PAS 6001:2020

Factors to be considered in making and assessing the business case for additive manufacturing and 3D printing – Guide

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Foreword

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It has been assumed in the preparation of this PAS that the execution of its provisions will be entrusted to appropriately qualified and experienced people, for whose use it has been produced.

Presentational conventions

The guidance in this PAS is presented in roman (i.e. upright) type. Any recommendations are expressed in sentences in which the principal auxiliary verb is "should".

Commentary, explanation and general informative material is presented in smaller italic type, and does not constitute a normative element.

Where words have alternative spellings, the preferred spelling of the Shorter Oxford English Dictionary is used (e.g. "organization" rather than "organisation").

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Compliance with a PAS cannot confer immunity from legal obligations.

0 Introduction

0.1 What is AM/3DP?

Additive manufacturing (AM), also referred to as 3D printing (3DP), as defined in Annex A, refers to the application of a group of technologies which use 3-dimensional (3D) computer-aided design (CAD) data to produce tangible objects. These objects are constructed through the addition of multiple layers of material, using information derived from the 3D CAD data. The material in each layer is consolidated thermally or chemically. Each subsequent layer is then bonded to the previous layer thermally, chemically or mechanically, resulting in a tangible facsimile of the original 3D CAD data. There are seven recognized configurations of the AM/3DP process as defined in BS EN ISO/ASTM 52900. Annex B describes the seven configurations along with details of the materials that each technology can process.

0.2 The benefits of AM/3DP compared to established manufacturing processes

0.2.1 Production flexibility and geometric complexity

There are many inherent benefits to using AM/3DP, which are primarily a function of production flexibility and geometric complexity leading to improved availability and product performance.

0.2.2 Flexible production – toolless manufacture (cost reduction)

As a digitally enabled process, AM/3DP allows users to manufacture items with no associated tooling. AM/3DP differs significantly from processes such as moulding, casting and machining, where tools, patterns, jigs and fixtures are needed to enable production. AM/3DP removes the capital investment and risk associated with this general "tooling", along with the economies of scale and the need to amortize "tooling" cost across large production volumes. AM/3DP can, therefore, enable cost-effective low-volume production that is highly flexible to changes in customer demand.

0.2.3 Improving product performance – smart parts (revenue enabler)

As AM/3DP uses a layered approach to manufacturing, it is also possible to increase the geometric complexity of items beyond the level achievable using traditional manufacturing processes. This complexity can be achieved with little if no impact on production economics, but enables several potential benefits to the customer, which can be monetized, such as improved product performance and efficiency.

0.2.4 Part consolidation – fewer parts, less assembly (cost reduction)

By increasing geometric complexity, it is possible to consolidate multiple parts of an assembly together into a single component. Consolidation reduces the complexity of the supply chain, eliminates manufacturing and assembly operations, removes potential points of failure and can reduce life-cycle service costs.

0.2.5 Personalization and customization – new markets (revenue enabler)

By coupling the geometric freedom of AM/3DP with the low-volume production economics of the process, it is well suited to the manufacture of customized and personalized products such as medical devices, consumer goods and fashion items.

0.2.6 Repair and reuse – after market opportunity (revenue enabler)

AM/3DP technology can also be used in the repair and remanufacture of existing products where material can be added using an AM/3DP process onto an existing object.

0.3 Limitations of AM/3DP compared to established manufacturing methods

0.3.1 Process, productivity and economic challenges

There are many benefits to AM/3DP. However, the process also has limitations and drawbacks.

0.3.2 Low productivity rates

AM/3DP processes have low production rates when compared to more established production methods. For example, whereas an injection moulding machine might take less than a minute to produce a plastic component, an equivalent part produced by AM/3DP could take several hours. Similarly, whereas the cycle time of a computer numerically controlled (CNC) milling machine, cutting metal, might be less than an hour from a solid billet to a finished part, the equivalent part could take over 24 hours to produce using metallic AM/3DP technology.

However, the use of AM/3DP can also mitigate the need for injection mould, die-cast or investment cast tooling, which can take many months to produce. Moreover, the use of AM/3DP can reduce the number of manufacturing and assembly steps needed to bring a product to market. Hence, making the overall approach faster. It is therefore critical that any AM/3DP business case considers the end-to-end production lead-time of parts across the value chain, not solely the AM/3DP production rate.

0.3.3 Questionable production economics

Some high-end AM/3DP machines can cost many hundreds of thousands of pounds. Moreover, the material feedstock used by AM/3DP machines can be significantly more per tonne than the equipment material used in moulding, casting or machining. The relatively low productivity of machines coupled with the high cost of machines and raw materials can result in very high-cost components.

However, AM/3DP can also mitigate the need for fixed assets such as tooling and can be used to reduce down-stream processes and assembly tasks. It is therefore critical that any AM/3DP business case considers the end-to-end production cost of parts, not solely the piece-part production cost of the AM/3DP step.

0.3.4 Limited process capability

AM/3DP is often considered as an alternative to established production processes such as moulding, casting and machining. Although AM/3DP is capable of making suitably sized parts in the same or similar materials, it might not be able to achieve the accuracy, resolution or surface finish of these processes without additional post-process machining, which increases part cost.

0.3.5 Limited material properties

Although AM/3DP machines can process conventional engineering polymers and metals, the resulting mechanical properties of the parts produced might not be equivalent to the same material when processed by casting, moulding or machining. In some cases, this can result in the need for post-process heat treatment and an increased level of part inspection, which increases part cost.

0.3.6 Costly product certification

Many of the benefits of AM/3DP are achieved through redesigning a product or part specifically for an AM/3DP process. In many cases this results in a new product, being made using a new method, in a material with new mechanical properties. In such a circumstance, it might be necessary to certify the capabilities of the product through testing; for example, a new medical device, aerospace component or consumer product. Product certification can add both time and cost to the adoption of AM/3DP.

0.3.7 Difficult process validation

When AM/3DP is used to manufacture certified products or products with a high level of criticality, it is essential that the process remains within specified limits. Like many manufacturing processes, the uniformity of parts produced using AM/3DP can vary significantly as a result of small changes in the process environment. It is therefore important to consider the cost of establishing, mitigating and monitoring any process variance.

Figure 1 details the primary value propositions of AM/3DP adoption and the fundamental limitations to consider when developing or assessing the business case for AM/3DP.

Figure 1 – Primary value propositions and limitations of AM/3DP

The value proposition of AM/3DP	Limitations and consideration for adoption
Flexible production	Limited productivity
Low-volume economic production	Production economics
Part count and assembly reduction	Process capability
Improved product performance	Material property and consistency
Personalization and customization	Product certification
Repair and reuse	Process validation

***NOTE** Other benefits and limitations to AM/3DP are explained in detail throughout PAS 6001.*

0.4 How to use PAS 6001

There are a multitude of economic, legal, social and human factors to consider when either building or assessing an AM/3DP business case. PAS 6001 provides the information needed in the evaluation of these factors.

PAS 6001 uses a number of hypothetical examples of financial business cases relating to different applications of AM/3DP. These financial models are provided for illustration purposes only, to help navigate the information provided within PAS 6001.

When building a business case for AM/3DP using the financial models presented in PAS 6001, the business model canvas presented in Annex C can be used. Based on the Alexander Osterwalder [1)] business model canvas, Annex C provides a framework to capture the value proposition of AM/3DP and the information needed to build a financial model and business case. This canvas can be used to capture ideas stimulated by PAS 6001. Annex D provides a series of self-assessment questions relating to the business drivers for AM/3DP adoption, capital investment and outsourcing, the implications of AM/3DP on human resources and commercial risk.

PAS 6001 does not make recommendations on which AM/3DP technology is the most appropriate for a given application; instead, it provides a framework for how technology investment and adoption should be assessed. It considers the broader implications of AM/3DP on the business, the supply chain and the customer.

[1)] www.strategyzer.com/canvas/business-model-canvas

1 Scope

This PAS provides guidance to directors, senior management and accountants of companies of all sizes who wish to explore or assess the business case for the adoption of AM/3DP for the production or repair of end-use products, systems and services.

The insight provided enables readers to understand where AM/3DP can contribute to top-line business growth, bottom-line profitability and productivity improvement.

This PAS considers how to build the most appropriate supply chain and how to quantify the broader social, environmental and economic benefits of the technology.

It considers the impact of AM/3DP technology adoption both internally and externally, including investment, risk, skills, change management and customer expectation.

This PAS does not cover the business case for rapid prototyping (RP) or digital product development.

NOTE *Although written in the language of profit and loss, this PAS can also be used by anyone looking to develop a business case for AM/3DP within their organization or, inversely, anyone looking to assess an AM/3DP business case presented to them by others.*

2 Terms and definitions

For the purposes of this PAS, the following terms and definitions apply.

NOTE *See Annex E for a list of initialisms and acronyms.*

2.1 additive manufacturing

manufacture of production, end-use or series parts made using technologies based on the principles of Additive Layered Manufacturing (ALM)

2.2 3D printing

process of manufacturing a tangible component part using ALM technology

2.3 3D printer

computer controlled machine that produces tangible components in a layer-wise fashion through the addition of material

2.4 voxels

three-dimensional volume of material at a known location

NOTE *The word "voxel" is an amalgamation of the words "pixel", a two-dimensional element at a known point, and the word "volume".*

2.5 customization

process of choosing from a pre-defined list of options, with the resulting options being combined into a customized product

NOTE *An example of this is the configuring of a new car.*

2.6 personalization

process of producing unique items using 3D design data, derived from, or produced by the customer or patient

NOTE *An example of this is a hearing aid or prosthetic implant cutting guide made using patient scan data.*

2.7 stair-stepping

occurs with all layer manufacturing processes, when parts with curved or angled surfaces are made

NOTE *As each layer is deposited, a pronounced step can be created if the previous layer has a different surface profile to the subsequent layer. Stair-stepping can be minimized by using thinner layers, but this is not always possible and can increase the build time.*

2.8 design for additive manufacture (DFAM)

enables component parts to be manufactured with a very high level of geometric complexity or with variable mechanical properties embodied within a single component

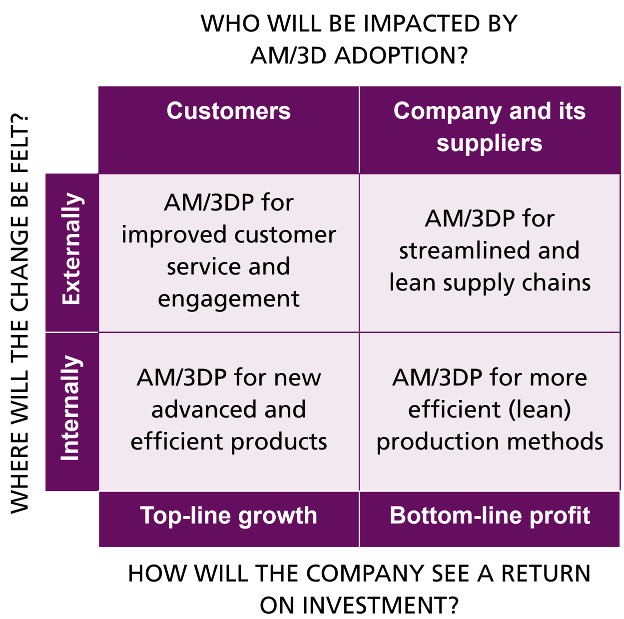
NOTE *DFAM is often achieved using dedicated software tools designed specifically for AM/3DP.*

3 Benefits and income streams from AM/3DP

3.1 Revenue growth and improved profitability

At the highest level, AM/3DP enables companies to grow their top line through new product and service innovation whilst also growing their bottom-line through shop floor productivity improvements and supply chain efficiency gains. Figure 2 shows the four primary organizational benefits of AM/3DP adoption and where change is experienced within an organization's value chain.

