.

[12] Additive Manufacturing Steering Group, "Additive manufacturing uk," National Strategy 25, 2018.

[13] T. Kellner, "The blade runners," GE.com, 2018. [Online]. Available: https://www.ge.com/reports/future-manufacturing-take-look-inside-factory-3d-printing-jet-engine-parts/

[14] T. Wohler, "Wohlers report," Wohlers Associates, Industry Report, 2018.

[15] R. Day, "Impulse - ecm, mtc, 3trpd innovate uk project," 2016, unpublished.

[16] F. Thewihsen, "Global 3d printing report," Ernst & Young, Industry Report, 2016.

[17] W. King, A. Anderson, R. Ferencz, N. Hodge, C. Kamath, S. Khairallah, and A. Rubenchik, "Laser powder bed fusion additive manufacturing of metals; physics, computational, and materials challenges," *Applied Physics Review*, vol. 2, no. 4, 2015.

[18] M. Langelaar, "Combined optimization of part topology, support structure layout and build orientation for additive manufacturing," *Structural and Multidisciplinary Optimisation*, vol. 57, pp. 1985–2004, 2018.

[19] M. Abdi, I. Ashcroft, and R. Wildman, "Design optimisation for an additively manufactured automotive component," *Int. J. Powertrains*, vol. 7, no. 3, pp. 143–160, 2018.

[20] Autodesk, "Netfabb software," 2018. [Online]. Available: https://www.autodesk.co.uk/products/netfabb/overview

[21] M. Francois et al., "Modeling of additive manufacturing processes for metals: Challenges and opportunities," *Curr. Opin. Solid State Mater. Sci*, vol. 21, no. 4, pp. 198–206, 2017.

[22] Y.-H. Kuo, C.-C. Cheng, Y.-S. Lin, and C.-H. San, "Support structure design in additive manufacturing based on topology optimization," *Structural and Multidisciplinary Optimisation*, vol. 57, pp. 183–195, 2018.

[23] H. Bliss, "Functional lattices for automotive components (flac)," 2018, innovate UK Project.

[24] Materialise, "Magics 23 software," 2018. [Online]. Available: https://www.materialise.com/en/software/magics/magics-23

[25] L. Parry, I. Ashcroft, and R. Wildman, "Geometrical effects on residual stress in selective laser melting," *Additive Manufacturing*, vol. 25, pp. 166–175, 2019.

[26] M. Simonelli, N. Aboulkhair, P. Cohen, J. Murray, , A. Clare, C. Tuck, and R. Hague, "A comparison of ti-6al-4vin-situalloying in selective laser melting usingsimply-mixed and satellited powder blend feedstocks," *Materials Characterization*, vol. 143, pp. 118–126, 2018.

[27] A. Yadollahi and N. Shamsaei, "Additive manufacturing of fatigue resitant mateirals: Challenges and opportunities," *Int. J. of Fatigue*, vol. 98, pp. 14–31, 2017.

[28] T. DebRoy, H. Wei, J. Zuback, T. Mukherjee, J. Elmer, J. Milewski, A. Beese, A. Wilson-Heid, A. De, and W. Zhang, "Additive manufacturing of metallic components – process, structure and properties," *Progress in Materials Science*, vol. 92, pp. 112–224, 2018.

[29] D. Bourell, J. P. Kruth, M. Leu, G. Levy, D. Rosen, A. Beese, and A. Clare, "Materials for additive manufacturing," *CIRP Annals - Manufacturing Technology*, vol. 66, pp. 659–681, 2017.

[30] M. Hirsch, P. Dryburgh, S. Catchpole-Smith, R. Patel, L. Parry, S. Sharples, I. Ashcroft, and A. Clare, "Targeted rework strategies for powder bed additive manufacture," *Additive Manufacturing*, vol. 19, pp. 127–133, 2018.

[31] S. Everton, M. Hirsch, P. Stravroulakis, R. Leach, and A. Clare, "Review of in-situ process monitoring and in-situ metrology for metal additive manufacturing," *Materials and Design*, vol. 95, pp. 431–445, 2016.

