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Beyond prototyping: mapping the relative advantages of adopting additive manufacturing for industrial production

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ABSTRACT

Additive Manufacturing (AM) offers significant potential for product and process transformation due to several Relative Advantages (RA) it holds over Traditional Manufacturing (TM) for low-volume industrial production. However, its adoption levels have fallen short of expectations, due to insufficient understanding on how to leverage combinations of its RAs in different applications and supporting contextual factors. This paper investigates the RAs influencing AM adoption decisions for low-volume industrial production. We qualitatively explored AM adoption decisions of 18 low-volume applications across Aerospace, Automotive, Power Generation, Rail and Marine sectors. We contribute to the AM adoption literature by developing two frameworks. The first framework identifies 11 key sources of RAs which contribute to product performance, process cost and process speed, within a set of four contextual factors, partly explaining the underlying logic guiding adoption decisions. We elaborate on Diffusion of Innovation theory, through specification of the RA construct by enriching it with empirically grounded sub-dimensions and contextual factors for more accurate predictions of managers' intention to adopt AM. The second framework defines seven types of adoption decisions to explain the RA rationale for adopting AM for industrial end-use components. Our framework offers managers a guide for manufacturing strategy decisions for low-volume components.

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Additive manufacturing; 3D printing; adoption; relative advantage; low-volume production; innovation diffusion

1. Introduction

Additive Manufacturing (AM) offers several Relative Advantages (RA) over Traditional Manufacturing (TM) for product and process transformation, including design freedom, product function optimisation, tool-elimination, small economical batch production, and Supply Chain (SC) simplification (Khajavi, Partanen, and Holmström 2014). These RAs have transformed AM from a mere prototyping technology into one that is viable for producing industrial end-use components. AM RAs have been exploited to various degrees in notable low-volume production applications, such as environmental control system ducting from Boeing (Khajavi, Partanen, and Holmström 2014), gas turbine burners from Siemens (Kandukuri et al. 2021), titanium brackets from Airbus (Friedrich, Lange, and Elbert 2022), and hearing-aid shells and hip-cups in healthcare (Sandström 2016). Whilst it is evident that these RAs impact organisations' decisions to adopt AM (Schniederjans and Yalcin 2018; Yeh and Chen 2018), the specific combination of RAs influencing those decisions remains unclear for the vast majority of production applications (Jimo et al. 2022). Developing a meaningful understanding of these RAs is essential for potential adopters to reduce uncertainty and facilitate adoption and diffusion of AM in industry. RA is an influential construct historically employed in innovation studies to identify the unique characteristics of an innovation that drive potential adopters to utilise it in achieving specific goals. It represents the extent to which an adopter views an innovation as having a performance advantage over previous methods of performing a task (e.g. robotics improving speed and cost of manufacturing processes and AM facilitating complex designs). It is a key construct in the Diffusion of innovation theory (DOI) (Rogers 2003), which enables researchers to understand the spread of innovations through a social system.

According to DOI, AM RAs are expected to catalyse its adoption in different industries; however, adoption levels remain far below anticipated levels, limiting its performance impact on operations (Jimo, Chandran, and Jayasekara 2023; Munsch et al. 2024). This shortfall has been partly attributed to: (a) the diverse range of RAs associated with AM due to its multi-dimensional nature, encompassing both product and process aspects, which complicates the assessment of its suitability for specific industrial contexts (Jimo et al. 2022); (b) the lack of