Figure 2 – The impact of AM/3DP on a company's value chain, revenue and profit



3.2 Driving top-line growth using AM/3DP

3.2.1 New and innovative products

AM/3DP can be used to enable the manufacture of new and innovative products. These products can then capture new revenue from increased market share driven by competitor attrition, entry into new vertical markets or entry into new geographic territories. Annex F, Table F.1 provides several discrete examples of where AM/3DP can be used to drive revenue through new and innovative products.

3.2.2 New and innovative services

AM/3DP can be used to enable increased levels of customer service, customer engagement or customer interaction, leading to increased customer spending. Annex F, Table F.2 provides several examples of where AM/3DP can be used to drive revenue through improved customer service or increase customer engagement beyond the traditional factory or product offer.

3.2.3 Example 1 – Top-line growth through new product innovation (hypothetical)

Figure 3 shows a 7-year business plan for a new (hypothetical) product enabled by AM/3DP investment. Compressor Valves Incorporated (CVI) has an idea for a new pressure relief valve that can operate at much higher pressures, due to its unique design. However, the design can only be produced using metallic AM/3DP. CVI has no AM/3DP capacity and limited experience. The CVI sales and marketing team believe that within 4 years, demand for the valve will reach 10,400 units per annum with an initial sales price of £100 per unit. In year 1, to mitigate risk, CVI takes the decision to outsource the manufacture of the initial pre-production prototypes to a third party, investing £50K on testing equipment and £20K in specialist design software. In year 2, CVI invests £500K on its own metallic AM machine and a further £50K in ancillary equipment whilst making changes to the facilities and staffing levels. The company depreciates the AM/3DP machine over 4 years (6 years for ancillary equipment). During year 2, the company undertakes rigorous product testing and certification by an outsourced third party. In year 3, CVI commences sales with the output from its one machine. In year 4, CVI adds a second machine. By year 6, CVI plans to introduce a wider range of new AM/3DP products, leading to market cannibalization and reduced sales of the original valve in years 6 and 7.

Figure 3 – Financial business case for investment in AM/3DP to enable a new product

More details can be found in these sections	PAS 6001 clause reference	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5	YEAR 6	YEAR 7
INCOME								
New product sales	3.2.1	£0	£0	£520,000	£1,040,000	£1,040,000	£884,000	£780,000
New services revenue	3.2.2	£0	£0	£0	£0	£0	£0	£0
		£0	**£0**	**£520,000**	**£1,040,000**	**£1,040,000**	**£884,000**	**£780,000**
DIRECT COSTS								
Staff cost	4.2 / 8.0	£50	£70,000	£100,000	£105,000	£110,000	£115,000	£120,000
Subcontractor costs	4.1 / 4.10	£150,000	£50,000	£0	£0	£0	£0	£0
Materials	4.6	£0	£50,000	£200,000	£300,000	£400,000	£400,000	£380,000
Waste and consumables	4.8	£0	£5,000	£20,000	£30,000	£40,000	£40,000	£38,000
Warranty	4.4.2	£0	£0	£50,000	£50,000	£100,000	£100,000	£50,000
Software	4.3	£20,000	£20,000	£10,000	£10,000	£10,000	£10,000	£10,000
Facilities	4.5		£20,000	£0	£0	£0	£0	£0
		£170,050	**£215,000**	**£380,000**	**£495,000**	**£660,000**	**£665,000**	**£598,000**
CONTRIBUTION		**-£170,050**	**-£215,000**	**£140,000**	**£545,000**	**£380,000**	**£219,000**	**£182,000**
INDIRECT COSTS								
Rental / mortgage		£100,000	£100,000	£100,000	£110,000	£110,000	£110,000	£110,000
Rates		£10,000	£10,000	£10,000	£110,000	£10,000	£10,000	£10,000
Utilities		£10,000	£10,000	£10,000	£10,000	£10,000	£10,000	£10,000
staff costs		£100,000	£100,000	£100,000	£100,000	£100,000	£100,000	£100,000
		£220,000	**£220,000**	**£220,000**	**£330,000**	**£230,000**	**£230,000**	**£230,000**
EBITDA		**-£390,050**	**-£435,000**	**-£80,000**	**£215,000**	**£150,000**	**-£11,000**	**-£48,000**
Depreciation (AM/3DP hardware)	4.4	£0	£125,000	£125,000	£250,000	£250,000	£125,000	£125,000
Depreciation (ancillary)	4.7	£8,333	£16,666	£16,666	£16,666	£16,666	£16,666	£8,333
EBIT		**-£381,717**	**-£293,334**	**£61,666**	**£481,666**	**£416,666**	**£130,666**	**£85,333**
Tax credits	7.2	£55,349	£42,533					
Grants	7.2	£25,000	£25,000					
Capital allowance	7.2							
PRE-TAX PROFIT		**-£301,368**	**-£225,801**	**£61,666**	**£481,666**	**£416,666**	**£130,666**	**£85,333**
CUMULATIVE RETURN		-£301,368	-£527,169	-£465,503	£16,163	£432,829	£563,495	£648,828

3.3 Driving bottom-line growth using AM/3DP

3.3.1 Making the factory more efficient

AM/3DP can be used within the production environment to address process inefficiencies. Figure 4 aligns the use of AM/3DP to the eight waste streams of lean manufacturing and shows how this can be used to increase profitability.

3.3.2 Improving the supply chain

The adoption of AM/3DP can have an external impact on the business through a more streamlined and lean supply chain. A more streamlined supply chain then presents gains in operational efficiency leading to higher levels of profitability. Annex F, Table F.3 provides several examples of where AM/3DP can be used to drive external supply chain efficiency.

Figure 4 – Alignment of AM/3DP with the eight wastes of lean manufacturing

More efficient lean production methods	
How does AM/3DP address lean waste?	**How does this drive profitability?**
Reduction in ***defects***	As a digital technology, errors are both traceable and can be rectified quickly with minimal risk. Some mistakes can also be corrected using AM/3DP repair technologies reducing scrap rates and financial losses.
Reduction in ***overproduction***	AM/3DP parts can be printed to order or to maintain minimal inventory. Printing to order frees up working capital while also reducing the associated cost of part storage and disposal of excessive end of life stock.
Reduction in ***waiting***	Part consolidation and replacing multiple manufacturing operations reduces inefficient waiting time during production, enabling faster task-times and freeing up working capital more quickly. AM/3DP can also be used to manufacture temporary or “bridge” jigs, fixtures and tooling, allowing more seamless production to take place with less down time.
Reduced ***transportation***	By reducing manufacturing production steps and by utilizing concurrent AM/3DP manufacture close to the point of product use, transportation time and associated costs decrease, while enabling products to reach customers more quickly.
Inventory ***excess***	AM/3DP processes require significantly less raw material to be held in stock, while also producing less scrap. Digital inventories enable the manufacture of spare parts, reducing the cost associated with storage and end of life disposal.
Reduction in ***motion waste***	As a digital “light-out” technology, AM/3DP requires a minimal level of human intervention. With a well-designed and automated facility, operator motion can be minimized, leading to higher levels of labour efficiency.
Reduction in ***excess processing***	As a digital technology, the acceptable level of part quality can be set before production, such as the use of thicker layers or lower resolution. These changes can significantly reduce the cost of manufacture while achieving a quality level acceptable to the customer.
Non-utilized talent	Companies can increase productivity by utilizing the talents, skills and knowledge of employees that have experience of AM/3DP technologies and processes. These experiences may have been gained at prior employers, through academic study or through the use of low-cost consumer 3D printing in the home.

3.3.3 Example 2 – Bottom-line growth through lean AM/3DP production (hypothetical)

Figure 5 and Figure 6 detail a simplified five-year (hypothetical) cost comparison between two similar products manufactured using injection moulding and assembly (Figure 5), and plastic AM/3DP as a single item (Figure 6).

Gadget Makers International (GMI) assemble and supply a range of high-end kitchen utensils. Due to skills shortages and market uncertainty, the company have closed their tool-room and mould-shop and are now reliant on third party suppliers of tools, mouldings and metal parts.

The company is in the process of bringing to market a new kitchen gadget, which they believe could be manufactured using AM/3DP. Using the design freedoms of AM/3DP the gadget can be manufactured as one single moving component, rather than three mouldings assembled with screws and a central bearing.

The company's sales and marketing team do not believe the AM/3DP product can be sold for a higher price than the moulded part and are suggesting a wholesale price of £15 per unit. The team are also suggesting annual sales volumes in the order of 10,000 units over a five-year product life.

The minimum order quantity for moulded parts is 20,000 units for each of the three components required, with a piece part price of £0.50 for each component. The bearings are readily available for £1 each and can be ordered in small quantities, albeit with less bulk discount. Assembly of the parts with the bearing and fixing screws takes 6 minutes with a fully loaded labour cost of £40 per hour. The cost of outsourcing AM/3DP batch products is £2,000 for a batch of 250 parts.

However, when in the market, sales of the product rapidly decline in year 4 due to low-cost competition from overseas. This results in a price reduction to £8 per unit by year 5, with the potential for significant levels of stock being scrapped.

Figure 5 – Cashflow projection of injection moulding and assembly

	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5
INCOME					
Sales Price	£15	£15	£15	£10	£8
Sales volume	5,000	10,000	10,000	2,000	1,000
	£75,000	**£150,000**	**£150,000**	**£20,000**	**£1,008**
DIRECT COSTS (TRADITIONAL)					
Product design cost	£5,000	£0	£0	£0	£0
IM tool design costs	£7,000	£0	£0	£0	£0
IM tool manufacture	£40,000	£0	£0	£0	£0
IM part procurement	£30,000	£0	£30,000	£0	£0
AM/3DP assembly procurement	£0	£0	£0	£0	£0
Bearing procurement	£5,000	£10,000	£1,000	£0	£0
Fixings (screws)	£50	£100	£100	£20	£10
Component storage	£100	£100	£100	£100	£100
Assembly cost	£20,000	£40,000	£40,000	£8,000	£4,000
Cost of excess stock disposal	£0	£0	£0	£0	£50
	£107,150	**£50,200**	**£71,200**	**£8,120**	**£4,160**
ANNUAL CASH IMPACT	**-£32,150**	**£99,800**	**£78,800**	**£11,880**	**-£3,152**
CUMULATIVE RETURN	-£32,150	£67,650	£146,450	£158,330	£155,178

Figure 6 – Cashflow projection of AM/3DP manufacture as a single part

	PAS 6001 clause reference	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5
INCOME						
Sales price		£15	£15	£15	£10	£8
Sales volume		5,000	10,000	10,000	2,000	1,000
		£75,000	**£150,000**	**£150,000**	**£20,000**	**£8,000**
DIRECT COSTS (AM/3DP)						
Product design cost	4.4.1	£7,000	£0	£0	£0	£0
IM tool design costs		£0	£0	£0	£0	£0
IM tool manufacture		£0	£0	£0	£0	£0
IM part procurement		£0	£0	£0	£0	£0
AM/3DP assembly procurement	5	£40,000	£80,000	£80,000	£16,000	£8,000
Bearing procurement		£0	£0	£0	£0	£0
Fixings (screws)		£0	£0	£0	£0	£0
Component storage		£0	£0	£0	£0	£0
Assembly cost		£0	£0	£0	£0	£0
Cost of excess stock disposal		£0	£0	£0	£0	£0
		£47,000	**£80,000**	**£80,000**	**£16,000**	**£8,000**
ANNUAL CASH IMPACT		**£28,000**	**£70,000**	**£70,000**	**£4,000**	**£0**
CUMULATIVE RETURN		£28,000	£98,000	£168,000	£172,000	£172,000

3.4 Non-financial benefits of AM/3DP adoption (soft value)

3.4.1 Environmental benefits of using AM/3DP in the value chain

In addition to the direct financial benefits of AM/3DP adoption, there are also several environmental benefits. Many of these environmental benefits will also lead to reduced indirect manufacturing costs and overheads; some also yield reduced operating costs for the end-user. Annex F, Table F.4 provides details of many of the environmental benefits that can be gained through AM/3DP adoption.