[32] M. Grasso, G. Repossini, and B. Colosimo, "Statistical process monitoring and control methods for in-situ detection and localization of defects in laser powder bed fusion," in *Conference Proceedings, SIG: Dimensional Accuracy and Surface Finishing in AM*. EUSPEN, October 2017.

[33] M. Grasso, F. Caltanissetta, S. Petro, and B. Colosimo, "In-situ monitoring of geometric accuracy in laser powder bed fusion processes," in *EUSPEN's 18th International Conference & Exhibition*, June 2018.

[34] Grow, "Protect & connect software," 2018. [Online]. Available: https://www.grow.am/

[35] S. Mahdavi et al., "Three-dimensional design and manufacturing systems," U.S. Patent 9 604 406B2, Mar 28, 2017.

[36] L. Sturm, C. Williams, J. Camelio, J. White, and R. Parker, "Cyber-physcial vulnerabilities in additive manufacturing systems: A case study attack on the .stl file with human subjects," *Journal of Manufacturing Systems*, vol. 44, pp. 154–164, 2017.

[37] M. Yampolskiy, W. King, J. Gatlin, S. Belikovetsky, A. Brown, A. Skjellum, and Y. Elovici, "Security of additive manufacturing: Attack taxonomy and survey," *Additive Manufacturing*, vol. 21, pp. 431–457, 2018.

[38] A. Gasper, B. Szost, X. Wang, D. Johns, S. Sharma, A. Clare, and I. Ashcroft, "Spatter and oxide formation in laser powder bed fusion of inconel 718," *Additive Manufacturing*, vol. 24, pp. 446–456, 2018.

[39] D. Cuthbert, "Powdercleanse - automated powder recycling and quality assurance for enhanced additive manufacturing material reuse," 2018, innovate UK Project.

[40] B. Smith, D. Gilbert, D. Adamuks, and M. Antar, "Towards post-processing as a key process variable in the am design chain," in *Conference Proceedings, SIG: Dimensional Accuracy and Surface Finishing in AM*. EUSPEN, October 2017, pp. 91–94.

[41] M. Duval-Chaneac, S. Han, C. Claudin, F. Salvatore, J. Bajolet, and J. Rech, "Experimental study on finishing of internal laser metling (slm) surface with abrasive flow machining (afm)," *Precision Engineering*, vol. 54, pp. 1–6, 2018.

[42] C. Cheung, C. Wang, Z. Cao, L. Ho, and M. Liu, "Development of a multi-jet polishing process for inner surface finishng," *Precision Engineering*, vol. 52, pp. 112–121, 2018.

[43] H. Zeidler, F. Bottger-Hiller, and A. Wunderlich, "Surface finish of additively manufactured parts using plasma electrolytic polishing," in *Conference Proceedings, SIG: Dimensional Accuracy and Surface Finishing in AM*. EUSPEN, October 2017, pp. 193–194.

[44] J. Guo, K. Au, K. Liu, S. Ng, and K. Shaw, "A novel vibration-assisted magnetic abrasive polishing method for complex internal surface finishing," in *EUSPEN's 17th International Conference & Exhibition*, May 2017.

[45] J. Ott et al., "Additive manufactured conglomerated powder removal from internal passages," U.S. Patent 0 144 382A1, May 25, 2017.

[46] N. Heidler, E. Hilpert, J. Hartung, and T. Albert, "Lightweight structures for metal mirrors," in *Conference Proceedings, SIG: Dimensional Accuracy and Surface Finishing in AM*. EUSPEN, October 2017, pp. 28–31.

[47] C. S. Lefky, B. Zucker, D. Wright, A. R. Nassar, T. W. Simpson, and O. J. Hildreth, "Dissolvable supports in powder bed fusion-printed stainless steel," *3D Printing and Additive Manufacturing*, vol. 4, no. 1, pp. 3–11, 2017, mary Ann Liebert Inc.