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clarity on how these RAs can be effectively leveraged in various contexts (Baumers et al. 2017; Thomas-Seale et al. 2018). In terms of their range, product-related RAs are well established in the AM adoption literature. For example, design freedoms facilitate complex geometries and lightweight structures for the medical and aerospace industries (Petrovic et al. 2011). Process-related RAs are often stated in generic terms and broadly applicable across various stages of the product life-cycle (e.g. prototyping, tooling, production etc.) as reflected in sampling data of studies applying the construct (Handfield et al. 2022; Schniederjans and Yalcin 2018). In terms of clarity to leverage RAs in different contexts, past research typically lacks the specificity and contextual detail required to demonstrate AM's particular applicability to industrial production (Cantini et al. 2024; Jimo et al. 2022). Existing qualitative research has attempted to refine these AM RAs specifically for industrial production, however insights are fragmented across different contexts. Consequently, extant research has not sufficiently examined the interplay between combinations of RAs and relevant TM contextual factors that define the conditions for adopting AM for low-volume industrial components (Cantini et al. 2024; Chaudhuri et al. 2019; Naghshineh 2024). Additionally, the literature lacks a clear identification of the different sources associated with RAs, and contextual factors that create these sources. Overall, the AM management literature lacks a holistic framework for evaluating the suitability of adopting AM for low-volume industrial production (i.e. component/product and spare parts production) based on the technology's performance-related attributes. This shortcoming hinders the diffusion potential of AM within the industry (Jimo et al. 2022; Patil et al. 2022; Ronchini, Moretto, and Caniato 2023). Therefore, this paper attempts to address these gaps through the following research questions:

RQ1: What are the key sources of relative advantages, contextual factors and interplays that shape AM adoption decisions?

RQ2: What combination of relative advantages and contextual factors influence AM adoption decisions for different low-volume industrial end-use components?

RQ1 aims to identify sources of RAs for AM and supporting contextual factors to explain the underlying logic behind adoption decisions. RQ2 aims to identify the relevant combination of RAs that influence AM adoption decisions and define types of low-volume production applications that AM supports. The focus on production applications is necessary for theory elaboration, specifically to refine the RA construct so it more accurately captures the characteristics of adoption for low-volume industrial production, thereby enhancing its ability to predict AM adoption using DOI (Fisher and Aguinis 2017). A qualitative approach, relying primarily on semi-structured interviews and thematic analysis, was adopted to explore the RA dimension across a range of low-volume industrial AM applications. Our sample consists of applications in Aerospace, Automotive, Power Generation, Rail and Marine sectors to provide a more focused understanding of RAs in the low-volume production domain, unlike existing studies which also consider high-volume production (Huang et al. 2021; Patil et al. 2022).

Our study's main objective is to investigate the RAs influencing AM adoption decisions for low-volume industrial production. This study makes three key contributions to the AM adoption literature. First, we address the fragmentation issue in the AM adoption literature by developing a framework which identifies key RA sources and links them to relevant contextual factors, some of which are lacking in the extant literature. This helps explain the underlying logic guiding AM adoption decisions. Secondly, in the form of our first framework, we elaborate theory through construct specification, by enriching the RA construct with empirically grounded specifications of RA subdimensions and contextual factors for more accurate prediction of managers' intention to adopt AM with DOI in the production and aftermarket domain (Fisher and Aguinis 2017). Thirdly, we developed a second framework that explains seven types of AM adoption decisions based on specific combinations of RAs, emphasising their interactions and the contextual factors relevant to low-volume industrial applications. We mapped out different classes of low-volume industrial components suitable for AM. Our study enhances the theoretical foundations of AM adoption, for production researchers to generate further insights about the diffusion of AM in different industries.

The remainder of the paper is organised as follows. Section 2 reviews the AM adoption literature, which follows exploratory and theory-testing approaches respectively. Section 3 presents the qualitative methodology adopted. Section 4 details the analysis and findings synthesised with existing literature and presents a framework for AM adoption. Section 5 discusses the theoretical and practical implications of the study. Section 6 concludes with a summary of the study and outlines limitations and future research directions.

2. Literature review

The introduction of AM for industrial production (Khajavi, Partanen, and Holmström 2014) has increased the curiosity of researchers on the factors which influence adoption decisions of organisations. This has led to the development of the AM adoption literature, which is subdivided into the exploratory and theory-testing streams. We discuss the contributions of these streams below in order to establish the relevant gaps.

