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Unpacking Additive Manufacturing Challenges and Opportunities in Moving towards Sustainability: An Exploratory Study

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Abstract: The global market for Additive Manufacturing (AM) is expected to grow, which may increase the prominence of sustainability aspects in the manufacturing process. A growing number of AM academics and practitioners have started to pay attention to the environmental and societal impacts of AM instead of only focusing on its economic aspect. Yet, AM is still not widely adopted, and the research on AM sustainability is still at the nascent stage. This paper aims to better understand AM's sustainable adoption and seeks to address three questions: what the sustainability implications of AM are; what challenges may prevent the broad adoption of AM; and what opportunities can enable AM sustainability. The research adopts a multiple case study method to investigate six AM companies that play different roles in the AM ecosystem, including AM design, AM machine, AM material, AM service, AM education, and AM consulting. The results from these studies reveal that AM has the potential to reduce environmental and social impacts; however, it might also cause negative consequences and lead to some rebound effects. We identified 43 categories (synthesized from 199 examples) of key challenges for AM adoption and proposed 55 key solutions in moving AM towards sustainability. It is evident that AM acts as a promising digital technology for manufacturing and has the potential to pave the way for a new era of sustainable manufacturing.

Keywords: additive manufacturing; sustainability; challenges; opportunities; solutions; value; technology adoption

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Citation: Liu, W.; Liu, X.; Liu, Y.; Wang, J.; Evans, S.; Yang, M. Unpacking Additive Manufacturing Challenges and Opportunities in Moving towards Sustainability: An Exploratory Study. *Sustainability* **2023**, *15*, 3827. https://doi.org/10.3390/su15043827

Academic Editor: Radu Godina

Received: 6 January 2023
Revised: 10 February 2023
Accepted: 14 February 2023
Published: 20 February 2023

1. Introduction

Additive Manufacturing, also known as 3D Printing, has seen significant advances in technology; however, companies may not fully understand how to maximize its value and whether it is environmentally or socially beneficial. The sustainability performance of AM has been positively portrayed in the grey literature, which highlights its ability to reduce the use of raw materials and reduce transportation distances. However, limited research has been done to determine if AM always has a positive impact on environmental sustainability [1]. It remains unclear if AM is more energy-efficient or environmentally friendly than subtractive manufacturing processes [2]. The impact on resource use and materials toxicity is also unclear, despite the process being materially efficient. There is a potential for health hazards to be generated during the handling of printed and unprinted materials. Further research into the sustainability implications of AM is necessary before the market matures globally. Early studies have shown that AM may not be as sustainable as previously thought, as it consumes more energy than casting and injection molding [3]. The research into AM's social and environmental implications is still in its early stages and the results remain inconclusive, making it challenging to determine its impact compared to other digital technologies [1,2].

This paper employs a multiple case study approach to examine various AM companies within the AM ecosystem and investigate the resulting sustainability implications and key challenges for sustainable AM adoption. The study extends the existing literature by using a theoretical replication logic to select contrasting cases that serve as examples of AM technology application [1,4]. A coding process was applied to extract the sustainability implications, challenges, and adoption opportunities from the case studies. This process led to the identification of critical challenges in different AM sectors, some of which have not been previously addressed in the literature. These challenges hinder the widespread adoption of AM and must be addressed for more sustainable outcomes. The results of the study reveal that, while AM has the potential to reduce environmental and social impacts, it can also lead to negative consequences and rebound effects. This paper contributes to the literature on sustainability in AM technologies by focusing on the critical challenges and opportunities for widespread adoption and provides both theoretical and managerial implications for AM development.

The paper begins by providing an overview of AM technologies, their characteristics, and the principles of AM processes, as presented in Table 1. This is followed by an analysis of previous studies that highlights the strengths and limitations of AM, presented in Table 2. The paper then delves into the sustainability of AM, focusing primarily on the environmental and social aspects. To gain a deeper understanding of AM's sustainability, different AM cases are investigated and presented in Table 3 and the sustainability implications of AM are illustrated in Table 4. Based on these insights, the key challenges facing different AM sectors are identified in Table 5, and theoretical implications are provided. The paper presents potential solutions that can lead to more sustainable outcomes, summarized in Table 6. These findings serve as a starting point for further exploration of the challenges, sustainability solutions, and new applications of AM. The results provide insights into the barriers that must be overcome in order to enable the wider adoption of AM technologies in Table 7. The paper concludes with theoretical implications for AM development, providing a foundation for future research in this field. The results can help guide companies and policy makers in their decision-making process, leading to a more sustainable future for AM technologies. It is clear that AM is a powerful digital technology for manufacturing and has the potential to lead the way towards a more sustainable manufacturing era.

Table 1. Characteristics and principles of AM processes for each category, adapted from [5–13].

Categories	Processes	Printing Materials	Power Sources	Implementation Challenges/Downsides	Strengthes/Opportunities	Applications
Vat photopolymerization	Stereolithography; Digital light process (DLP); Masked stereolithography (MSLA)	Photopolymer resin; Ceramic suspension	Ultraviolet laser	Brittle quality, not suitable for mechanical parts; High costs for materials	Smooth surface finish; Fine feature details; High resolution and accurary; High printing speed	Injection mold-like prototypes; Casting patterns; Soft tooling; Investment casting; Jewelry and dental application; Hearing aids
Directed energy deposition	Laser engineered net shaping (LENS); Directed light fabrication (DLF); Direct metal deposition (DMD); Direct laser deposition (DLD)	Polymer; Ceramics; Metal powder (cobalt chrome, titanium)	Laser beam	Post processing required to achieve desired effect; Limited material use	High quality for repair work; Good balance between surface quality and speed	Prototypes; Repairing and maintaining parts; Tooling; Functional parts
Powder bed fusion	Selective laser sintering (SLS); Direct metal laser sintering (DMLS); Selective laser melting (SLM); Electron beam melting (EBM)	Thermoplastic powder (Nylon 6, Nylon 11, Nylon 12); Metal powder (aluminum, stainless steel, titanium Ti6Al-4V; cobalt chromium); Ceramic powder	Laser/electron beam	Longer lead times; Higher cost than other printing processes; Small build sizes	Functional dense parts; High mechanical properties; Complex geometris; High accurary; High strength and stiffness; Strong functional parts; Powder recycling; Fine feature details	Complex ducting (hollow designs); Functional metal parts (aerospace and automotive); Medical and dental parts
Material extrusion	Fused deposition modelling (FDM); Fused filament fabrication (FFF)	Thermoplastic filament; Wax	Thermal energy	Brittle quality, not suitable for mechanical parts; Higer cost than SLA/DLP for visual purposes; Poor surface finish; Limited part resolution	Full color and multi-material printing; Machine relatively low cost	Prototypes; Jigs and fixtures; Casting patterns
Material jetting	Polyjetl Wax casting technology; Drop on demand (DOD)	Photopolymer resin; Wax	Thermal energy	Brittle quality, not suitable for mechanical parts; Higher cost than SLA/DLP for visual purposes	High surface finish; Full color and multi-material printing	Full-color product prototypes; Injection mold-like prototypes; Medical and dental models; Tooling
Binder jetting	Inkjet 3D printing; Sand binder jetting; Metal binder jetting	Sand or metal powder; Ceramic powder; Polymer powder	Thermal energy	Low mechanical properties; High porosity	Low cost; Large build volumes; Wide material selection; Full color printing	Casting patterns; Functional metal parts; Full-color objects; Sand casting
Sheet lamination	Laminated object manufacturing (LOM); Ultrasonic additive manufacturing (UAM)	Plastic film; Sheet metal (aluminium, copper, stainless steel and titanium)	Laser beam	Post processing required; Limited material use	High speed; High surface finish; Low cost for material and machine; Ease of material handling	Injection mold-like prototypes; Casting models

Table 2. Strengths and limitations of AM (adapted from [14–20]).