3.4.2 Social benefits of using AM/3DP products

In addition to the direct financial benefits and environmental benefits of AM/3DP adoption, there are also several social benefits relating to improved healthcare and product ergonomics. Several examples can be found detailed in Annex F, Table F.5.

3.4.3 Marketing and PR benefits

AM/3DP has been popularized in the media, there might therefore be some marketing benefit from associating the use of the technology to the manufacture of a product.

3.5 Prioritizing the use of AM/3DP within the organization

Although many organizations can derive value from AM/3DP in two or more of the quadrants in Figure 2, it is advisable to focus initial implementation activities around the quadrant that will yield the most significant impact.

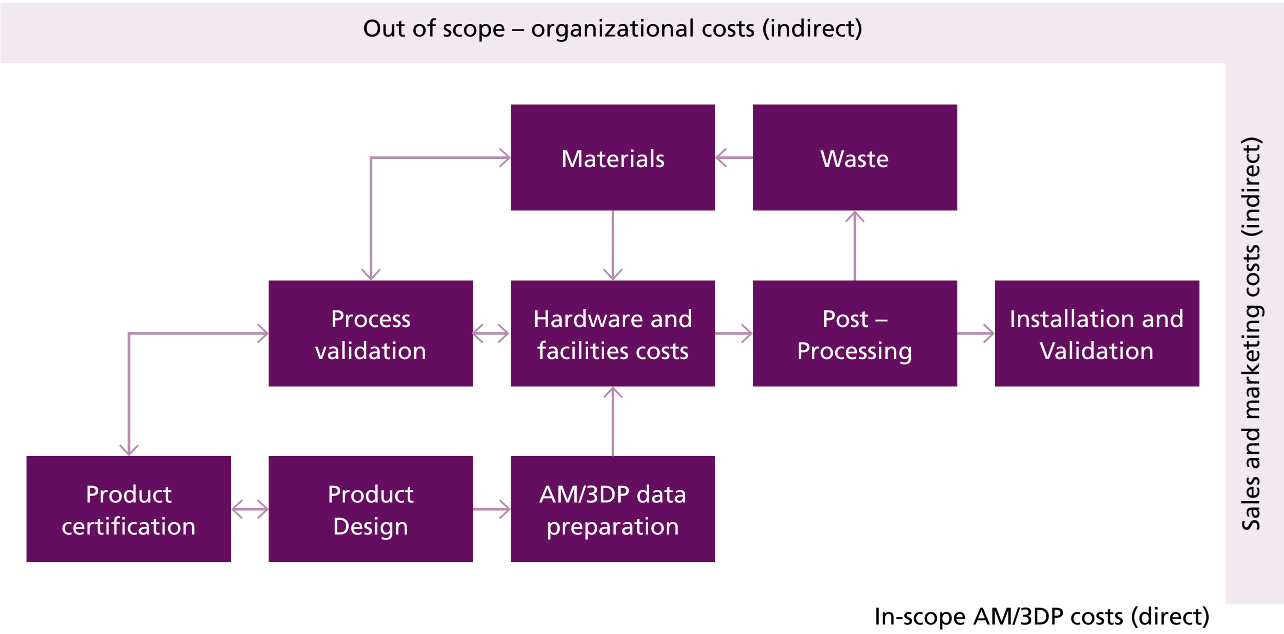
NOTE Annex D, Table D.1 can be used to support this high-level prioritization of AM/3DP across the organization.

4 Costs associated with AM/3DP hardware implementation

4.1 The direct costs of AM/3DP adoption within the organization

Figure 3 detailed a business case for the acquisition of AM/3DP hardware for the in-house manufacture of a new product. Within this clause, consideration is given in more detail to the direct costs associated with AM/3DP, based on the in-scope elements of the schematic in Figure 7. It should be noted that this section does not consider indirect costs and activities relating to organizational structure, sales, marketing and management. These factors are covered later within Clause 6 to Clause 8 of this PAS.

Figure 7 – Direct cost consideration when building an AM/3DP business plan



4.2 Product certification

If AM/3DP is to be used to manufacture a critical part, such as a medical device or aerospace component, it might be necessary to seek certification for any design changes or changes in the production processes.

NOTE 1 *It is recommended that the design and manufacture of the component is certified by a relevant authority, such as the Civil Aviation Authority (CAA) or the Medical & Healthcare Regulatory Authority (MHRA).*

NOTE 2 *Certification may include extensive part testing using test coupons and external validation of test results by a third party authority.*

4.3 Process validation

If AM/3DP is to be used to make critical parts or certified products, it might also be necessary to ensure the AM/3DP production process has been validated. AM/3DP processes can suffer from a high level of process variance, and as such, it is critical to establish safe operating tolerances. Other factors such as material inconsistency and machine-to-machine inconsistency can also affect the quality and repeatability of final parts. As such, a robust process validation and inspection method should be developed and implemented [2]. This can incur significant upfront costs to establish safe working parameters and to enable a controlled end-to-end process from raw material supply through to the finished part.

[2] https://reevesinsight.com/wp-content/uploads/2020/08/Technical-limitations-of-AM-3DP.pdf

4.4 The cost of data

4.4.1 Product design software costs

It is critical to design parts for each individual AM/3DP process to maximize the benefits of the technology. To do this, it might be necessary to invest in new design software, including:

a) 3D solid modelling or surface modelling CAD software to design part geometry, unless a third party supplier provides the design data;

b) 3D scanning hardware and software, if there is a need to capture existing part geometry before reverse engineering (such as when AM/3DP is being used as a repair technology);

c) 3D scanning hardware and software, if there is a need to capture body geometry for consumer or medical applications;

d) highly specialized segmentation software, if computer tomography (CT) or magnetic resonance imaging (MRI) are being used to capture geometric or medical data;

e) topological optimization or generative design software, if there is a need to produce parts with the optimum distribution of material based on loading conditions and constraints;

f) lattice generation software, if there is a need to reduce the bulk volume of material used within a part while maintaining structural integrity, or if there is a need to design structures with specific properties such as vibration damping; and

g) FEA software, if there is a need to design parts that can dissipate vibrations or cope with certain loads.

4.4.2 AM/3DP production data software costs

Once the initial design data has been created for a part, it is important to consider how best it can be manufactured. This decision should take into consideration factors such as quality, cost and delivery time. Specialist software tools are needed to support this task, including:

a) build simulation software;

b) orientation optimization software;

c) support structure generation software;

d) packing optimization software;

e) slicing software; and

f) scheduling and load planning software.

It might be necessary to use specialist software to simulate the build of a particular geometry within the AM/3DP process, before manufacture. Simulation can highlight potential problems and possible modes of build failure. Simulation software tools are available for some metallic processes including selective laser melting (SLM), direct metal laser sintering (DMLS) and electron-beam melting (EBM). Simulation software is also available for some polymeric methods including fused deposition modelling (FDM) and stereolithography (SL).

It might be necessary to use specialist software to find the optimum orientation of the part before printing. Part orientation in the AM/3DP process can have a significant impact on part quality, build time and production economics.

For SL, FDM, DMLS and SLM, it might be necessary to generate support structures to either hold the part above the build platform or to anchor the part on the build platform. Software tools are available to create appropriate support, depending on the AM/3DP process selected.

To ensure maximum process efficiency, it might be necessary to nest or pack parts together within the build chamber of the AM/3DP machine. Nesting or packing can be undertaken manually or using specialist software tools.

Once a part has been placed in the optimum orientation, supported and packed, it is digitally sliced into layers, and the machine parameters for each slice generated into the build file. Slicing software used to create the build file typically comes with the AM/3DP hardware, however, there could be ongoing licensing costs.

Once a build file has been generated, a production schedule might be needed for the appropriate AM/3DP machine. Scheduling and load balancing software is available for single-site production facilities and distribution facilities with machines in multiple locations.

4.5 Hardware cost

4.5.1 Asset purchase and ownership

A suitable production facility is needed to turn the build file into a physical object. This facility should contain at least one machine, located in an appropriate working environment.

For part manufacture, the most appropriate AM/3DP machine should be used based on a comprehensive and structured evaluation of technical capabilities and constraints. Although PAS 6001 is not a technical evaluation standard or specification, an overview of what to consider in a technical assessment can be found online [3].

4.5.2 Leasing and non-balance sheet methods of securing hardware (non-acquisition based)

In addition to the typical hardware purchase and depreciation business model, there are other ways of securing AM/3DP production capacity on the shop floor. Many industrial AM/3DP machine vendors offer a fixed-term hardware lease option with either asset return or purchase at term-end. In some cases, asset finance might be available from third party lenders. However, this might not be advantageous given the low perceived residual value of AM/3DP machines by the financial community. For high-value production applications, some industrial machine vendors can consider partnership agreements where they will deploy and operate AM/3DP hardware (on their balance sheet) on an ongoing fee-based model.

Where there is a high probability of consistent machine use, some AM/3DP vendors might offer a pay-per-use business model. Pay-per-use business models are based on a minimum use threshold where the asset remains on the balance sheet of the vendor. The user pays a fixed monthly minimum fee irrespective of usage, plus an additional hour's usage charge.

In a limited number of cases, the machine vendor might only offer a fixed-term lease agreement with no option to acquire the capital asset.

4.5.3 Warranty and maintenance

In addition to the purchase of AM/3DP hardware it is also important to consider the ongoing maintenance and support of the capital asset. Hardware vendors typically provide support as part of an annual extended warranty or maintenance package. Different service level agreements (SLA) are typically available depending on the level of cover required. Agreements differ based on the speed of response and the degree of replacement parts provided. Maintenance and warranty are typically considered inclusive within the first year of machine operation.

4.6 Facilities costs

AM/3DP hardware should be housed and operated in a suitable working environment. For some smaller, desktop machines this could be an office or workshop environment. However, for other, high resolution or high deposition rate industrial machines this might necessitate a specialist working environment in order to maintain part quality and operational efficiency.

Depending on the type of AM/3DP technology adopted, the ambient operating temperature and relative humidity should be considered, and the possible need for air conditioning. Consideration should also be given to the cleanliness of the working environment and possible contamination of the build material. It might also be necessary to consider issues such as vibration on the shop floor and the extraction of fumes within the machine shop environment.