2.1. Exploratory studies on AM adoption

In the early days of AM management investigation, researchers applied exploratory approaches to understand factors driving AM adoption for various industrial applications. Mellor, Hao, and Zhang (2014) conducted a single case study on a manufacturing organisation exploiting the design freedoms in AM to produce lighter components for aerospace. Through case studies, Rylands et al. (2016) demonstrated how two MSMEs used design freedoms in AM to create complex geometries and durable components to compete with customised offerings. Sandström (2016) investigated how AM enabled hearing-aid manufacturers to eliminate manual production processes and produce higher quality products at reduced cost and lead times, whilst meeting personalisation requirements of customers. Beltagui, Kunz, and Gold (2020) investigated how 3D printing facilitates open design and production of mobile phone accessories, social sustainability being a major driver for adoption. In construction, Adaloudis and Bonnin Roca (2021) investigated how AM provides a solution to skilled labour shortage problem in central and northern Europe, reducing labour costs and increasing productivity, making economic benefits the primary motivation for adoption. Ronchini, Moretto, and Caniato (2023) conducted 10 case studies in various industries demonstrating how design freedoms with AM enabled manufacturers to make products with enhanced functionality and aesthetics, meeting customisation requirements and supporting differentiation strategies. However, the study found no process or SC-related benefits associated with AM adoption. Dhir et al. (2023) explored AM adoption in large and small firms and identified four facilitators influencing AM adoption: agility, versatility, efficiency and effectiveness, strategic leverage and sustainability; however, there was no clear delineation of the application context. Haug et al. (2023) developed a model to show the importance of organisational maturity in realising AM adoption benefits in terms of quality, cost and time. Peron et al. (2025) conducted a Delphi study in various sectors showing the importance of design flexibility in AM for customisation and lightweight components, as well as scope for SC simplification and spare parts provision for ageing products. Priyadarshini et al. (2023) conducted a systematic literature review of AM in the health sector and summarised adoption benefits into 6 categories (time, cost, performance, sustainability, human resource management and customer-oriented benefits) at various stages of products' lifecycle. Through a systematic literature review, Naghshineh (2024) identified AM's critical role in enabling a wide product range, customisation and shortened lead time in the production phase.

These studies are summarised in Table 1 in terms of application, drivers of adoption and contextual factors. Whilst this is not an exhaustive list of exploratory AM management research, collectively they highlight the context-dependent nature of AM adoption decisions based on the alignment of performance-related attributes of AM with industry and market conditions. The dominant AM adoption drivers are product-centred, aiming to create a wide variety of products for personalised markets (for instance, in the case of medical products), and also to reduce lifecycle costs through lightweighting (for instance, in the aerospace and automotive industries). Process-related drivers such as SC simplification and lead time reduction appear to exist in sectors with complex assemblies such as Aerospace and Automotive. These sectors also provide opportunities for spare parts provision with AM for ageing products as opposed to the medical sector where there is appetite for new products to guarantee patient safety (Peron et al. 2025). Cost reduction opportunities exist for AM in labour-intensive applications in medical and construction, especially where labour shortages exist (Adaloudis and Bonnin Roca 2021). Sustainability dimensions, which are least mentioned, exist in open-design for consumer markets, bio-materials and distributed manufacturing for medical products (Beltagui, Kunz, and Gold 2020; Priyadarshini et al. 2023). According to DOI theory, these performance-related attributes of AM usually reflect the degree to which AM is perceived as superior to traditional manufacturing or its RA and influences the adoption intention of managers (Rogers 2003, 229). However, the existing fragmentation in the adoption literature makes it difficult to delineate the specific sets of RAs that are suited to particular application contexts (Fisher and Aguinis 2017), which remains a major research gap and challenge for further adoption of AM in practice.