Categories	Strengths	Limitations
Design-related:	•Enables design freedom and design optimization for product development •Trigger efficient and flexible model design and part production with better function	•Lack of talents skilled in designing 3D models and R&D •Legal issues about who should be responsible for should the component design and manufacturing process goes wrong
Manufacturing-related:	•Enable to manufacture of products with lower labor requirements •Open the possibility of manufacturing parts with very complex geometry •Efficient prototype and test of the viability and feasibility of physical parts •Decrease manufacturing lead time •Generate a decentralized manufacturing process, closer to the point of consumption •Help manufacturer and designer to get feedback faster due to rapid prototyping	•Manufacturing speed is slower than the conventional manufacturing process, which makes it difficult for high-volume production •Process qualification and certification need to be improved •Need post-processing due to "stair-stepping" effects •Existing manufacturing systems predominantly rely on rapid prototyping, not direct manufacturing
Product-related:	•Develop new products more effectively before committing to expensive manufacturing processes and tooling •Product can be manufactured at a location close to the customer •Produce highly customized and complex low-volume products	•3D printed parts show rough and imperfect surface finish •Poor product surface accuracy caused by residual stress and stair-stepping •3D printed parts repeatability and consistency need to be improved •Size limitation, low printing speed and low precision of product need to be improved
Material-related:	•Potential to save materials as some typical filaments or resins can be recycled •Reduce the volume of materials required for production •Metal powders during SLS or melting processes can be recycled up to 95%	•Photopolymers/plastics unable to produce large-sized objects due to lack of materials strength •Limitations of materials include standardization, dimension accuracy, process productivity •Material properties for a given AM process cannot be guaranteed •Support structure materials cannot be recycled, so need to be minimized through a good build-up orientation
Business-related:	•Trigger new business model development with an improved carbon footprint	•Extensive industrial applications need to be identified and broadened •Many parts fail to meet the business application needs
Customer-related:	•Transform consumer to designer and manufacturer and encourage user innovation and the maker movement	•Full acceptance and adoption in many sectors are not achieved
Cost-related:	•Decrease transportation costs •Not impose the additional expenses of creating new physical tools •Decrease large-scale investment in factories and machinery to reduce costs	•High costs remain a significant barrier to wide AM adoption •Prohibitive material costs
Supply chain-related:	•Increase supply chain proficiency through shortening time-to-market •Reduce the weight of transport-related products in the supply chain	

Table 3. An overview of six AM cases.

	Sectors	Intervewees/Time (mins)	Data Source	Country
Case A	**Sector**: AM design and data service **Description**: Design service; data management; 3D printing coffee shop; 3D printing museum	**A1**: Founder and CEO (180) **A2**: Digital design director (60) **A3**: Chief marketing officer (70)	4 face to face interviews; emails follow up; observations; phone calls; company reports	China
Case B	**Sector**: AM machine development **Description**: Machine; printing process; software; printing parts	**B1**: Business development director (200) **B2**: Product development manager (160) **B3**: Human resource manager (80) **B4**: Manufacturing manager (80) **B5**: Market representative (60)	7 face to face interviews; emails follow up; phone calls; observations	USA
Case C	**Sector**: AM material research and development **Description**: Materials; printing process; printing accessories	**C1**: Chief technology officer (160) **C2**: Business development director (100) **C3**: Sales manager (60)	4 face to face interviews; emails follow up; phone calls; observations; company reports	Japan
Case D	**Sector**: Printing platform service **Description**: Machine; printing service; design service; ODM	**D1**: Founder and CEO (200) **D2**: Sales manager (90) **D3**: Operation manager (80) **D4**: Industry development manager (100) **D5**: Project development engineer (100)	6 face to face interviews; emails follow up; phone calls; observations; company reports; site visits	China
Case E	**Sector**: AM education service **Description**: curriculum; textbook; certification; training programs; STEM education	**E1**: Founder and CEO (220) **E2**: Chief operation manager (170) **E3**: Senior technology development director (190) **E4**: Sales manager (80) **E5**: Strategy planning director (60) **E6**: Business development manager (60)	9 face to face interviews; emails follow up; phone call observations; company reports; site visits	China
Case F	**Sector**: AM consultancy service **Desription**: Technology roadmapping; stratey management and planning; R&D management	**F1**: Associate (220) **F2**: Senior consultant (100) **F3**: Eagagement manager (120)	4 face to face interviews; emails follow up; phone calls; observations; company reports; site visits	Japan

Table 4. Sustainability implications of AM from the value perspective in each case.

Sustainablity Implications	AM Design	AM Machine	AM Material	AM Printing Service	AM Education	AM Consulting
Social Value	•Improve customer relationship •Close partnership with suppliers •Improved service efficiency •Serve education/science	•Improve customer relationships •Strong relationship with resellers and suppliers •Close engagement with multi-stakeholders •Customized treatments for patients •Low-cost custom dental products •Efficient printing with cost/time savings •Encourage creativity/immersive learning in maker education	•Improved customer relationships •Strong relationship with resellers and suppliers •Close engagement with multi-stakeholders •Printer Manufacturers Partnership Program •Online customer community •Open forum for communication and suggestions •Materials customization	•Encourage student creativity in schools •Support immersive learning and maker education •Close customer engagement for R&D and design •Maintain strong relationships with suppliers and resellers •Reduce ABS usage for health safety •Rapidly verify ideas with prototyping	•Maker education •Improvement in innovation capabilities and design thinking •Hands-on experience •Physical realization of students' work •Support for immersive learning in schools •Improved safety •Cultivation of STEM skills •Portable and safe to use printer •No annoying tweaks or adjustments needed	•Custom solutions for organizations & society •Strategic decision-making •Improved customer relations •Increased job opportunities •Close stakeholder engagement
Environmental Value	•No equipment/materials needed •Reduce waste	•Reduce waste •Less material consumption •Reduce energy by reducing over-production •Improved material efficiency •Reduced environmental impact	•Biodegradable materials •Soluble support material (Nylon) for waste reduction •Improved material efficiency •Reduced environmental impacts •ABS with reduced odor during printing	•Improved material efficiency •Reduced environmental impacts •Generate fewer material wastes •Less material consumption	•Reduced environmental impacts •Use of biodegradable materials •Generation of fewer material wastes •Use of non-toxic materials •Absence of large hot moving parts for safety	•Reduced energy/material consumption •Improved material efficiency •AM integration into traditional manufacturing •Reduced waste during manufacturing
Economic Value	•Outsource technology •Reduced initial investment •Diversified products/services •3D designer training •Innovation design center for R&D •Café/museum for brand promotion •IP protection/management	•Professional and customized service •Affordable desktop SLA printer •Reduced costs for customers •Higher material utilization •No need for moulds/casting/tooling	•Custom material service Range of material options •Convenient printing accessories •Testing & characterization •Scaled manufacturing capacity •Extensive facilities & equipment •Materials customization	•Platform for design, printing, and lifecycle management •High precision printers •No need for molds, casting, tooling •Shortened process and supply chain •Smart pricing system with secure transactions	•AM bundles with printer, materials, training, and support •Integrated AM education solutions with personnel training and certification •Professional service for customer problem solving	•Increased consulting revenue •Improved manufacturing efficiency •Strategic planning & technology road mapping •Reduced costs and increased business profitability for clients.