The type of AM/3DP hardware can also impact on the utilities needed such as a robust 240 V or 415 V power supply, with uninterruptable back-up, compressed air, shielding gases, such as argon or nitrogen, and connectivity to a local area network.

4.7 Material costs

In addition to the enabling cost of data and the hardware cost of machines, there are also several costs associated with materials, including stock holding, maintaining quality and safety and the prevention of spoilage.

[3] https://reevesinsight.com/wp-content/uploads/2020/08/Considerations-for-the-technical-evaluation-of-AM-3DP.pdf

In terms of stock holding, it is crucial to hold sufficient raw material to operate the chosen AM/3DP system. For some processes, such as FDM, this could be as little as the volume of the part to be manufactured. However, for other methods, such as SLS, DMLS, multi jet fusion (MJF), EBM or SL, the user might require sufficient powder or resin to fill the entire build volume of the machine. Some processes such as FDM might also require an additional feedstock of material to act as the support structure. Moreover, in addition to the primary raw material, some processes such as binder jetting (BJ), high speed sintering (HSS) and MJF use additional consumables such as binders or radiation absorbent agents to promote material bonding.

In terms of cost associated with material quality and safety, appropriate transportation and storage equipment should be considered to ensure material is kept in the optimum environmental conditions. Some powdered AM/3DP materials, such as aluminium and titanium, are highly volatile and can pose a risk of explosion. Appropriate storage and handling equipment should be made available and used.

It should also be noted that some resins used in AM/3DP have a limited shelf life, and as such, it is essential to ensure an appropriate rotation of stock to prevent waste. Similarly, some filament materials are susceptible to moisture. In specific locations, it might be necessary to use humidity-controlled storage to prevent moisture absorption from the atmosphere into the build material.

4.8 Post-processing costs (excluding down-stream machining or assembly)

Once a part has been produced, it might be necessary to undertake an element of post-processing before the part can pass to the next stage of the supply chain, as follows.

a) For powder-based processes, this involves the removal of any unconsolidated powder from the part. Some AM/3DP machines come with a built-in or ancillary depowdering station.

   NOTE 1 *External depowdering hardware such as a blasting cabinet and compressor can add additional cost.*

   NOTE 2 For liquid resin-based processes, this involves the removal of any uncured liquid from the part. Some AM/3DP machine come with a built-in or ancillary washing station.

   NOTE 3 *Wash stations, centrifuges and other equipment for resin removal and washing may be an additional cost item.*

b) For extrusion-based processes, it will be necessary to manually remove any additional support structure material. This process can be partially automated with the use of soluble secondary support structure material which can also be useful when building complex geometries with internal features.

   NOTE 4 *It might then be necessary to invest in an ultrasonic or agitation-based wash tank to dissolve unwanted support material. The residue from this process then becomes another waste stream.*

c) For some metallic processes, where support structure is used, it might be necessary to remove the part and support structure from the build platform of the machine.

   NOTE 5 *Part and support removal might require access to wire-erosion Electrical Discharge Machining (EDM) hardware or an accurate band saw.*

d) For some metallic powder-based processes, it might then be necessary to use CNC machining, EDM or hand tools to remove support structure from the part.

e) For some processes, it might be necessary to undertake heat treatment to remove stresses built up during the manufacturing process before the removal of the part and support structure from the machine.

   NOTE 6 *Post-process heat treatment might require suitable furnaces which could require additional consumables such as shielding gases and electricity.*

f) For some processes, in particular those making complex shapes and/or lattices, additional time and specialized cleaning equipment might be needed, such as an ultrasonic cleaner, which require additional validation.

4.9 Cost of wasted material

Before part use, it might be necessary to undertake several post-process operations such as support removal or depowdering. These post-processes can create several material waste streams, as follows.

a) The consolidated material used in any support structure is a waste stream and should be accounted for as such. It cannot be used again and should be either recycled or disposed of as waste.

b) For the FDM process, soluble support structure should be considered both material waste and a waste stream. Soluble support structure costs money to buy (material cost), money to process (print cost) and money to dispose of (waste disposal of wash tank sludge).

c) With near net-shaped AM/3DP technologies, parts might require post-process machining to attain the final part accuracy and surface finish. Post-process machining could result in additional waste material.

d) With all AM/3DP processes, a percentage of raw material can be lost from the process due to spillage, entrapment within the part and entrapment within the AM/3DP hardware.

4.10 Costs of reprocessing and reusing material

In some AM/3DP processes, it is considered standard practice to reuse unconsolidated or unprocessed raw material. However, some material might not be suitable for reuse or might require significant testing and analysis prior to reuse. For example:

a) with some thermal powder-based processes, such as SLS, it is not possible to reuse all the unprocessed raw material feedstock that has not been used in part manufacture. As such, a percentage of unused feedstock material should be considered waste;

b) to evaluate the quality of pre-used plastic material before reuse, it might be necessary to measure the melt flow index of the powder to establish suitability;

c) for metals powder reuse, it might be necessary to undertake particle size distribution and chemical analysis; and

d) the cost of materials analysis hardware and training should be taken into account when developing the business case.

4.11 Cost of part inspection

Before a part can be used for a specific application, it might be necessary to undertake validation and inspection of either the part or the part build environment, as follows.

a) Contact or non-contact measurement and inspection might be needed to ensure the geometric integrity and accuracy of parts produced by AM/3DP. Inspection might be to compare the manufactured part with the enabling design data, or the variance between different series of AM/3DP parts.

b) Non-destructive testing (NDT) such as 2D X-ray radiography inspection, X-ray computed tomography (XCT) or dye-penetration are useful inspection techniques to ensure the homogeneity of the AM/3DP parts. NDT can ensure there are no subsurface defects such as cracks or excess porosity. However, depending on the inspected component geometry, size, and region of interest, NDT can add high cost and lead time to the manufacture of parts.

c) Destructive tensile or impact testing of sacrificial coupons made alongside parts might be needed to ensure critical mechanical properties are maintained.

d) It might be necessary to produce and test multiple specimens to ensure the statistical validation of data.

***NOTE** Annex D, Table D.2 might be a useful aid in capturing and evaluating information on hardware, material and data costs.*

5 Outsourcing AM/3DP part production

5.1 The use of third parties for the manufacture of AM/3DP parts

In some cases, although there might be a business benefit for AM/3DP adoption, there might also be several reasons not to invest in hardware, infrastructure and people, but to develop an outsourced supply chain, as described in the example scenario in Figure 6. If this is not the case and there is a commitment to AM/3DP hardware investment, the guidance in Clause 6 should be followed.

5.2 Internal factor influencing the use of outsourcing

There are several justifiable reasons why a company might choose not to invest in AM/3DP hardware. Figure 8 outlines several reasons and the steps that can be taken to maximize the business benefit of AM/3DP through alternative sources.

5.3 Wider benefits of outsourcing part manufacture

In some cases, there are additional business benefits that can be gained through the procurement of AM/3DP parts outsourced to external suppliers. At the most simplistic level, outsourcing removes the need for capital investment, keeping high-cost assets off the balance sheet. Figure 9 details several additional benefits to outsourcing.

5.4 Limitations and risks of outsourcing AM/3DP part manufacture

There might, however, be several disadvantages associated with outsourcing part manufacturer. Figure 10 lists several potential problems and the actions that can be undertaken to mitigate these problems.

Figure 8 – Reasons not to invest in AM/3DP hardware

Reason	Solution to maintain AM/3DP adoption
Insufficient clarity over the sales trajectory of AM/3DP products	Use an external part supplier to manufacture components until there is a clear picture of market demand. Look to negotiate a cost-down strategy to maximize margins during ramp-up phase.
Insufficient clarity over the internal demand for AM/3DP parts	Use an external part supplier to manufacture components until there is sufficient internal demand to justify Capex.
Inability to raise finance for capital expenditure and investment	Look to identify a production partner that can work on a “cost-down” strategy as demand volumes increase. This can ensure a more equitable split of long-term profits leading to better fluidity and Capex potential.
Skills shortages	Look to develop relationships with Research and Technology Organizations (RTOs) and universities. Look to engage in student placements. Look at potential staff secondments or placements within AM/3DP machine vendor facilities.
Organizational culture of outsourcing	Look to identify a production partner that can work on a “cost-down” strategy as demand volumes increase.

Figure 9 – Wider benefits of outsourcing AM/3DP part procurement

Reason to outsource	Benefit to the business
Reduced reliance on a critical asset – machine failure	Where AM/3DP parts are essential to a broader solution, it might be advantageous to use a network of external suppliers to maintain a robust supply chain, rather than invest in in-house capacity, particularly if that investment is in a single platform with no redundancy.
Machine upgrades and obsolescence management	When a critical technology such as AM/3DP is maturing rapidly and being used by competitors, it might be advantageous to use a network of external suppliers offering parts made on more frequently updated technology platforms.
Mitigate bottleneck caused by volatile demand	Using an external network of AM/3DP part suppliers, it might be possible to load balance better between customers' demand fluctuations and machine capacity. In some cases, a blended option could work with both outsourcing and internal capacity.
Requirement of parts at multiple locations in the supply chain	Using a network of external suppliers, it might be possible to minimize transportation costs and lead times by sourcing parts manufactured close to the point of use or closer to the next point of integration into the supply chain.

Figure 10 – Potential problems associated with AM/3DP part procurement

Problem with outsource	Mitigation strategy
Maintaining intellectual property control over critical data	Ensure there is a robust supply contract which covers IP ownership, non-disclosure, data storage and data deletion. There are several DRM solutions available to manage the flow of data within the AM/3DP supply chain.
Data security and corruption	Ensure the supplier has a robust IT policy covering data transfer protocols and storage. Ensure all staff are familiar with data transfer protocols.
Higher cost per component than manufacturing in-house (due to supplier margins and logistics costs)	Work with suppliers to look at minimizing waste and driving out cost (lean AM/3DP). Look at forecasting demand and optimizing build platforms to reduce build time and waste. Look at bringing post-processing operations in-house.
Miscommunication across the supply chain	Agree to work against recognized standards such as BS EN ISO/ASTM 52900 and BS EN ISO/ASTM 52901 which ensures common terminology across the supply chain.
Loss of manufacturing control	Look to maintain critical technological know-how within the organization by becoming the "intelligent" customer, as this can result in less supplier dependency and the ability to change suppliers more easily if needed.
Lack of internal skills development	Look to develop a manufacturing partnership model with a critical supplier, where there is an element of knowledge transfer and skills development.
Commercial rights management and counterfeiting	Outside of legal contracting, it is possible to embed digital watermarking into AM parts to prevent or monitor counterfeiting. DRM tools are also available to manage online digital data inventories and provide access management tools for third party manufacturers.
Difficulty in controlling quality remotely	It might be more difficult to ensure continuity of quality and material properties if the machines are remote or parts come from a number of suppliers.

5.5 Contractual considerations to outsourcing

In addition to the benefits and drawbacks of outsourcing, several contractual factors should be taken into account when engaging a third party supplier.

a) When using a third party to provide specialist DFAM expertise, it is crucial to ensure that any design inputs or software tools used are not proprietary and that there is an open licence agreement to have parts manufactured using the design data by other suppliers.

b) When using a third party to optimize the build parameters of parts such as orientation and support structure, it is essential to secure access to this information along with machine parameter settings to enable migration to other suppliers with minimal quality impact.

c) When using a supplier for validating the production of a component, including simulation and redesign for AM/3DP, it is essential to have contractual documentation relating to the ownership of the resulting machine build file. In some cases, suppliers might retain ownership of the build file unless a premium is paid. This can prevent the transfer of critical build file data to other potential suppliers.