2.2. Theory testing studies on additive manufacturing adoption

Management research has a longstanding tradition of applying innovation theories in identifying factors which influence adoption decisions of emerging technologies by organisations. The same approach has been adopted in the AM context to understand why different entities are adopting the technology. These theories differ in terms of

Table 1. AM adoption drivers and contextual factors.

Reference	Methodology	Industry Application	AM Adoption drivers	Contextual factors
Mellor, Hao, and Zhang (2014)	Qualitative case study	Rapid prototypes, aesthetic models, low volume components for Aerospace, automotive, medical	Design freedom and lighter parts	Unstable market
Rylands et al. (2016)	Qualitative case study	Filter and tool production	Complex geometries, durability, agility	Competitive pressures, batch production environment, customisation
Sandström (2016)	Qualitative case study	Medical devices/Hearing aid	Enhanced quality, cost and time-consuming manual labour reduction.	Stable and consolidated industries, low-bargaining power of buyers and high prices
Beltagui, Kunz, and Gold (2020)	System dynamics	Mobile phone accessories/ Electronics	Facilitates open design, social sustainability	Aftermarket customisation, innovative customers
Adaloudis and Bonnin Roca (2021)	Qualitative interviews	Construction	Labour cost	Automation and skilled Labour shortages.
Dhir et al. (2023)	Qualitative open-ended essays	Small Scale Enterprises (SMEs) and Large Scale Enterprises	Agility, versatility, efficiency and effectiveness, strategic leverage, and sustainability-orientation	Firm size, Variances in outcomes
Ronchini, Moretto, and Caniato (2023)	Qualitative case study	Rapid manufacturing, prototyping and tooling/ Oil and gas, aerospace, medical, industrial production, automotive	Enhanced product functionality (weight reduction) and design freedom	Customisation, differentiation strategies
Peron et al. (2025)	Structured Literature Review and Validated Delphi Study	Medical, aerospace and automotive sectors	Aerospace, medical and automotive – Design flexibility. Aerospace and automotive – Simpler Supply Chains, parts consolidation, Spare parts provision for aging products, repair	Customisation, light components, complex SCs.
Priyadarshini et al. (2023)	Structure Literature Review	Health sector	Time, cost, product performance, design, sustainability, ethical, customer oriented	Personalisation
Naghshineh (2024)	Structure Literature Review	Not context specific	Wide product range, customisation and shortened production lead time	Not context specific

the dimensions of technology adoption drivers that are tested for relevance, however there are some similarities between dimensions (e.g. relative advantage and performance expectancy) (Schniederjans 2017). Dimensions captured by these theories include attributes of the innovation in question, individual users, organisations and industries. Collectively, the values of these dimensions assist researchers in understanding the conditions which lead to the adoption of a particular innovation, because of their influence on adoption intentions of managers (Schniederjans and Yalcin 2018). In a consumer context, Wang et al. (2016) applied DOI theory and Technology Acceptance Model to investigate 3D printing adoption, concluding that perceived ease of use, usefulness, enjoyment and compatibility significantly influenced adoption decisions of users of 3D printers in China. Calli and Calli (2020) applied the Technology Acceptance Model and determined that personal innovativeness of 3D printer owners significantly affects their intention to use, distinguishing them from non-owners who are motivated by perceived ease of use and enjoyment.