Table 5. Identification and analysis of 199 key challenges in different AM cases.

Similar Codes/Negative Root Causes	Thematic Coding/Key Challenges	Sectors/Categories
1.Lack of design guidance for embodiment and detail design	Design guidance	AM design process
2.Lack of design guidance that considers AM process characteristics★		
3.Suitability of AM process for conceptual, embodiment and detail design		
4.Lack of design guidelines, rules, and influential factors★		
5.The difficulty of leveraging the advantages of AM for direct manufacturing		
6.Need improved dimensional accuracy and surface quality	Design quality	
7.Insufficient of proper build-up orientation to reduce support structure materials in the design process		
8.Weak process consistency leading to printed parts having significant dimensional deviations		
9.Cautions of overhangs, abrupt thickness transitions, trapped volumes, layering		
10.Need improved composite simulation capabilities for primitive shapes, material compositions, functionally gradient materials		
11.Limitations of anisotropy, discretization, post-processing issues		
12.Challenges of conceptual design stage for AM due to the process-related factors; for instance, part consolidation, part accuracy, part strength, materials properties, materials shrinkage, mechanical properties, ease of printing and assembly, post-processing, printing costs, shape and size of each key feature, printing quality, lamination effects, anisotropy, product functionality (adding mounting points and pivot points)	Design factors	
13.Wall thickness, outer and inner edges, slot depth, width and length, and overhang length		
14.Lack of focus on build orientation, layer thickness, support structure and removal, machining method for post-processing and inspection procedures		
15.Lack of factors for impact on design, manufacturing, and post-processing★		
16.Lack of methods for design process considering AM capabilities, limitations and resulting design freedoms and constraints★	Design methods	
17.Lack of methods for new design★		
18.Lack of conceptual design methods to aid designers in defining and exploring design spaces enabled by AM for representations of shape, property, process, and other variations		
19.Methods for simultaneous product and process design and multi-functional design		
20.Lack of methods of assessing lifecycle costs and environmental impacts of AM fabricated components and products		
21.Lack of methods for simultaneous multi-functional product design and AM process design		
22.Lack of a comprehensive set of AM design rules and materials data sheets that designers can rely on★	Design rules	
23.Design rules missed including wall thickness, printable feature size, fillet radius, hole diameters, support structures, wear characteristics, clearances, and tolerance		
24.AM design to be compatible with a traditional process		

Table 5. *Cont.*

Similar Codes/Negative Root Causes	Thematic Coding/Key Challenges	Sectors/Categories
25.Lack of sustainability considerations into AM design	Design sustainability	
26.Lack of new design thinking (e.g., life cycle thinking, sustainability)		
27.Lack of development of various AM-oriented design tools★	Design tools	
28.Lack of tools for representing complex geometries with repetitive features (e.g., cellular structures), multiple and gradient materials, and other variations		
29.Need improved design optimisation and simulation tools for minimising material and maximising process efficiency★		
30.Need improved CAD systems to overcome the limitations of parametric, boundary representations, and solid modelling in representing very complex geometries and multiple materials	Design software	
31.Lack of improved finite element analysis software for 3D model design		
32.Lack of IP and design rights protection (copyright)★	Design IP	
33.IP security is a significant concern★		
34.Lack of certification of new components and repair process	Design certification	
35.Lack of AM standards including design and equipment standards, application-specific standards, finished AM part standards, feed-stock material standards, general standards (terminology, test methods, safety;) ★	Design standards	
1.Low printer speed due to the machine limitation★	Printer speed	AM machine development
2.Need for research in machine design and dynamics to achieve a drastic increase in fabrication speed and a reduction in costs★		
3.Lack of R&D in industrial printers for high speed and strength	Printer development	
4.Lack of development of multi-materials and multi-color printing systems		
5.Lack of modelling, sensing, control, and process innovation for printer		
6.Lack of talents and qualified engineers in printer development★		
7.Incapable of printing large-size objects using SLA printer		
8.Low machine reliability	Printing quality	
9.Low-quality consistency		
10.Lack of repeatability and consistency of the manufactured parts★		
11.Need for process sensing and feedback control to improve part performance and consistency		
12.Uncertainties of part quality and mechanical properties to make functional parts★		
13.Limited strength, rigidity and heat resistance for 3D printed parts which is not conducive to long-term preservation★		
14.Lack of integrating control algorithms with existing AM machine through machines' proprietary controllers		
15.Clogging resulting from the support structure		

Table 5. *Cont.*

Similar Codes/Negative Root Causes	Thematic Coding/Key Challenges	Sectors/Categories
16.Lack of manufacturing efficiency through improved automation of AM systems and process planning		
17.Precision and stability of the parts need improvement★		
18.Lack of intensity with exposure to high stresses for produced parts		
19.High investment for industrial printer development★	Printer cost	
20.High industrial machine costs★		
21.High costs for machine maintenance and downtime		
22.No or little recycling for the broken printer, used printer and print accessories	Printing sustainability	
23.Lack of awareness of the conversion of waste and by-products into products		
24.Need for capacity and capital to undertake to remanufacture		
25.Lack of awareness and knowledge of remanufacturing		
26.Noise from the printing process		
27.Potential health issues of handing glue or resin★		
28.Waste streams in the printing process (materials, scraps, printing support, etc.) ★		
29.Lack of equitable indicators and measurement metrics for measuring sustainability in printing processes and products★		
30.Lack of sustainability metrics and the corresponding measurement science		
31.Limited reclaimed and reused of waste materials, misprint, and undesired outputs		
32.Challenge of educating the customer about the recycling of plastics and other materials		
33.Unawareness of sustainability concepts to integrate into printing practices		
34.Hard to retrieve and remanufacture the old printers		
35.Limitations of recycling due to quality and purity issues★		
1.Low physical properties of polymers to achieve better fabrication	Material properties	
2.Weak strength of materials properties particularly for resin and PLA		
3.Materials toxicity such as ABS and resin★		
4.Uncured PolyJet model materials cannot be recycled		
5.Uncured model materials require special handling, packaging, transportation, and disposal		
6.Relatively poor part accuracy caused by the stair-stepping effect and residual stresses★		
7.Challenges of forming and mixing of materials with desired properties in desired forms		
8.Unclear about how the process parameters affect the material properties and part performance under the extremely high material deposition rate		

Table 5. *Cont.*

Similar Codes/Negative Root Causes	Thematic Coding/Key Challenges	Sectors/Categories
9.Adhesion and thermal mismatch between heterogeneous materials and functionally gradient materials		
10.Lack of understanding of melting and recrystallisation in polymers to develop robust mathematical models		
11.The toxic smell produced when printing ABS★		
12.Reduction in the material properties and color contamination of materials		
13.Limited recycling and reusing printed materials and scraps★	Material recycling and reuse	
14.Insufficient use of broken printed parts and waste materials		
15.Materials generate uncomfortable smell and may cause health issue★		
16.Lack of awareness and knowledge of recycling and reuse★		
17.Lack of awareness and knowledge of material sustainability		
18.Wastes of energy (electricity, cooling system, heat) with more energy-intensive per unit produced		
19.Limited recyclability due to mixed materials		
20.The low percentage of recycled materials percentage in materials inputs		
21.Non-recyclability of multi-materials products		
22.Challenges of separating wood-polymer composites for recycling		
23.Only certain materials can be recycled, but the recycling result is not valid, e.g., PLA★		
24.Lack of recycling support and method★		
25.Materials waste generation★		
26.Limited recyclability of materials due to quality loss★	Material quality	
27.Incompatibility between non-standardized and non-recyclable materials		
28.Critical material quality loss during the recycling process		
29.Recycled materials may cause contamination of other materials		
30.Need new regimes of materials transformation due to extreme heating and cooling rates		
31.Plastic parts are fragile along with the layer lamination		
32.Weak adhesion of plastics, ceramics, and wax		
33.Different degrees of distortion of parts and materials		
34.Lack of recycling and remanufacturing guidance and standard★	Material standard	
35.Lack of standardisation of material development★		
36.Lack of standards in material data reported by various companies★		