[48] W. Hansal et al., "Electropolishing method and electrolyte for same," Austria Patent A50 716/2017, June 14, 2018.

[49] A. Hassen and M. Kirka, "Additive manufacturing: The rise of a technology and the need for quality control and inspection techniques," *Materials Evaluation*, vol. 76, no. 4.

[50] T. Pinto, "Open architecture additive manufacturing (oaam)," 2018. [Online]. Available: https://gtr.ukri.org/projects?ref=113164

[51] M. Seifi, M. Gorelik, J. Waller, N. Hrabe, N. Shamsaei, S. Daniewicz, and J. J. Lewandowski, "Progress towards metal additive manufacturing standardization to support qualification and certifaction," *The Minerals, Metals & Materials Society*, vol. 69, no. 3, pp. 439–455, 2017.

[52] ISO, *Additive Manufacturing Standards*, tc 261 ed., DIN, 2018. [Online]. Available: https://www.iso.org/committee/629086.html

Table 1. A list of key challenges in metal ALM

Value Stream	Area[1]	Challenge	Impact[2]					Interaction[3]				Solutions/ Research	Gap?
			£	t	Q	H	S	D	B	P	T		⊙
Design	Digital	Optimisation of build layout, orientation & density.	▪	▪	▪			○	○	○		[17] [18]	
		Design for metal ALM (automated software).	▪	▪	▪		▪	○	○	○		[19] [20]	
		Analyse design with FEA software to predict the build behaviour.		▪	▪		▪	○	○	○	○	[17] [21] [20]	
		Topology optimisation / advanced supports (e.g. lattice structures).		▪	▪	▪	▪	○	○	○		[22] [23] [24]	
	Control	Robust and reliable support strategies.		▪	▪		▪	○	○	○			⊙
		Parameter sets by build requirement (quality, time, material, geometry).	▪	▪	▪		▪		○			[25]	⊙
	Material	Enhanced properties of AM-exclusive materials.			▪			○	○	○	○	[26]	⊙
		Accessible database of full-sets of material properties		▪	▪			○			○	[27] [28] [29]	
Build	Physical	Requirements for Total Productive Maintenance of AM machines[4]		▪	▪				○		○		⊙
	Digital	In-situ build monitoring & feedback (i.e. melt-pool and defects).		▪	▪				○		○	[30] [31] [32] [33]	⊙
		Build verification by checking input data against approved reference.			▪	▪	▪		○		○	[34]	
		Secure transfer of design data from office to AM machines via encryption.						○	○			[35] [36] [37]	
	Material	Recycling/rejuvenation and in-process testing for conformance of powder.	▪		▪				○		○	[38] [39]	
Process	Physical	Automated surface finishing of selective surfaces.	▪	▪	▪	▪	▪	○		○		[40]	
		Develop effective surface finishing of internal channels.			▪			○		○	○	[41] [42] [43] [44]	⊙
		Develop a technique for effective powder removal within internal channels.	▪	▪	▪	▪		○		○	○	[45] [46]	⊙
		Automated removal of supports.	▪	▪	▪	▪	▪	○	○	○		[47] [48]	⊙
	Digital	Optimisation of post-processing strategy (incl. fixtures) at design stage.		▪	▪		▪	○		○			⊙
Test	Physical	Develop methods for non-destructive testing of AM parts[5]	▪	▪	▪			○	○	○	○	[49] [50]	
	Control	Standardise certification of AM parts.			▪		▪	○	○	○	○	[51] [52]	

[1] Physical (e.g. hardware), Digital (e.g. software), Control (e.g. standardisation), Material (e.g. powder)
[2] £ (cost), t (time), Q (quality), H (health), S (skills)
[3] D (design), B (build), P (process), T (test)
[4] e.g. gas supply purity, filter age, laser power health, galvanometer scanner accuracy, z-axis accuracy
[5] e.g. wall thickness, cracks, sub-surface porosity, internal channels