5.6 Outsourcing of post-processing

Although it might be possible to justify internal investment in AM/3DP design tools and production hardware, it might not be possible to justify investment in post-processing technologies. In some cases, it might be advantageous to outsource essential post-processes such as hot isostatic pressing (HIP), tempering and case hardening, along with post-process machining operations.

***NOTE** Annex D, Table D.3 can be a useful aid in capturing and evaluating the implications of outsourcing AM/3DP production.*

6 The impact of AM/3DP on sales channels, commercial activities and risk

6.1 Commercial and organization implications of AM/3DP

Once the business benefits, investment requirements or outsourcing implications have been explored, consideration should be given to how the technology could impact the organization commercially. Consideration should also be given to the risks AM/3DP adoption brings and the impact the technology has on the customer's experience.

6.2 Impact of AM/3DP on customers and the sales channel

The use of AM/3DP is often invisible to the end-user or customer, as it is the value that the technology brings that is critical to success. When considering the adoption of AM/3DP, it is, therefore, essential to clearly articulate the benefit that the approach enables, rather than the method itself. It is also necessary to consider how any changes enabled by AM/3DP impacts the customer engagement process and the broader sales channel.

6.3 The impact of AM/3DP on business to consumer or patient transactions

Where AM/3DP is being used to offer a personalized or customized product, it is essential to consider the customer journey and the digital and physical thread that starts and ends with that customer. Consideration should be given to the following questions.

a) Where physically or virtually can the customer be engaged, and how can their design input be captured?

b) What technologies are required to capture the customers' or patients' input? Should this be a web-based interface or through interaction with other people?

c) If required, have the costs of developing, hosting and maintaining a web-based interface been fully explored?

d) Where face-to-face engagement with the customer is necessary, who should be responsible for engaging with the customer and what skills and technologies will they need?

e) Who will employ the person engaging with the customer and how does that company fit within the business model and cost base?

f) Once codesign input has been captured from the customer, how can it be processed to make it manufacturable? Can this process be automated, or will it require manual intervention?

g) Have the costs of an automated workflow been fully explored?

h) Alternatively, have the costs of manual data processing been included in the business model?

i) Where manual data processing is required, where should this take place and by who? Have these costs been fully explored?

j) How can the customer be "tagged" to the physical part to ensure the correct part reaches the right customer?

k) Has the cost of automated or manual part marking or tagging been taken into consideration?

l) Following production, how can the resulting product reach the customer? Should this be through a face-to-face retail experience or by shipping?

m) At what point should payment be taken for a personalized or customized product? Should this be at the point of data capture or the point of product delivery?

n) Have the implications of product rejection been taken into consideration? Should customers be offered alternative products?

o) Have warranties and guarantees been put in place, along with a returns and repairs policy?

p) How is customer data stored and used for future product manufacture, such as product replacement? Has the General Data Protection Regulation[4] (GDPR) been taken into account when storing customer or patient data?

[4] www.gdpr.eu

6.4 Impact of AM/3DP on business to business transactions

To exploit the benefits of AM/3DP for an existing application, it is often necessary to redesign the product using DFAM. It is also likely that a substitute material may be selected or an equivalent AM/3DP material, which may exhibit different properties to the original material used. This new material and design are then manufactured using a new process, AM/3DP.

This change in the manufacturing process, material and design may cause concern for some customers in highly regulated or conservative sectors. It is, therefore, essential to clearly articulate the benefits that new and enhanced AM/3DP part can bring to customers. Many of these benefits were discussed in clause 3 of this methodology.

6.5 Understanding and mitigating commercial risk of AM/3DP adoption

As with the implementation of any new technology, there are business risks associated with AM/3DP. With planning, these risks can be addressed and mitigated.

Figure 11 details several commercial risks from across the organization and how these risks can be mitigated.

Figure 11 – Commercial risk associated with AM/3DP part outsourcing

Risk	Mitigation strategy
Freedom to operate – there are an extensive number of patents covering both AM/3DP manufactured products and AM/3DP business models. Such IP may impact on the use of AM/3DP for certain products and services	Ensure a thorough patent review is undertaken to ensure no infringements or to identify potential licensees
Vendor failure – it is essential to consider that many AM/3DP machine vendors are start-ups and small business. The failure of a critical supplier may impact on the servicing and maintenance of assets and prevent future scale-up	Ensure any suppliers are vetted accordingly, consider third party service providers and how easy it can be to switch vendors in future
AM/3DP part supplier failure – As in all supply chains, an AM/3DP part supplier may fail. Although it is theoretically easier to change supplier as no tooling exists it may be necessary to requalify a new supplier or new AM/3DP technology	Try to identify secondary sources of parts before they are needed. Build-in resilience by using a network of suppliers rather than a single source
Insufficient production demand to justify capital investment – For some applications, it may be challenging to build a credible economic model for the adoption of AM/3DP as production volumes are insufficient to warrant investment.	Consider where else AM/3DP could be used within the enterprise. Are there potential applications in product development or manufacturing where excess machine capacity can be shared
Intellectual property theft by supplier – Design file given to suppliers may be shared externally with 3rd parties and used maliciously to produce "off-book" parts	Ensure robust contracting or only use suppliers that can offer a DRM solution integrated into their AM/3DP workflow
Poor machine utilization due to capacity planning – As demand for AM/3DP parts increases, there is the potential to introduce bottlenecks into the process inadvertently. This can result in reduced machine utilization	Look to implement a dedicated AM/3DP shop floor Management Information System (MIS), which can highlight and alleviate bottlenecks

7 The implications of AM/3DP on tax, tariffs and intracompany accounting

7.1 Accounting implications of AM/3DP investment

In addition to the impact of AM/3DP on customers, the adoption of the technology may also affect the company's accounting practices. There are several potential tax, tariff and intercompany accounting implications that should be considered when applying AM/3DP into the value chain.

***NOTE** Clause **7.2** relates to the UK business environment, different conditions may apply elsewhere.*

7.2 Favourable implication of AM/3DP adoption on accounting practices

There are a number of favourable accounting implications to the adoption of AM/3DP:

a) Research and Development (R&D) tax credits may be available where AM/3DP technology is being used for product validation and certification, but not at the production stage.

b) Under the Annual Investment Allowance (AIA), AM/3DP equipment up to the value of £1M is eligible against the current capital allowance. It should be noted that the current allowance of £1M is the result of a temporarily increased until Dec. 31, 2020, replacing a £200K benefit in place since January 2016.

c) By printing parts in the country of use, customs, export and import duties and tariffs could be circumvented. However, given many global governments concerns about the taxation of digital data, any business strategy should be robust enough to withstand taxes similar to those applied to the export and import of tangible goods.

d) As companies transition products away from traditional factories to AM/3DP supply chains, there may be a necessity for current factory closures. In some cases, this may attract exit taxes if it is deemed that intellectual property (IP) is being taken out of the country. However, it could be argued that new AM/3DP product have fresh IP which may have resulted outside the country of the traditional factory. Although tenuous, the transition to an AM/3DP product could be sufficient argument to re-shore manufacturing while circumventing exit tariffs.

e) AM/3DP could shift the tangible and intangible value of products on a company's balance sheet.

   ***NOTE** For example, less importance may be placed in the manufacturing (visible), and more may be placed on design and IP (intangible). This would impact a company's balance sheet as the digital design data and IP could have a significant book value that is currently under-represented.*

7.3 Risk implication of AM/3DP on accounting practices

There can be a number of negative accounting implications to the adoption of AM/3DP:

a) If a company is looking to use AM/3DP to move up the value chain, such as engaging directly with customers, it is essential to consider the implications of local taxes. How can Value Added Tax (VAT) or Goods and Services Tax (GST) impact on the product price? How can this impact on the pricing strategy of the product to the end consumer and how can tax be offset across the supply chain?

b) Transfer pricing within a company may need to change as goods are no longer moving between factories, currencies or territories. Could this impact on Foreign Exchange (Forex) revenues or offsetting arrangements?

c) Could a dedicated 3D printer in the supply chain constitute a permanent establishment which may attract local taxes?

***NOTE 1** For example, if a supplier has their machine in a customer's factory making spare parts this could be deemed to be a "permanent establishment" of that supplier, in which case local taxes may be due.*

***NOTE 2** Annex D, Table D4 may be a useful aid in capturing and evaluating the commercial risk of implementing AM/3DP.*

8 Identifying the human resources and skills needed to implement AM/3DP

8.1 People and skills issues

Having defined which quadrant or quadrants of Figure 2 represent the most significant impact from AM/3DP on the business, consideration should be given to what information is required to build a business case, and more importantly where and who that information comes from.

For example, if a business case was being made to use AM/3DP for shop floor jigs or fixtures to improve productivity, only limited information would be needed on AM/3DP technology costs and capability and the productivity gains required to support a return on investment (ROI). This information is readily available from a small group of manufacturing and production engineers, backed by finance, procurement and quality.

However, if AM/3DP was to be used to add value to a new and innovative product or custom facing service, a much broader group of roles may be needed to support the evaluation. In this case, the team may need to include sales and marketing who can establish the new value proposition and revenue model, along with teams from engineering, manufacturing and quality which can ensure both product certification and process validation.

Figure 12 details the different business functions that may be impacted by the adoption of AM/3DP. These business functions should be considered and consulted when developing any AM/3DP evaluation or business strategy.

Figure 12 – Primary roles affected by AM/3DP relative to value chain applications

	Engaging with customers and products	Engaging with the supply chain and the organization
Externally (retail or supply chain)	**Improved customer service and engagement** Marketing Sales Product engineering Manufacturing Procurement (raw materials) Procurement (Capex) HR Business Systems Finance Quality Legal	**Streamlined and lean supply chains** Manufacturing Procurement (parts) Logistics Finance Quality
Internally within the organization	**New advanced and efficient products** Marketing & Sales Product engineering Manufacturing Procurement (raw materials) Procurement (Capex) Facilities Quality Legal Maintenance H&S	**More efficient (lean) production methods** Manufacturing Procurement (raw materials) Procurement (Capex) Facilities Quality Maintenance H&S

8.2 The impact of AM/3DP on organizational roles

Figure 13 details the different organizations' roles that may be impacted by the adoption of AM/3DP as well the input and considerations that these business functions should provide to the planning process.