Table 5. *Cont.*

Similar Codes/Negative Root Causes	Thematic Coding/Key Challenges	Sectors/Categories
37.Need for low-cost remanufacturing technology	Material costs	
38.Relatively high materials costs★		
39.Costs of recycling and reuse are very high		
40.Overall limited material availability and selection in the AM industry	Material selection	
41.Limited materials available for use in AM processes★		
42.Lack of development of new materials for AM processes★		
43.Challenges of coordinating material flow control with machine motion control in the AM processing within each layer and between layers	Material control	
44.Challenges of realizing more material options, better resolution, faster production, more reliable operation, robust certification, and lower costs★		
45.Lack of development of new materials for AM processes★		
46.The disconnection between high-fidelity modelling research and real-time online process control efforts		
1.Low slicing speed	Printing service speed	AM service platform
2.Low printing speed due to the FDM machine limitation★		
3.The whole process of online printing service is quite slow		
4.Materials toxicity for ABS★	Printing quality	
5.Low fault tolerance		
6.Low-quality consistency		
7.Limited material available in online printing★		
8.Difficulty of predicting the microstructures and fatigue properties of materials during the printing process		
9.Hard to guarantee material properties for a given process		
10.Lack of online control of material composition and phase transformation, and the repair of defects such as pinholes/porosity, micro-cracks, and segregation		
11.Slicing failure of broken object face or hole	Printing software	
12.Online printing software is not open source and strictly bounded with machine		
13.Limited printing service capability for mass production	Service capability	
14.Challenge of achieving mass customization through online printing		
15.Deficits in designers and engineers skilled in AM to provide service★		

Table 5. *Cont.*

Similar Codes/Negative Root Causes	**Thematic Coding/Key Challenges**	**Sectors/Categories**
16.Printed parts are less reliable than injection molding	Printed parts	
17.Low machine reliability for printing		
18.Lack of repeatability and consistency of the manufactured parts		
19.Poor service effectiveness and efficiency	Service quality	
20.Printing service is fragmented and unevenly distributed		
21.Inconvenience of changing wire during the printing process		
22.Lack of effective use of online resources		
23.Lack of facility for cloud manufacturing enabling sharing of manufacturing resources online	Cloud manufacturing service	
24.No readily applicable systems can be used for cloud-based AM		
25.Lack of cyber-facturing (cyber-enabled manufacturing) that manufacture products at geographically dispersed locations via communication and control online★		
26.Lack of recycling and reuse support and method★	Printing sustainability	
27.Lack of remanufacturing guidance and methods★		
28.Uncomfortable smell produced when printing ABS★		
29.Lack of fundamental modelling, analysis, and simulation in the online printing process	Printing process	
30.Lack of system to model the temperature, stress, and composition history		
31.Lack of fast in situ measurements of temperature, cooling rate, and residual stress in sensing of AM processes		
32.Lack of integrating AM process with other manufacturing technologies in design and production (machining, injecting molding, casting) ★		
33.Lack of in-process monitoring of geometric dimensions and the surface quality of finished layers		
34.Lack of understanding of how process parameters affect the material properties and part performance		
35.Hard to coordinate material flow control with machine motion control in the printing processing within each layer and between layers		
36.Existing printing systems are still predominantly based on rapid prototyping machine architectures		
37.Lack of certification of equipment, materials, and personnel★	Printing Standardization	
38.Lack of open and unified standards for printing development★		
39.Lack of unified printing principles, rules, guidelines, and regulations★		
40.Lack of development and standardization of new materials★		
41.Challenge of the fabrication of large-scale parts to produce parts of nearly unbounded size		

Table 5. *Cont.*

Similar Codes/Negative Root Causes	Thematic Coding/Key Challenges	Sectors/Categories
1.Lack of resources for developing AM textbook and curriculum★	Education materials	AM education service
2.Limited quality of teaching textbook and lesson plans		
3.Lack of teaching standard and education quality evaluation		
4.AM education and training materials are still very limited in schools★		
5.Challenge of incorporating AM into teachers' curriculum		
6.Lack of AM courses for the training of engineering students in 2-year community colleges		
7.Challenge of incorporating AM technologies into the existing curriculum while meeting the Accreditation Board for Engineering and Technology (ABET) requirements in colleges and universities		
8.Lack of qualified teachers for AM education★	Qualified educator	
9.Lack of sufficiently trained personnel to deliver quality AM products and teaching materials★		
10.Some teachers have trouble with clear and concise communication with students		
11.Lack of knowledge of AM technologies and processes★		
12.Lack of general awareness of AM for K-12 schools		
13.AM educators lack of teaching qualification★		
14.Lack of machine to meet the teaching requirement	Education equipment	
15.High-level educational tools are missing in community colleges, particularly for AM		
16.Industrial printing equipment (SLM, EBM, etc.) may be financially out of reach for many community colleges		
17.Lack of financial support and funding for high-end AM equipment in community college		
18.Lack of integrating AM process with other manufacturing technologies in teaching and demonstration		
19.Challenge of fabrication of large-scale parts for a printing demonstration		
20.Difficulty of integrating sustainability considerations into education	Sustainability education	
21.Difficulty of educating students about recycling 3D printed materials		
22.Challenges of educating recycling plastics and other materials		
23.Material wastes generation during printing practice and demonstration		
24.Need further development of AM design methodology for teaching	Design for education	
25.Lack of readily applicable and proved 3D models for AM education and training★		
26.Students fear failure which limits their experimental potential		
27.Lack of online education resource management	Education capabilities	
28.Lack of regulation of fixed teaching time in schools		
29.Lack of integrated software solutions for model design, printing management, etc.★		

Table 5. *Cont.*

Similar Codes/Negative Root Causes	Thematic Coding/Key Challenges	Sectors/Categories
1.Lack of qualified AM professionals for AM consulting	Qualified consultant	AM consulting service
2.Lack of professional consulting service in the AM industry		
3.Challenge of innovation and generating new ideas for AM consultants		
4.Inefficient and ineffective use of data for consulting	Service quality	
5.Challenges of understanding clients evolving requirements★		
6.Need to use time and resources more effectively★		
7.Lack of user-friendly software solutions for model design, printing management, etc.★		
8.Lack of structured and strategic framework for AM★		
9.Continuously changing the set of competitors in service bureaus★	External environment	
10.AM market changes and investment environment uncertain issues cause risks★		
11.Lack of embedding sustainability considerations into consulting service	Sustainability consulting	
12.Clients don’t consider sustainability		
13.Lack of hard data on the comparison between AM products and traditionally manufactured products in terms of energy use, supply chain, material consumption, CO_2 emission		

Table 6. Development of 55 sustainability solutions for different AM sectors.