In an industrial context, Schniederjans (2017) applied DOI and Unified Theory of Acceptance and Use of Technology to manufacturing companies in the US to determine that RA, performance expectancy, compatibility and facilitating conditions were key AM adoption drivers; however, 74% of the organisations in the sample used AM for prototyping and demonstration purposes. Schniederjans and Yalcin (2018) reached similar conclusions by applying Unified Theory of Acceptance and Use of Technology, Diffusion of Innovation, Institutional theory, Technology Acceptance Model and Theory of planned behaviour on adoption drivers, adding perceived usefulness, social and coercive pressures as significant adoption drivers; again 76% of companies in the sample used AM for prototyping. Yeh and Chen (2018) explored AM adoption decisions in Taiwanese manufacturing enterprises using the Technology-Organisation-Environment-Cost framework, concluding that cost (material, machine, software) was the most critical factor influencing adoption decisions, as well as RA, top management support, competitive pressures and market trends. Tsai and Yeh (2019) surveyed Taiwanese manufacturers, applying Technology-Organisation-Environment frameworks and rough set theory, reaching similar conclusions namely environment, technology, cost and organisation being significant AM adoption drivers. Using system dynamics and DOI theory, Kunovjanek and Reiner (2020) concluded that AM's RA in reducing raw material inventory by 4% would enhance diffusion rates in different industries. Handfield et al. (2022) applied Rogers and Shoemaker's technology adoption framework to a small sample of Canadian manufacturers concluding the RA of AM is the most crucial in adoption decisions, as well as compatibility, complexity, trialability and observability. Using institutional theory, Ukobitz and Faullant (2022) also emphasised the importance of technological attributes in adoption decisions by highlighting the mediating role of AM's perceived value between isomorphic pressures and adoption intentions of Mexican footwear manufacturers. Using Technology-Organisation-Environment-Cost frameworks and Technology Acceptance Model, Almahamid et al. (2022) concluded that technological usefulness and ease of use are critical for adoption decisions for stakeholders in the gulf region, albeit with a very small sample size.

A summary of these studies is provided in Table 2 to highlight the theoretical orientations, methodological approach, sampling considerations and pertinent AM adoption drivers. DOI has the highest prevalence across studies whether used as a standalone or in combination with other theories. The studies show a significant reliance on the innovation characteristics, specifically as relates to its performance-related attributes (i.e. RA, performance expectancy, perceived usefulness etc.) as dominant predictors of AM adoption. However, the specifications of these constructs apply to generic advantages of AM across the manufacturing lifecycle (See appendix A for existing specifications of AM performance attributes). To improve the predictive efficacy of these constructs for industrial production applications, construct refinement is needed to accurately reflect AM's relative advantages in reality (Fisher and Aguinis 2017).

2.3. Theoretical framing

The preceding review shows the salience of performance-related innovation attributes of AM in predicting the adoption decisions of managers. These decisions usually involve evaluation of innovation capabilities against other existing alternatives. RA from DOI theory adequately captures this attribute, as it expresses the degree to which AM is perceived as being superior in performance to TM (Rogers 2003, 229). Therefore, the higher the RA of

Table 2. Theory testing studies in Additive Manufacturing adoption.

			Adoption Drivers						
			Innovation				Organisational	External/Environment	
Reference	Application context	Theory	RA, PE, PU, PV	Complexity, EE, PEOU, PBC	Trialability, Observability	Perceived enjoyment,PI	Compatibility, Facilitating conditions	Social influence, Normative pressures	Mimetic, Coercive pressures
Schniederjans and Yalcin (2018)	76% prototyping applications	DOI, IT, TAM, TPB, UTAUT	✓					✓	✓
Schniederjans (2017)	74% prototyping and demonstration; 10% finished parts	DOI, UTAUT	✓				✓		
Wang et al. (2016)	Home 3d printing	TAM and DOI	✓	✓		✓	✓		
Calli and Calli (2020)	Home 3d printing	TAM	✓			✓			
Kunovjanek and Reiner (2020)	Not clearly specified	DOI	✓						
Handfield et al. (2022)	60% production, 40% prototyping	Technology adoption framework	✓	✓	✓				
Ukobitz and Faullant (2022)	Not clearly specified	Institutional theory	✓					✓	✓
Almahamid et al. (2022)	Not clearly specified	TOEC & TAM	✓	✓					
Yeh and Chen (2018)	Not clearly specified	TOEC	✓						✓
Tsai and Yeh (2019)	Not clearly specified	TOE	✓						

Note: **Key**: RA: relative advantage; PE: performance expectancy; PU: perceived usefulness; PV: perceived value; EE: effort expectancy; PEOU: perceived ease of use, PI: personal innovativeness.