Figure 13 – The impact of AM/3DP on organization roles and business case considerations

Role	The potential benefits, costs and risks of AM/3DP adoption	Considerations in the business case
Marketing	AM/3DP could enable new classes of products with new functions and value propositions. AM/3DP could open up new geographic markets or customer verticals.	Do marketing believe the benefit of AM/3DP enabled products outweigh the risk of adopting the technology? Can they secure market share with new products or territories?
Sales	AM/3DP may significantly increase the number of product variants the company offers. AM/3DP may also increase the sale price along with the value proposition. AM/3DP may also enable a direct sales channel to the customer.	Do the current sales channel or sales processes allow for AM/3DP products which could be higher value or sold in lower volumes? Sales may also shift from B2B to B2C. Can the organization accommodate such a shift?
Product engineering	To gain the maximum business benefit from AM/3DP, new DFAM approaches can be used. This can ensure that the parts produced are optimized with the highest down-stream value.	Does the organization have the internal skills and capacity to embrace DFAM? This may require investment in new design, analysis and simulation software and the associated skills to use that software.
Manufacturing	Although AM/3DP technologies are CNC machines, they have several differences to more traditional CNC machines such as lathes and mills, where is something of a "black art" to becoming an expert operator. AM/3DP parts may also require post-processing using traditional CNC machines.	Does the company have the available skilled machine operators to dedicate to training and on-site skills and know-how development? Does the manufacturing environment contain all the associated technologies needed to go from 3D CAD data to the final required part?
Procurement (raw materials)	Although some large metallic and polymeric materials suppliers have started to offer AM/3DP material feedstock, some materials are only available from smaller specialist supplier or directly from the AM/3DP machine vendors. This may mean there is less choice of supplier than for more traditional materials, and there may be a higher risk of supply shortages.	Purchasing departments may have to relax their position on single-source supply or the use of smaller, less well-established supplier for critical materials sourcing.
Procurement (Capex)	Industrial AM/3DP hardware suppliers are highly specialized companies with many being based outside the United Kingdom. Some of these companies are also early-stage growth business with less than 5-years of trading history and a balance sheet often supported by third party investment capital. As such, they may appear a high-risk supplier given the potentially high cost of AM/3DP hardware.	Purchasing departments may have to relax the ratio's used to assess risk when buying high-cost capital equipment from relatively small new companies. They may have to accept being the 1st customer or even an early stage beta customer.

Figure 13 – The impact of AM/3DP on organization roles and business case considerations *(continued)*

Role	Potential impact of AM/3DP adoption	Considerations in the business case
Procurement (parts)	In some cases, companies may opt to purchase AM/3DP parts rather than invest in the technology and manufacture in-house. When procuring parts, it is vital to understand the different types of AM/3DP technology class, as described in Annex B, but also the nuances of the various technologies in each class, along with the capabilities of different machine vendor solutions.	How can a purchasing professional develop a high-level understanding of different AM/3DP process capabilities and constraints to identify which part suppliers are appropriate? How can they gain an understanding of AM/3DP production cost to understand and develop fair pricing policies and cost-down strategies with suppliers?
Logistics	In some cases, AM/3DP is being used to shift from mass production to mass customization or mass personalization, shifting a company's business model from business-to-business (B2B) to business-to-consumer (B2C). This can have a significant impact on "goods-out" and logistics as there may be a substantial increase in the number of individual shipments to domestic customers.	Do the company's current "goods-out" processes and infrastructure allow for a transition to B2C sales? Can existing internal or third party logistics providers accommodate this transition, or could new supplier or investment be needed?
HR	AM/3DP adoption can bring the need for new technical and commercial skills and knowledge within the organization. Except for technical staff operating RP machines within product development, it is highly unlikely these skills may already reside within the organization. Within a retail or healthcare environment, the AM/3DP machine operator may not come from a manufacturing background.	Can the company recruit AM/3DP skills locally, or will these need to be developed internally? Are there local sources of knowledge, expertise or future personnel that could be engaged, such as universities or RTOs? What trade groups or networks could be accessed to accelerate understanding? How can non-manufacturing staff be involved in AM/3DP and could this have any impact of employee relations/unions?
Business systems	Where AM/3DP is being used for personalized or customized parts, it is vital to consider the volume of data that the organization may need to transfer, process, translate and store. This data can also be managed either internally within the AM/3DP shop floor or securely with third party part suppliers.	Does the company have the IT infrastructure to support the transition to AM/3DP? Do existing product lifecycle management (PLM) systems support AM/3DP or will third party software solutions be needed to manage machine utilization? Do the organization's supplier agreements provide sufficient data protection or could Digital Rights Management (DRM) solutions be needed?

Figure 13 – The impact of AM/3DP on organization roles and business case considerations *(continued)*

Role	Potential impact of AM/3DP adoption	Considerations in the business case
Finance	AM/3DP technology and its associated infrastructure can be costly when compared to more traditional machine tools. It is critical that a robust business case and ROI model be built, which may rely heavily on forecast utilization rates, ongoing cost of ownership, depreciation and labour.	Have all costs of ownership been considered and how could they change in the future? Is the depreciation period and residual value for the capital asset realistic?
Facilities	AM/3DP machines require several inputs along with raw material. They may need shielding gases or compressed air, stable, uninterrupted single or three-phase power supply and fixed network connectivity. They may also need an air-conditioned, humidity-controlled and clean environment in which to operate or be located in a secure non-accessible interlocked facility compliant with laser or electron beam safety requirements.	Does the company's current facility accommodate the types of AM/3DP machines needed? Has the cost of facility changes been included in the business case along with ancillary hardware such as uninterruptible power supplies, back-up generators, compressors or shielding gas generators?
Quality	There are a growing number of AM/3DP specific standards and quality methodologies emerging from organizations such as BSI, ISO, Lloyds Register (LR) and Underwriters Laboratories (UL). These address issues such as standard material testing methods and compliance procedures. In some cases, large OEM customers in aerospace or defence may have developed internal working standards for AM/3DP part supply.	Are the company's quality and compliance functions aware of applicable published standards on AM/3DP or any customer-specific standards to be addressed? Does the quality function understand the potential variance of AM/3DP technologies and the impact on Statistical Process Control (SPC) methods? Has the cost of quality been included in the operating expenditure (OPEX) and capital expenditure (CAPEX) model including the procurement of any specialist materials testing or metrology equipment?
Health and Safety (H&S)	Some AM/3DP machines use high powered laser and electron-beam energy, which present serious exposure risks to skin, eyes and organs. Machines also use moving platforms, gantries and robots which present potential crush injuries. Metallic and polymeric powered feedstock can present significant explosion risks, particularly volatile metals powders and the gases resulting from oxidation. Shielding gases present a risk of asphyxiation with exhaust gases introducing small air-born particulates.	Has a full risk assessment been undertaken from "material-in" to finished goods-out? Has the cost of safety been factored into the business model?

Figure 13 – The impact of AM/3DP on organization roles and business case considerations *(continued)*

Role	Potential impact of AM/3DP adoption	Considerations in the business case
Legal	There are several legal implications associated with the AM/3DP value chain. The company should consider the requirements of any certification bodies and ensure it is legally compliant. Product liability should also be considered given the interrelationship between AM/3DP process, material and design data and the resulting part. Data protection and data compliance should also be considered, where data is being shared with third parties in the supply chain or where personal or healthcare data is being captured from consumers or patients. IP protection or infringement should also be considered for new and innovative AM/3DP enabled products and services.	Have the potential points of failure been identified and a risk mitigation strategy put in place? Can liability of failure be established? Has all IP, including patents, design rights, trademarks and copyright, been secured and has the Freedom to Operate (FTO) been established? Are third party supply contracts robust and can data be shared freely, or should DRM be introduced? Has provision been put in place to ensure compliance with GDPR and are the needs of applicable regulatory bodies being addressed?
Maintenance	AM/3DP machines are typically maintained directly by the hardware vendor or by the local reseller or channel partner. For some technologies and territories, third party service providers are also available. Planned and preventative maintenance is usually packaged into the on-going warranty cost of the AM/3DP hardware along with software upgrades and differing levels of spare parts provision. Different service level agreements (SLA) are also available, covering the speed of response and the cost of parts and labour needed to repair defective hardware.	Is the SLA sufficient to support the needs of the organization and the potential risk of revenue loss from machine downtime? Has the cost of warranty and the SLA been included in the OPEX model? Are 3rd party service providers available to support the technology? Can the technology be procured from a local supplier that also provides service?

NOTE *Annex D, Table D5 can be used to support the high-level evaluation of human resources and the impact of AM/3DP on organization roles.*

8.3 Labour and skills requirements for an AM/3DP operation

8.3.1 Ensure the correct skills mix

When establishing an AM/3DP facility, along with Capex, there is also an investment needed in people and skills. In some cases, existing staff can quickly learn these skills through specialist training courses.

***NOTE** Examples include those available at the MTC [5].*

In other cases, skills and know-how may need to be brought into the company through external recruitment. Several specialist recruitment agencies operate within the AM/3DP ecosystem.

8.3.2 Product design skills and knowledge

There are a range of skills and knowledge needed during the product design stage:

a) *(Designer)* Basic level 3D CAD skills suited to the design of products traditionally made using processes such as injection moulding or CNC machine are sufficient to enable AM/3DP. However, design engineers should understand the DFAM constraints of different AM/3DP processes.

b) *(Designer)* Design engineers should understand the material properties and capabilities of AM/3DP materials and the impact that AM/3DP processes can have on the properties of part manufactured.

c) *(Designer)* When generative design or topological optimization tools are used, it may be necessary for engineers to have higher-level skills. These skills include Finite Element Analysis (FEA) or mechanical engineering and stress analysis knowledge.

8.3.3 Materials skills

There are a range of skills and knowledge needed during the handling of materials:

a) *(Basic operator)* Manual handling and health and safety knowledge of raw materials is critical to ensure a safe operating environment, part quality and optimum material reuse.

b) *(Purchasing)* When selecting and purchasing raw materials, it is vital to understand the limitations of different supply models.

   ***NOTE** For some applications, it may prove advantageous to use an open-source format of raw material that can be supplied by multiple vendors. For other applications, to maintain certification, a single source, closed format material supply chain may be better suited.*

c) *(Advanced operator)* It may be necessary to have staff with a material science background if new feedstock is being used, as, with new materials, there may be a requirement to analyze and characterize the input material feedstock.

8.3.4 Skills needed to produce AM/3DP machine data

There are a range of skills and knowledge needed to prepare AM/3DP build file data:

a) *(Basic operator)* Most industrial AM/3DP machines are sold with operator training included or as an additional line item. This training includes both the operation of the machine and the preparation of the enabling data.

b) *(Basic operator)* Basic level operator know-how may be sufficient to generate build files for a new geometry on a machine where there is no change in material between builds.

c) *(Basic operator)* When producing build files, operators may need to understand the impact of factors such as layer thickness, part orientation, support structure position and support structure design. They may need to understand the implications of process parameters and the effect these can have on final part quality.

d) *(Advanced operator)* Higher-level skills such as material science, metallurgy and Statistical Process Control (SPC) maybe needed to characterize new materials for an existing AM/3DP process, where no parameters for that material exist.

e) *(All operators)* Tacit knowledge and experience may be needed when optimizing the position of parts within the build chamber to maximize throughput while maintaining part quality.

8.3.5 Hardware operating skills requirements

There are a range of skills and knowledge needed during the operation of AM/3DP machines:

a) *(Basic operator)* AM/3DP machines are a form of CNC machine. They require skilled operators to prepare the machine for production, to instigate builds and to unload the machines. Initial operator skills are gained through training provided by the machine vendor. This training may have an initial and on-going cost.

b) *(Advanced operator)* Personnel with high-level skills may be needed when processing new material or manufacturing a sophisticated geometry for the first time. Higher-level skills develop over time through technology exposure or external recruitment.

[5] https://the-amtc.co.uk/training/engineer-training/additive-manufacturing/

c) *(Basic operator)* When parts are printed for the first time, it may be necessary to employ lower skills machine minders to monitor the part build.