Categories	Design for sustainability	Material for sustainability	Machine for sustainability	Printing for sustainability	Service for sustainability	Education for sustainability
Key solutions /Tactics	Develop design capabilities, guidance and principles	Maximize AM materials and energy efficiency	Deliver functionality rather than ownership	Improve the efficiency of the online printing process	Implement the subscription service for the customer	Develop large-size and high-speed printers for education purposes at a lower price
	Incorporate sustainability concepts into product design	Improve the knowledge of wasted and printed materials recycling and reuse for AM practitioners	Provide machine sharing, subscription, and leasing service	Provide a sustainability-oriented strategy and solution for printing	Strengthen the maintenance service team	Develop ease-of-use and affordable printers for the education market
	Integrate design thinking into the design process	Develop environmentally friendly materials for printing	Accelerate the development of AM standards and specifications that consistent with stakeholder needs	Develop scale-up solutions for printing	Develop the printers and materials to print large size objects for demonstration	Develop the subscription and leasing service for school
	Improve design knowledge of AM characteristics and limitations	Provide mask or protective kits for operating harmful materials	Develop advanced printers that can print multi-color materials with good quality	Explore the open-source approach and establish a local and replicable production network	Develop the user-friendly software with different functions for printing service	Provide training classes to customers about sustainability principles and methods
	Strengthen the communication between designer and manufacturer	Provide solutions for wastes reduction and material recycling	Develop printer with the compatibility of different materials	Develop printing standards and requirements	Use service data efficiently and effectively	Improve the knowledge of sustainability concepts
	Expand the data pool to have more design models that can be printed with no flaws and defects	Develop recycling and reuse technologies for mixed materials and multi-color materials	Reuse broken 3D printers and failed products	Develop the printing service platform with high efficiency, low cost, and high flexibility	Clearer about customer needs (real needs, potential needs, hidden needs and future needs) to provide high-quality service	Develop the teaching standards and certification for AM teacher qualification
	Leverage the advantages of AM for direct manufacturing	Develop recycling technologies to separate recycled mixed materials without compromising quality and properties	Develop high-quality printer without flaw and deformation in printed parts	Innovate the printing process to print high-quality products without increasing the printing time	Develop all-in-one software solutions	Provide training to the employee about the teaching method for sustainability education
	Improve IP management and protection of the 3D model	Develop guidance and standards for recycling		Use biodegradable PLA and other environmentally friendly materials for printing	Develop functions of model design, printing optimization, testing, management, and post-processing	Collaborate with universities to develop an undergraduate-level class in AM major

Table 6. *Cont.*

Categories	Design for sustainability	Material for sustainability	Machine for sustainability	Printing for sustainability	Service for sustainability	Education for sustainability
	Develop AM design education system	Standardize materials data				Establish AM education centres at schools with skilful teachers and equipment for demonstration
	Build up the data management system	Implement sustainable PSS such as user-oriented and result-oriented models				Provide training to improve the teaching capabilities and skills of the employees
	Improve the efficiency of data utilization through data management and configuration					Improve communication with students during the teaching and service process to clearly understand their needs

Table 7. The 43 categories of key challenges for wide AM adoption.

AM Design	AM Machine	AM Material	AM Printing Service	AM Education	AM Consulting
Design guidance	Printer speed	Material properties	Printing service speed	Education materials	Qualified consultant
Design quality	Printer development	Material recycling and reuse	Printing quality	Qualified educator	Service quality
Design factors	Printing quality	Material quality	Printing software	Education equipment	External environment
Design methods	Printer cost	Material standards	Service capability	Sustainability education	Sustainability consulting
Design rules	Printing sustainability	Material costs	Printed parts	Design for education	
Design sustainability		Material selection	Service quality	Education capabilities	
Design tools		Material control	Cloud manufacturing service		
Design software			Printing sustainability		
Design IP			Printing process		
Design certification			Printing Standardization		
Design standards					

2. Literature Background

2.1. The AM Processes

This section reviews the literature on AM technologies, focusing on their processes, strengths, and weaknesses. AM has experienced significant growth over the past three decades and differs from conventional manufacturing processes such as casting, milling, forming, and machining. The American Society for Testing and Materials (ASTM) has classified AM processes into seven categories: vat photopolymerization, directed energy deposition, powder bed fusion, material extrusion, material jetting, binder jetting, and sheet lamination [5–9]. These categories have been widely recognized and adopted. The paper investigates the characteristics of each AM process category and provides a comprehensive review of the principles of AM processes in terms of printing materials, power sources, implementation challenges, applications, strengths, and opportunities in Table 1. AM can produce 3D physical objects using raw materials such as powders, liquids, or filaments, with minimal waste and good geometric accuracy [5–7]. It has the potential to transform the manufacturing industry and bring new design and market opportunities [2]. However, the economic value of AM remains based on conceptual studies, and ongoing research mainly focuses on the technological aspects of AM processes, with limited focus on AM management, operations, and strategy [21]. While AM has demonstrated benefits such as customized and functional products in various industries, its resource efficiency and environmental friendliness are still in question for some applications [22]. The implementation of AM technologies is still in its early stages, with several challenges in direct production contexts, and it may not make conventional manufacturing processes obsolete [22].

This paper aims to gain a better understanding of the challenges and opportunities for the adoption of Additive Manufacturing (AM) compared to traditional manufacturing methods. Table 2 presents both the strengths and limitations of the development and implementation of AM. The strengths and limitations addressed in the literature provide valuable insights into AM technologies. Researchers and practitioners have been working tirelessly for decades to improve AM processes to overcome these barriers. It is crucial to develop a method and framework to guide the adoption of AM technologies in a well-informed and sustainable manner [23]. The widespread adoption of AM would disrupt the way that manufacturing companies operate and capture value. Therefore, there is a need for empirical studies to examine the challenges faced by AM companies and the opportunities for widespread implementation of AM in practice.

2.2. AM Sustainability

Researchers argue that AM can bring several benefits from a sustainability perspective and can become a key manufacturing technology in the sustainable society of the future [1,2,9,14,24]. To support this claim, it is necessary to investigate and estimate the environmental and social impacts of AM processes. Research in this area is still in its early stages and has focused on the resource efficiency of different AM processes [15,25]. Some studies have monitored AM production processes and quantified their environmental impacts [15,26,27], while others have compared the consumption of materials and energy use between AM and conventional manufacturing methods such as injection molding and casting [2,14]. For example, Frazier [28] reviewed metal AM processes to demonstrate how they reduce energy, materials, and other resource consumption. Despite the technological advancements in AM, including the improvement of mechanical properties and materials, the research on its sustainability is still limited and lacks consistency and continuity [29]. The absence of a strategic plan for sustainability in AM calls for further investigation and understanding of its impact on the environment and society [16].

AM may not be as sustainable as some suggest, as in some cases it may generate more energy consumption compared to casting and injection molding [3]. There is no clear conclusion that AM is more energy-efficient or environmentally friendly compared to subtractive manufacturing processes overall [22]. The literature suggests that coming to the conclusion that AM processes have lower environmental impacts than traditional manufacturing is biased, as data on total waste are missing, and uncertainties exist [22,30]. The sustainability of AM, especially in terms of its environmental sustainability, can vary depending on the specific circumstances and on a case-by-case basis [31]. More comprehensive sustainability evaluations are required to assess the performance, accuracy, and feasibility of the environmental impacts of AM.

The literature on the social impacts of AM is under-explored [14,22,32]. The social aspects typically relate to work safety, health conditions, employment schemes, quality of life, and human well-being, among others. Some printed materials have the potential to negatively affect health conditions. Harsh skin reactions, eye irritation, and allergies may occur if powder or liquid materials come into contact with skin. Prolonged exposure to certain materials and chemicals may impact health and result in chronic allergies [22]. The adverse effects of some AM materials are not yet well understood [22]. It is important to gain a better understanding of the potential health and occupational hazards and toxicities associated with AM. Few conclusions have been made about its sustainability implications in both the environmental and social dimensions. To conclude, AM is likely to have a greater sustainability impact if (1) closer integration and deeper cross-disciplinary collaboration is established, and (2) timely and comprehensive research is conducted to identify opportunities for energy-efficient and environmentally friendly improvements. AM is expected to play a key role in the sustainable manufacturing of the future.

2.3. Research Questions

The research shows that the current theoretical and empirical studies on AM sustainability are still in their early stages. The focus of AM research has been mainly on material development, process innovation, and energy consumption [2,3,15], and the sustainability implications of AM have received limited attention [1,33,34]. While some studies have explored the broad sustainability implications of AM [1,18,26], a better understanding of the sustainability implications and wider adoption of AM are needed.

In light of this, the objective of this research is to address the gap in the current literature by exploring the challenges and opportunities for the wide adoption of AM. The following research questions are proposed:

RQ1: What are the sustainability implications of AM from a value perspective?

RQ2: What are the key challenges that prevent the widespread adoption of AM?

RQ3: What opportunities and solutions can promote more sustainable outcomes in AM?

3. Research Methods

This research addresses a real-world problem identified in the AM industry and offers new knowledge to enable AM sustainability. The purpose of the research is to explore the challenges and opportunities regarding AM in moving towards sustainability. This research primarily relies on practitioners' opinions, experiences, and perspectives of the current AM companies to build new knowledge from empirical evidence. Using a qualitative approach is considered adequate for addressing the research questions through inductively building theory and moving from particular to general themes [35]. The richness of the data will be a key factor for this qualitative study. It is believed that the case study method is an effective empirical approach for gaining exploratory, real-life insights and building theory [4]. Therefore, a qualitative approach has been proposed as the primary method to enhance the understanding of the research questions and findings. Despite the increasing amount of literature on AM technologies, few studies offer insights into the challenges and solutions regarding the sustainable adoption of AM based on empirical evidence. The main focus of this research is to understand a practical problem and develop an in-depth description of multiple cases in the AM industry. The case study was chosen as a fundamental data collection method because it is deemed suitable for this research.

The aim of this paper is to understand a practical problem by talking directly with people, visiting workplaces, and conducting fieldwork [4]. Multiple case studies will be conducted to generate robust theory and validate the findings through replication in various situations [4,36]. Thus, six cases were identified following a theoretical replication logic for contrasting results from three countries: China, the USA, and Japan. The case selection criteria targeted exemplars of AM sectors that have a significant market impact and share substantial business experiences. Six cases were chosen due to the degree of theoretical saturation reached when incremental improvement is minimal and gathering new data no longer sparks new insights [36,37]. The data were directly drawn from semi-structured interviews with managers, fieldwork in workplaces, and factories. The interviews typically lasted 1–3 h and were conducted in English. All interview processes were audio-taped with prior consent for later transcription and analysis. Table 3 presents the details of the case studies, including 6 companies, 34 interviews, and 25 participants for data collection. The cross-case analysis interpreted different data forms and looked for patterns across multiple cases. The data analysis process was conducted through three stages of coding: open coding (i.e., reading the data, noting codes for related statements and assigning them to categories), axial coding (i.e., re-reading the data, confirming the concepts and categories accurately), and thematic coding (i.e., identifying patterns in coding and clustering codes into common themes); this was done until saturation was reached to explore how the categories are related [35].

We selected six case companies from different AM sectors based on the product life cycle, starting from the stage of conceptual and product design, moving through process selection, planning, and material processing, to production activities such as prototyping and direct manufacturing, and, finally, to the use, maintenance, and recycling, reusing, and repairing of printed products and waste materials to close the loop, as shown in Figure 1. The AM ecosystem perspective informed our decision to choose the six most representative cases that encompass various technology functions and business orientations, including a 3D model design company, a material development company, a machine manufacturer, a printing service platform, an AM education provider, and an AM consulting firm. As depicted in Figure 1, designers create 3D models, material suppliers develop materials, machine manufacturers produce 3D printers, and products can be printed through online platforms or in-house facilities. The printed products are then used by customers and industrial users; however, the arrows with dashes indicate that recycling, reuse, and repair are not always well executed, and not all used parts return to the system to close the loop. We used multiple sources of evidence to reduce bias and increase validity, including industry reports, website articles, newspapers, observations, and interview transcripts. The data analysis was conducted using a thematic coding process until saturation was reached to extract the sustainability implications and challenges from the case descriptions. The sustainability implications from the value perspective of the six cases were identified and extended throughout the multi-case study analysis to move AM towards sustainability, as shown in Table 4. The cross-case analysis also investigated the social, environmental, and economic value systems of each case to ensure research validity and reliability [4]

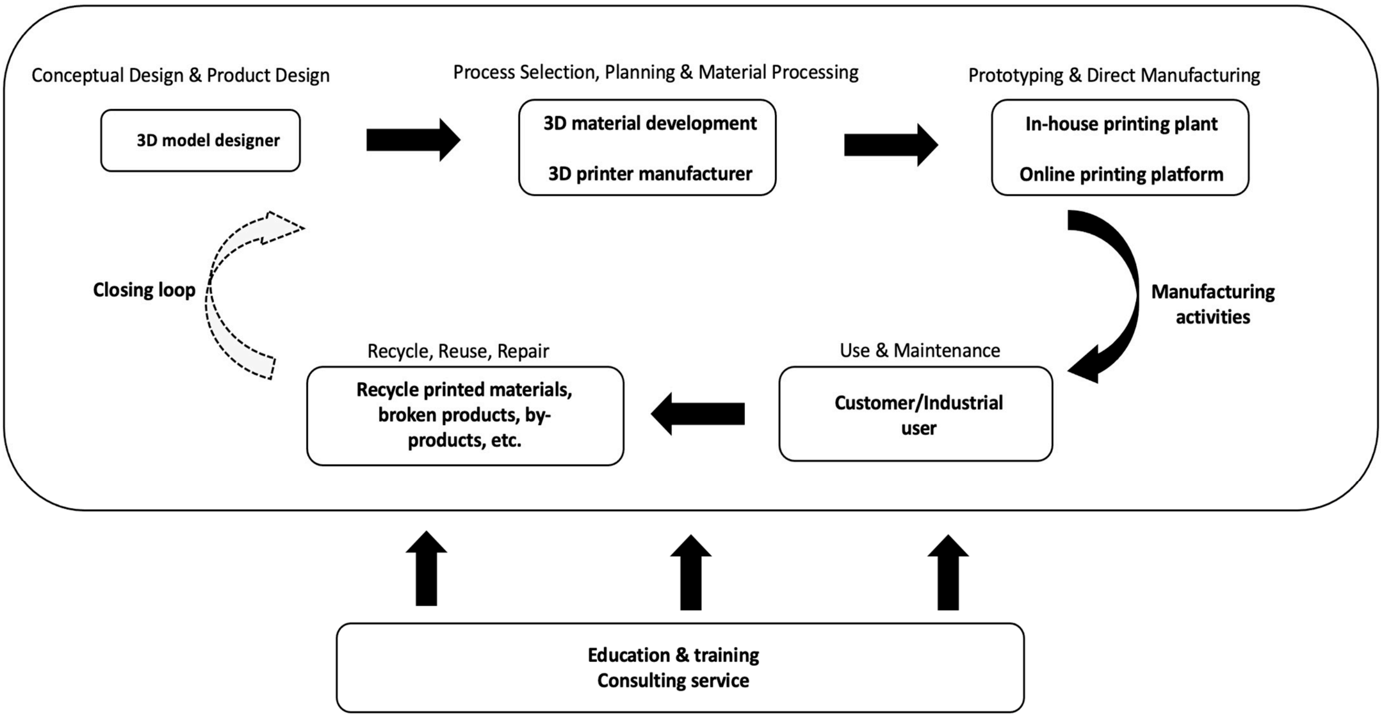

Figure 1. Case study selection based on the AM ecosystem.