8.3.6 Materials knowledge

There are a range of skills and knowledge needed when characterizing new materials for AM/3DP:

a) *(Advanced operator)* Expert level skills are needed when characterizing a wholly new material for a process, or when pushing the capabilities of the technology. Expert level skills are gained through post-graduate level university degrees or specialist short courses provided by systems vendors, Universities or RTOs.

b) *(Basic operator)* Manual handling and H&S knowledge is required to ensure the safe handling and use of materials such as volatile powders or irritants such as resins.

8.3.7 Post-processing skills

There are some skills and knowledge needed during the post-processing of AM/3DP parts:

a) *(Wider shop floor)* Post-processes such as EDM, heat treatment and CNC machine require specific skillsets. These may be very different from the skills needed to operate an AM/3DP machine.

8.3.8 Waste handling skills

There are some skills and knowledge needed during the handling and disposal of waste materials:

a) *(Basic operator)* Manual handling of waste materials which may be volatile along with the safe, legal and environmental disposal of waste material in-line with the companies environmental and health and safety policies.

Annex A (informative)
Definition of additive manufacturing and 3D printing

The term Additive Manufacturing (AM) is an evolution of the now-defunct name Rapid Manufacturing (RM). It is used to describe the manufacture of production, end-use or series parts made using technologies based on the principles of Additive Layered Manufacturing (ALM).

Historically, ALM was used for the production of prototype parts made during the development phase of a new product. This application was called Rapid Prototyping (RP). As the technology matured, other applications for ALM parts were established including Rapid Tooling (RT) which referred to the use of ALM technologies for the production of tool cavities, and Rapid Casting (RC) which referred to the use of ALM technologies for the production of investment casting patterns or sand-casting cores. Some time at the end of the nineteen nineties, a number of production, end-use and series applications of ALM parts were identified. These applications were initially referred to as Rapid Manufacturing or RM. This term was later amended to additive manufacturing or AM. The term ALM is no longer commonly used.

3D Printer (3DP) was originally a product name used to describe the powder bed binder jetting process manufactured and sold by US corporation Z-Corp. The technology is described in US patent 5387380A. However, with the advent of open-source and low-cost consumer systems between 2005 and 2010, the term 3D printing was widely adopted and is now used in a broader context to describe any ALM technology.

In summary, AM describes the application of ALM technology for end-use part production. 3DP relates to both the ALM technology and the use of technology.

The acronym AM/3DP, therefore, relates to both ALM technology and the broader application of the technology for the production of end-use parts, products, systems and services.

Annex B (informative)
ASTM terminology for AM/3DP

As defined by the International organization for Standards (ISO) and the American Society for the Testing of Materials (ASTM) in ISO/ASTM 52900:2015 (ASTM F2792), there are seven types of ALM process. They are described in Table B.1.

Table B.1 – ISO/ASTM classification of AM/3DP technologies and the description of each process

ISO/ASTM classification	Description of process	Materials used in the process	Technologies in this classification (see Annex F for an explanation of each acronym)	Notes
Vat Photopolymerization	An open vat of photocurable liquid resin is exposed to a moving energy source causing localized photopolymerization of the liquid resin into a solid thermoset layer of material, while also bonding to the material below	Thermosetting resin	SL, DLP, CDLP, CLIP	Thermosetting plastic resin can have ceramic content for increased strength and performance
Powder Bed Fusion	An open chamber of powdered material is exposed to a moving heat source causing localized melting and solidification of the powder into a consolidated layer while also bonding to the material below	Thermoplastics Ferrous metals Non-ferrous metals Nobel metals	DMLS, SLM, EBM, MJF, HSS, SLS, LS, STEP	Energy sources can include laser beams, electron beams and infrared heat lamps
Binder Jetting	An open chamber of powdered material is positioned under a moving print head which selectively deposits a chemical agent onto the surface of the powder below causing localized bonding of the material into a layer while also bonding to the material below	Ceramics Thermoplastics Ferrous metals Non-ferrous metals	BJ, DM	In some cases, the chemical agent is a binder which binds the powder together following evaporation. In other cases, the agent is a solvent causing localized chemical melting

Table B.1 – ISO/ASTM classification of AM/3DP technologies and the description of each process *(continued)*

ISO/ASTM classification	Description of process	Materials used in the process	Technologies in this classification (see Annex F for an explanation of each acronym)	Notes
Material Jetting	A moving print head is positioned above a moving platform on to which a liquid material is selectively jetted from the print head. The phase of the liquid material is then changed to a solid while also bonding to the material below.	Thermosetting resin Ceramic loaded resin Metallic loaded resin Wax	MJ, NPJ, DOD	In many cases, the liquid has a solid component in suspension. The phase change from liquid to solid is through either forced evaporation or exposure to an external stimulus such as ultraviolet (UV) light
Sheet Lamination	A preformed layer of material is positioned above a moving platform. An energy source or physical tool is then used to cut the contour of a layer before a separate energy source, or chemical binder is used to bond the cut layer to the material below	Paper Ferrous metals Non-ferrous metals Carbon Fiber	LOM, UC, CBAM	In some cases, heat energy or a binder is used to bond layers together. In other cases, it is a combination of pressure and Ultrasonic agitation
Material Extrusion	A moving extrusion nozzle is positioned above a moving platform. Molten Thermoplastic is then selectively extruded from the nozzle before solidification takes place. solidification of the molten polymer results in a consolidated layer of material while also bonding to the material below	Thermoplastic Loaded Thermoplastics Composites	FDM, FFM, FFF, BAAM	Using this configuration, it is possible to produce plastic parts with embedded composite filaments
Directed Energy Deposition	A moving energy source is positioned over a moving platform. Material in either powder or wire form is then fed into the energy source where it changes to a liquid phase before being selectively deposited onto a moving substrate before rapid solidification. By changing the position of the energy source and substrate, layers of material can be deposited onto previous layers or the surface of an existing component	Ferrous metals Non-ferrous metals	DED, LENS, EBAM, WAAM	The energy source can be a laser beam, electron beam or electrical arc. The feedstock can be wire, powder or bar stock. This technology can be retro-fitted onto existing CNC machines

Annex C (informative) Business model canvas

The business canvas (see Table C.1) can be used to capture the information needed to develop a high-level business case for the adoption of AM/3DP. The canvas can be used to capture ideas for either new products or services aimed at top-line revenue growth or uses of AM/3DP focused on increased productivity, lean manufacturing and profitability improvement.

Table C.1 – Canvas to capture critical information needed for a high level AM/3DP business case

<table>
<tr>
<td rowspan="2">Key partners
Identify which organizations may be able to provide the resources needed to execute the plan. This could include providing access to hardware, raw materials, parts, skills, staff, a sales channels, process validation and part certification.</td>
<td>Key activities
Identify what primary activities need to be undertaken within the organizations. This could include establishing a facility, establishing a supply chain, validate AM/3DP processes or parts, building a sales channel, building a team or developing a skills base.</td>
<td rowspan="2">Value proposition
Clearly define what will be done with AM/3DP, what problem will be solved or what new value AM/3DP will create. Define why AM/3DP is the solution and how this will impact on either or both internal and external customers. Establish the benefit of using AM/3DP will be articulated to customer, stakeholders and staff.</td>
<td>Customer relationships
Establish how customer engagement will be established and conducted. Identify who will own the customer relationship, whether this is the direct sales function or product resellers. If AM/3DP is being used to support internal customers, establish how they will engage in the design and manufacturing process.</td>
<td rowspan="2">Customer segmentation
Establish who the customer is and the scope and scale of the customer base. Establish if the customer is internal or external, mass market of niche. Establish the geographic location of the customer base and how best this can be supported through either internal investment in AM/3DP capability or the development of a robust supply chain.</td>
</tr>
<tr>
<td>Key resources
Identify what key resources would be needed to execute the business plan. This could hardware, software, people, facilities, quality systems or working capital.</td>
<td>Channels
Establish how customers will be reached, whether this will be through a physical presence such as a retail environment or on the shop floor, through an online virtual presence or through a third party, such as a channel partner or reseller.</td>
</tr>
<tr>
<td colspan="2">Cost structure
Based on projected machine utilization, working capital and human resources, establish whether investment is needed in hardware and software to realize the value proposition or whether this can be done using a supply chain partner. If internal capacity needs to be developed, consider a different operating model, such as hardware purchasing, leasing hire or lease purchase. Also consider the cost associated with either developing or recruiting a skilled workforce.</td>
<td colspan="3">Revenue streams
From the value proposition, establish what the market will pay for AM/3DP products or services.
Consider how any revenues might need to be split across the value chain if partners are involved. Also consider if there are other ways to profit from the supply of AM/3DP parts, such as sharing in customers cost saving from optimized AM/3DP products. When AM/3DP is used to support lean manufacturing, consider the cost saving.</td>
</tr>
</table>

Annex D (informative)
Self-assessment review questions

Self-assessment review questions to assist with the information collation needed to ensure a fully inclusive AM/3DP business case

Annex D provides a series of tables which can be used to review the content and considerations within AM/3DP business cases. The tables provide a list of self-assessment questions, which can be used to ensure that the critical elements of an AM/3DP business plan have been considered and addressed.

Using Table D.1, the drivers for AM/3DP adoption can be considered along with the relevance and impact on the organization. This can then be used to assist prioritization.

Table D.1 – Business drivers for AM/3DP adoption

	Not applicable or no impact	Low impact	Noticeable impact	Extensive impact
The ability to cost-effectively manufacture low-volume or small batch production				
The ability to produce customized or personalized products for consumers or patients				
The ability to increase the functionality of products adding value to the end-user or customer				
The ability to rationalize and reduce the size and complexity of the supply chain				
The ability to improve the life-cycle sustainability of products and services				
The ability to reduce or eliminate stock				
The ability to introduce a more flexible production environment to allow for more responsive manufacture				
The ability to better support aftermarket repairs and the reuse of existing products through spare part provision				
The ability to reduce raw material consumption and associated waste streams				
The ability to eliminate end-of-like stock write-offs				
The ability to improve shop floor efficiency through the introduction of personalized or job specific jigs, fixtures and tooling				
The ability to improve the green credential and sustainability of the organization through more efficient production processes				

Table D.1 – Business drivers for AM/3DP adoption *(continued)*

	Not applicable or no impact	Low impact	Noticeable impact	Extensive impact
The ability to improve the lives of staff and customers through better ergonomics				
The ability to extend the life of products by supporting the circular economy				

Table D.2 provides a checklist outlining the key cost considerations in development of an AM/3DP business plan.

Table D.2 – Capital investment, operational costs and skills implications of in-house AM/3DP implementation

What factors have to be considered when implementing in-house AM/3DP	Not relevant	Not yet considered	Considered and inconclusive	Considered and accepted
Have the product design costs of using AM/3DP been considered?				
Has the cost of preparing AM/3DP data been considered?				
Have the hardware and facilities costs associated with AM/3DP been considered?				
Have alternative business models to secure AM/3DP capacity been considered?				
Have the costs of raw materials and associated handling been considered?				
Has the cost of part post-processing been considered?				
Has the cost of waste, recycling, disposal and reprocessing been considered?				
Has the cost of part validation and certification been considered?				
Have the skills needed to design AM/3DP products been considered?				
Have the skills needed to handle AM/3DP materials been considered?				
Have the skills needed to prepare AM/3DP machine data been considered?				
Have the skills needed to operate AM/3DP hardware been considered?				
Have the skills needed to post-process AM/3DP parts been considered?				
Have the skills needed to inspect AM/3DP parts been considered?				