4. Results

4.1. Key Challenges of Different AM Sectors

We identified and summarized 199 key challenges across the AM design processes, machine development, material development, printing service platform, education, and consulting service that AM firms encountered. The root causes were extracted and analyzed from interviews, observations, documentary analysis, and the existing literature in the AM field. The findings confirmed some previously established results (indicated by a "★" symbol), while other results were original. The extracted codes related to root causes were categorized into different types, as shown in Table 5. For example, in Case Study E, the root causes of the challenges in AM education services were analyzed and categorized into 29 examples, which were further classified into 6 categories: educational materials, qualified educator, education equipment, sustainability education, design for education, and education service. In Company F, the root causes of customer problems were used as practical evidence to confirm the challenges in AM consulting services. The data were analyzed, and similar root causes were classified into 13 examples under 4 categories: qualified consultant, consulting service, external environment, and sustainability consulting(as shown in Table 5).

Overall, the data from AM cases were analyzed and produced into different key challenges. For instance, the negative root causes in the AM design process impede the broad adoption of AM for practitioners and traditional manufacturers. In particular, the lack of qualified designers in the market has negatively impacted the development of AM design and value creation. This indicates that the key challenges in AM design were hidden within the existing business models and uncovered through root cause analysis. Further, the key challenges of AM machine development were identified and grouped into five categories: printer knowledge, printing speed, printing market, printing development, printing quality, and printing cost and sustainability. The negative root causes of AM materials were categorized into 46 examples and were summarized into 7 categories: material properties, material recycling and reuse, material quality, material standard, material costs, material selection, and material development. Identifying the root causes can help to uncover sustainable opportunities for the companies, and particularly for the environment and society.

4.2. Sustainability Solutions for Different AM Sectors

The case studies indicate that identifying challenges in AM helps to reveal sustainability solutions. We then developed effective sustainability solutions for each AM sector, enabling the generation of sustainable outcomes. The examples of solutions were categorized into six types: design for sustainability, material for sustainability, machine for sustainability, printing for sustainability, service for sustainability, and education for sustainability. For example, in the AM design case, we identified 35 key challenges (see Table 5). Based on these challenges, we uncovered 11 critical tactics for design for sustainability, as shown in Table 6. Some tactics were deleted or merged into others based on their significance and frequency. We then developed and synthesized the key tactics consecutively for AM material, machine, printing service, education, and consulting service for sustainability. It is important to note that some of the sustainable solutions overlap and some might not be feasible for certain companies. As a result, 55 types of sustainability solutions were uncovered, forming a comprehensive set of actions that will enable AM companies to generate more sustainable outcomes. Some of these key solutions are novel and have not been covered in the previous literature.

The 55 types of tactics were presented to AM companies and reactions were sought. We applied the AM sustainability solutions to the interviews and workshops to validate the key tactics. Notably, the CTO of the AM material company said: "We try to develop the polymers that can be recycled and reused as sustainability solutions; however, these recycled polymers are typically not mechanically strong. They are quite weak mechanically [. . .]." The Director of the AM material company also commented: "We will not put the recycled materials into our new materials production process, which would negatively affect the properties of the overall material." The solutions indicate a need for developing recycling and reuse technologies for wasted and printed materials. However, it is still quite challenging to recycle and reuse most AM materials, particularly for multi-material products and mixed materials with different colors. The interviewees indicated that the recycling technologies were immature and that recycled materials properties were not good enough. The AM materials manufacturers lacked knowledge and awareness of material sustainability concepts.

The research findings showed that very few AM companies are taking action in material recycling and reuse. Only a minimal number of printed materials were dealt with in the recycling process and sent back to the inputs of the new materials. The CTO of the AM materials company also emphasized: "Material recycling is pretty difficult. The recycled filament is not good quality with small porosity and dust inside, which negatively affect the nozzle." One sustainability solution for materials is to develop environmentally-friendly printing materials. However, the printing service company only considered PLA for recycling, as it is is biodegradable, and did not consider ABS, TPU, and PC, which are not recyclable. It should be noted that recycled materials have fragile mechanical properties and low strength that are not ideal for re-printing and negatively impact the overall material properties. The Sales Manager of a printing service company emphasized: "Senior managers in our company are not paying the materials recycling much attention. We still set making profits as the priority." The CTO of the printing service company also mentioned: "The generated wastes of traditional manufacturing are million times more than that of 3D printing. We do not need to care about the wastes in 3D printing because it is too little and has minimal impact on the environment."

The data validation showed that the sustainability solutions for AM are valuable and helpful. However, sustainability considerations have not been embedded into the current production systems and business models. As the interviewees indicated, AM material companies still set making profits as the priority without paying much attention to environmental and social value. Furthermore, 3D printer manufacturers sell the machines with limited additional services. One of the 'machine for sustainability' solutions is to provide machine sharing, subscription, and leasing services. Delivering functionality rather than selling product ownership to fulfil customers' needs would bring resource efficiency and environmental benefits. However, 3D printer manufacturers are not likely to change current business models and deliver functionalities rather than ownership through machine subscriptions, although the companies are aware of the environmental and social benefits. Still, the companies would only consider it if it were combined with economic value. This confirms the findings from the case studies that AM companies intend to consider environmental and social value when they can make financial profits. It is expected that more AM companies would sell the availability of the printers without customer ownership because industrial printers are quite expensive and not widely adopted by industrial customers. In sum, we developed the critical sustainability solutions list, which could be helpful for AM companies to improve competitiveness and sustainability. In comparison, the implementation effectiveness of the sustainability solutions is not discussed in the scope of this research but could be further investigated in the future. The 55 significant tactics could help AM companies to develop sustainable business models and technologies. However, due to the limitations of the data, the summary list might not be complete. Table 6 can be extended to embrace more AM sectors and develop more tactics in future work. The summary of the sustainability solutions contributes to the concept of sustainability in the context of AM technologies.

5. Discussion of Key Challenges for AM Adoption

We conducted a comprehensive analysis of the negative root causes that exist in various AM companies to answer the research question of "what are the key challenges preventing the wide adoption of AM?" By identifying these key challenges, we aimed to gain a better understanding of AM technologies and investigate how they can be more widely adopted. The limitations of AM technologies have been discussed in the previous literature; however, this study goes beyond by examining challenges in a range of AM applications, including design, printing service, education, consulting, etc. [2,3,15,17,20,22,38]. This study is novel because it combines both the literature and empirical data to identify challenges, encompassing broader concerns regarding business, management, and operational perspectives. As a result of our analysis, we uncovered 199 key challenges for different AM sectors, which were classified into 43 categories to better understand their sustainability implications, as shown in Table 7. These challenges help to explain why AM is not yet widely adopted and what needs to be overcome for more sustainable outcomes. For example, both AM machine and service companies face challenges in printing sustainability, such as "waste streams in the printing process (materials, scraps, printing support, etc.)" and "lack of materials recycling and reuse." Similarly, AM material and service companies also face common challenges in material quality, such as "limited recyclability of materials due to quality loss" and "difficulty in guaranteeing recycled material properties for a given process." We compared the key challenges in each AM case with the existing literature to validate our results, as shown in Table 8. This study provides the first categorization of challenges for these AM sectors, which has theoretical implications for AM development.

Table 8. Literature confirmed/extended/contradicted for key challenges in each AM case.

AM Design	AM Machine	AM Material	AM Printing Service	AM Education	AM Consulting
The challenges of design standards, certification, IP, software, tools, and rules confirm the implementation and challenges of AM process [10,11]. For instance, the findings confirm the shortage of designers and engineers skilled in designing 3D models and the legal issues of who should be responsible when the component design goes wrong.	The challenges of printing speed and printing quality confirm the literature [10,11,39]. It provides new perspectives on essential technology elements and system integration [2].	The challenges of material properties, qualities, material development and standard confirm and extend the literature about AM materials characteristics and principles [2,10,11,17]. Notably, it provides new perspectives on the principles of AM processes. The findings also confirm the limitations of materials standardization, process productivity, and dimension accuracy.	The challenges of printing speed, printing quality, printing process, and standardization confirm and extend the literature about the strengths and limitations of AM [2,10,12,39]. Notably, the printing speed process is slower than conventional manufacturing, and process qualification, certification, and low precision need improvement.	The challenges of education materials, qualified teachers, and education equipment were mainly derived from interviews and workshops, which contribute to the social impacts of AM [14,22,32].	The lack of qualified consultants and consulting services was derived from interviews and workshops, which have not been identified in the existing literature [22,39].
The challenges of design methods, design factors, quality, guidance and sustainability extend the literature about AM strengths [1,2,39]. For instance, the findings confirm the existing literature about the lack of design guidance, guidelines, lack of sustainability considerations in AM design, etc.	The sustainability challenges confirm and extend AM sustainability literature [1,15,16]. Mainly, there is a lack of sustainability metrics, unawareness of sustainability concepts, and recycling limitations for broken and used printers.	The challenges of material recycling and reuse, selection, and standard confirm the strengths and limitations of AM technologies and AM sustainability [1,14,16,40]. Notably, it confirms that support structure materials cannot be recycled, though metal powders can be mostly recycled during melting processes.	The challenges of printing sustainability extend the AM sustainability literature [1,14,16,40]. Notably, it confirms a lack of recycling and reuse methods and remanufacturing guidance. Furthermore, the printing glue is harmful to the customer and unsuitable for the environment, which is not discussed in the current literature.	The challenges of sustainability education and design for education extend the literature about AM sustainability in the education sector. There is a lack of education equipment, qualified teachers, and 3D model service in the AM industry, which has not been developed in the literature [14,22,32].	The external environment regarding the uncertain AM market extends the literature on AM industry and development [1,2,41,42].
	The challenges of printer development and cost confirm AM cost and AM business [17,43]. For instance, limitations relating to high prices and low printing quality need to be overcome; full industry acceptance and adoption are not achieved.	The challenges of material costs confirm the literature about AM costs [43]. Notably, high material costs remain a significant barrier to widely adopting AM technologies.	The challenges of printing software, service capability, service quality and cloud manufacturing were mainly developed from interviews and workshops, which extend the literature of Huang et al. [2].		The lack of sustainability considerations in consulting services, particularly hard data on energy use and material consumption, provides new perspectives on AM service and AM sustainability [23,29].

Figure 2 illustrates the percentages of key challenges across all six cases. It shows that more than half of the total 199 challenges (59%) are identified, respectively, in the AM design (18%), AM material (23%), and AM machine (18%) categories. This confirms the findings from the literature that the prominent AM limitations of the design methodology, materials development, and modelling, sensing, control, and process must be addressed [2]. This also indicates that AM technology innovation lays the foundation for broad adoption. We evaluated and compared the findings with the literature. It should be noted that some of the key challenges in this research correspond to the AM adoption challenges in SMEs [39]. The challenges identified in this paper extend the scopes and implications related to technology, strategy, supply chain, operation, organization, and other external clusters [39]. Regarding the technology-related challenges, we analyzed the technical difficulties from the perspectives of machine, materials, design, and processing issues. Martinsuo and Luomaranta [39] only investigated AM machines and materials challenges, and developed only 26 AM adoption challenges regarding the strategy, operation, and external marketing-related challenges. In comparison, this paper provides 199 examples/explanations for design, machine, materials, printing process, education, and consulting services that confirm and extend the existing literature regarding the abovementioned strategy, supply chain, operational, and organizational challenges.

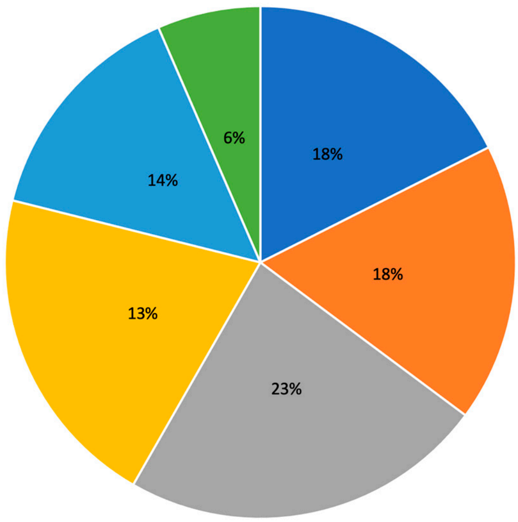

Figure 2. Percentage of key challenges in different AM cases.

6. Conclusions

AM technologies are still in their infancy and require further improvement. Therefore, it is no surprise that the research on AM sustainability is also at the nascent stage. This early study has shown that AM is not as sustainable as many have suggested, as it generates more energy consumption than casting and injection molding. Due to the immaturity of AM technologies in terms of mass production and customization, the realization of wide AM adoption highly depends on overcoming these key challenges in various aspects. The research questions were answered, and the theoretical and practical contributions were highlighted and reinforced. It is hoped that more AM companies will place importance on sustainability and incorporate sustainable solutions into their value creation and capture processes while advancing their technologies. The research findings provide opportunities for further work that would benefit both theory and practice, including investigating solutions to the key challenges and enabling mass customization regarding AM. The sustainability solutions could be applied in a broader context and the effectiveness of their implementation and execution could be studied in the future.

Author Contributions: Conceptualization, W.L., X.L. and S.E.; methodology, W.L., S.E. and M.Y.; validation, W.L., X.L. and S.E.; formal analysis, W.L., S.E. and M.Y.; data curation, W.L. and M.Y.; writing—original draft preparation, W.L., X.L. and S.E.; writing—review and editing, W.L., X.L., Y.L., J.W., S.E. and M.Y.; supervision, X.L., J.W. and S.E; project administration, W.L., X.L., Y.L., J.W. and S.E.; funding acquisition, X.L., S.E., J.W. and Y.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Natural Science Foundation of China (71932009), National Natural Science Foundation of China (72272140), and EPSRC Centre for Innovative Manufacturing in Industrial Sustainability (EP/I033351/1).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

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