Table D.3 provides a checklist outlining the key implications of using an outsourced AM/3DP supply chain.

Table D.3 – The implications of outsourcing AM/3DP production

What factors need to be considered when outsourcing AM/3DP	Not relevant	Not yet considered	Considered and inconclusive	Considered and accepted
Have all the outsourcing risks and benefits been considered?				
Has a justifiable reason been identified to not invest in AM/3DP hardware?				
Have the wider benefits associated with outsourcing AM/3DP been considered?				
Have the risks associated with outsourcing been considered?				
Has the process for mitigating any risks associated with outsourcing been considered?				
Has the contractual position of using external part designers been considered?				
Has the maintenance of critical build parameter knowledge been considered?				
Has the ownership of build files and their transfer to others been considered?				

Table D.4 provides a checklist outlining the key commercial risks of implementing AM/3DP within the organization.

Table D.4 – The implications of AM/3DP on commercial risk and the sales channel

Who will be affected by the implementation of AM/3DP within the organization	Not relevant	Not yet considered	Considered and inconclusive	Considered and accepted
Has the impact of AM/3DP on customer engagement been considered?				
Have the customer journey and the touchpoints been mapped out?				
Has a clear strategy to communicate the benefits of AM/3DP been developed?				
Have the possible commercial risks of AM/3DP adoption been identified?				
Have ways to mitigate risk been identified?				
Are there any positive implications of AM/3DP on accounting practices?				
Are there any adverse consequences of AM/3DP on accounting practices?				

Table D.5 provides a checklist of the different roles and responsibilities within a company that could be impacted by AM/3DP adoption. In some cases, these roles might not be relevant to the applications in mind (see Figure 2).

Table D.5 – The implications of AM/3DP adoption on human resources

Who will be affected by the implementation of AM/3DP within the organization	Not relevant	Not yet considered	Considered and inconclusive	Considered and accepted
Have all the people impacted, change management and skills issues associated with AM/3DP adoption been considered?				
Has the impact of AM/3DP on technical teams in design, engineering and manufacturing been considered?				
Has the impact of AM/3DP on commercial teams in sales, marketing, procurement and HR been considered?				
Have the skills needed to maximize the design and manufacturing benefits of AM/3DP been considered?				
Do external sources of skills development need to be identified, such as vendors, universities or RTOs?				
Do specialist skills need to be recruited into the organization from outside? If so, have suitable recruitment specialists been identified?				

Annex E (informative) Initialisms and acronyms

E.1 Initialisms

3-dimensional (3D)
3D printer (3DP) - noun
3D printing (3DP) - verb
additive layer manufacturing (ALM)
additive manufacturing (AM)
American Society for the Testing of Materials (ASTM)
Annual Investment Allowance (AIA)
big area additive manufacturing (BAAM)
binder jetting (BJ)
Civil Aerospace Authority (CAA)
composite based additive manufacturing (CBAM)
computer-aided design (CAD)
computer numerical control (CNC)
computer tomography (CT)
continuous digital light projection (CDLP)
continuous liquid interface production (CLIP)
design for additive manufacturing (DFAM)
digital light projection (DLP)
digital metal (DM)
digital rights management (DRM)
directed energy deposition (DED)
direct metal laser sintering (DMLS)
drop on demand (DOD)
electrical discharge machining (EDM)
electron beam additive manufacturing (EBAM)
electron beam melting (EBM)
finite elements analysis (FEA)
freedom to operate (FTO)
fused deposition modelling (FDM)
fused filament fabrication (FFF)
fused filament modelling (FFM)
General Data Protection Regulation (GDPR)
Goods and Services Tax (GST)
health and safety (H&S)
high-speed sintering (HSS)
Intellectual Property (IP)
laminated object manufacture (LOM)
laser engineered net shaping (LENS)
laser sintering (LS)
Lloyds Register (LR)
magnetic resonance imaging (MRI)
management information system (MIS)
manufacturing technology centre (MTC)
material jetting (MJ)
Medical and Healthcare Regulatory Authority (MHRA)
multi jet fusion (MJF)
nanoparticle jetting (NPJ)
non-destructive testing (NDT)
product lifecycle management (PLM)
rapid casting (RC)
rapid manufacturing (RM) (now defunct)
rapid prototyping (RP)
rapid tooling (RT)
research and development (R&D)
Research and Technology Organization (RTO)
return on investment (ROI)
selective laser melting (SLM)
selective laser sintering (SLS)
selective thermoplastic electrophotographic processing (STEP)
service level agreements (SLA)
statistical process control (SPC)
ultrasonic consolidation (UC)
ultraviolet (UV)
Underwriters Laboratories (UL)
Value Added Tax (VAT)
wire arc additive manufacturing (WAAM)
X-ray computer tomography (XCT)

E.2 Acronyms

business to business (B2B)
business to consumer (B2C)
capital expenditure (CAPEX)
foreign exchange (Forex)
hot isostatic pressing (HiPping)
International Organization for Standards (ISO)
operating expenditure (OPEX)
stereolithography (SL)

Annex F (informative) Quantifying the value of AM/3DP in terms of revenue and profitability

Table F.1 describes a number of ways that AM/3DP can be used to drive top-line revenue growth through the introduction of new and innovative products.

Table F.1 – Ways of driving top-line revenue growth through new and innovative products

New advanced and efficient products	
What does AM/3DP enable?	**How does this drive revenue?**
Production of low-volume batches	Capture new markets by providing products and services to ever-smaller customer demographic groups
Products with new styles and aesthetics	Capture and retention of further market share by ensuring products remain on-trend to all with no cost penalty
Products with optimized design such as weight or flow	Increased market share and revenue by providing products that financially benefit the customer during use
Consolidation of assemblies into single parts	Increased market share and revenue by providing products that cost less to maintain during service life
Products with "designed" material properties [6)]	Enables new classes of products to be brought to market currently unattainable using traditional manufacturing
Products with "designed" material density [7)]	Enables new classes of products to be brought to market with minimal if no cost implications over current products
Products with "embedded" functionality [8)]	Enables products to be brought to market with cost savings over current multi-part assembled products
Products made from new high-performance materials	Increased market share and revenue by providing products made from materials only available via AM/3DP

[6)] The voxel-based nature of AM/3DP enables the manufacture of parts with anisotropic properties such as variable hardness, variable elongation, variable compression, impact and shock resistivity or controlled optical clarity.
[7)] The voxel-based nature of AM/3DP enables the manufacture of parts with different levels of material porosity or density, which can then be used to control fluid or gas flow or control the rate of dissolution or absorption of a product.
[8)] Some AM/3DP processes allow for the concurrent or consecutive consolidation of multiple materials. If these materials are dissimilar, they can be used to embed functionality into a product such as electrical or thermal conductivity, electro-magnetic functionality, hydrophilic or hydrophobic surface effects or variable colour.

Table F.2 describes a number of ways that AM/3DP can be used to drive top-line revenue growth through external customer engagement.

Table F.2 – Ways of driving top-line revenue growth through customer engagement

Improved customer service and engagement	
What does AM/3DP enable?	**How does this drive revenue?**
Product customization	Drives customer spending by providing an increased level of aesthetic choices and options to the product mix
Product personalization	Enables higher value individualized products to be sold with improved ergonomics and function
Product co-design	Allows customers to be an integral part of the product design process providing "stickiness" and spend loyalty
Point of sale experiences	Enables in-store "retail-theatre" or experience leading to impulse purchasing and cross-selling opportunity
Product servitization	Enables new responsive business models that shift revenue away from single transaction to ongoing spend
Spare parts on demand	Captures revenue from third party spare part suppliers, while maintaining customer loyalty
Repair on demand	Captures short term "repair" revenue but ensures longer-term customer loyalty and continued service revenue

Table F.3 describes a number of ways that AM/3DP can be used to drive bottom-line profitability through a streamlined and lean supply chain.

Table F.3 – Ways of driving bottom-line profitability through a streamlined and lean supply chain

Streamlined and lean supply chains	
What does AM/3DP enable?	**How does this drive profitability?**
Reduced part count through assembly consolidation	Less chance of supply chain failure, missing parts or delays
Reduced supplier base through reduced part count	Lower transactional costs such as invoicing, supplier accreditation, quality compliance or bad debt
Reducing or eliminating the need for tooling within suppliers	Enables suppliers to pass on cost saving to customers and for customers to use multiple supplier as no tooling is necessary
Reduced supplier stockholding	Lower part cost due to the reduction of supplier waste streams such as warehousing and end-of-life write-offs
Manufacturing process consolidation	Results in less manufacturing operations necessitating lower demand for distribution and logistics infrastructure
Optimized manufacturing location	Enables concurrent manufacture at multiple locations close to the point of demand, reducing distribution costs

Table F.3 – Ways of driving bottom-line profitability through a streamlined and lean supply chain

Streamlined and lean supply chains	
What does AM/3DP enable?	**How does this drive profitability?**
Localized manufacture in territory of use	Reduces or eliminates export and import tariffs by replacing tangible products crossing borders with data

Table F.4 describes a number of ways that AM/3DP can be used to improve the environmental performance of a company and its products.

Table F.4 – The environmental benefits of AM/3DP adoption

Where in the product life cycle is the environmental benefit of AM/3DP achieved?	How is the environmental benefit achieved?
Resource consumption	Less raw material required to enable part production
	Less post-process waste to be recycled and repurposed
	Less hydrocarbon cutting fluids and lubricants used by removing machining operations
	Less water consumption and wastewater disposal by reducing cutting fluid usage
Transportation	Lower supply chain miles and associated embedded carbon by mitigating manufacturing steps
Product usage	Geometrically optimized product can result in optimized systems. Optimized systems can have a lower energy consumption when used in industries such as petrochemical manufacture
	Geometrically optimized and lighter-weight components can reduce the fuel consumption of vehicles into which they are assembled, such as aircraft
Recycling	The potential to process reclaimed and recycled thermoplastics along with a growing list of sustainable green polymers
	Most single material metal and thermoplastic components are readily recyclable alongside traditional materials
Repair and reuse	The ability to extend the life of damaged and failed products through spare part production, reducing end-of-life product waste
	The ability to repair products using deposition technologies, reducing end-of-life product waste

Table F.5 describes a number of social benefits resulting from the adoption of AM/3DP by companies.

Table F.5 – Social benefits of AM/3DP

What types of social benefits are achieved by the adoption of AM/3DP?	How is the societal benefit of using AM/3DP achieved?
Ergonomic benefits	Better fitting and more comfortable healthcare and consumer products manufactured using body scan data
	More ergonomic shop floor assembly aids leading to less repetitive strain injuries and improved operator performance
Improved healthcare	Patient-specific anatomy models to support healthcare and surgery, resulting in shorter surgical procedures and faster recovery times
Historical conservation	Maintaining and faithfully replicating historical artefacts and legacy information for the benefit of society and education
Supporting entrepreneurism	Democratizing manufacturing within the local community by making technology accessible to all
Reducing waste	The ability to remanufacture products supporting the circular economy

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Useful websites

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BSI, 389 Chiswick High Road
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