AM compared to TM, the higher its likelihood of being adopted by potential users in different contexts (Rogers 2003). RA more accurately reflects the emphasis on relative performance of two technologies, as opposed to other constructs (e.g. performance expectancy and perceived usefulness), which focus on the intrinsic performance of the emerging innovation (Schniederjans 2017; van Oorschot, Hofman, and Halman 2018). It therefore represents the principal construct in this study. RA has featured in past AM adoption literature, however the studies have shortcomings which affect their efficacy in predicting AM adoption for industrial end-use components. Firstly, samples in the theory-testing studies are not focused on industrial production of end-use parts. Some study samples lack clear statistics on the kind of AM applications (Almahamid et al. 2022; Tsai and Yeh 2019; Ukobitz and Faullant 2022; Yeh and Chen 2018); some are consumer applications (Calli and Calli 2020; Wang et al. 2016), others possess this information but are a mixture of prototyping, customer demonstration and production applications (Handfield et al. 2022; Schniederjans 2017; Schniederjans and Yalcin 2018). This is reflected in the specifications of the RA construct in most studies, which do not reflect the specific use of AM for industrial production (Fisher and Aguinis 2017). For example, specifications of RA in existing studies refer to the use of AM to improve employee productivity, prototyping, design validation, speed of product introduction etc. (refer to appendix A). Application of these formative dimensions in theory-studies could provide misleading insights about diffusion of AM into mainstream production, where it has promised much potential for process transformation (Diamantopoulos and Winklhofer 2001). On the other hand, the exploratory approaches are able to tease out contextual factors around AM adoption, however, these insights are fragmented across application contexts. Collectively, both literature streams lack holistic framework, which explains the combination of RAs that influence adoption decisions for different industrial applications, the sources of these RAs and associated contextual factors (Jimo et al. 2022; Patil et al. 2022; Ronchini, Moretto, and Caniato 2023). Therefore, by means of the two research questions presented in the introduction, we seek to address these gaps by generating empirical details to refine the RA construct for DOI theory in the context of industrial AM (Fisher and Aguinis 2017). Consequently, the study focuses on the innovation-attribute dimension of DOI, and does not cover other aspects of adoption in DOI such as the innovation process, adopter categories and communication channels, which are beyond its scope.

3. Methodology

3.1. Research approach

Our research explored 18 industrial AM applications where the technology was used to produce end-use components to specifically investigate RAs associated with production, distinguishing it from earlier approaches that included prototyping in the study sample (Handfield et al. 2022; Schniederjans 2017). A qualitative approach was employed to elaborate on the RAs of adopting AM and associated contextual factors in a production context, in line with our RQs (Bryman 2015; Miles 2019). This approach enables the isolation of relevant adoption factors related to AM's RAs to facilitate construct refinement for theory building (Fisher and Aguinis 2017). Qualitative approaches are suitable for investigating phenomena in emerging contexts where theoretical foundations are developing (Flick 2018; Meredith 1998). Our qualitative approach relied primarily on semi-structured interviews to build evidence of factors surrounding AM RAs for low-volume industrial production. These interviews were complemented by other secondary sources, including company websites, online case studies, project directories, and company brochures, which provided information about respective industrial applications (Miles 2019). These applications involved the use of AM to make components, which were formerly produced with TM, for assembly and maintenance and repair operations (MRO). This approach enabled us to identify and group the key themes related to individual AM adoption decisions. The unit of analysis of our study is the AM adoption decision associated with particular low-volume production components (Mena, Humphries, and Choi 2013). We deliberately excluded prototyping applications from our study because we were interested in decision criteria for industrial end-use production in-line with our research objectives (Delic and Eyers 2020).

3.2. Study sample and data collection

A purposive sampling approach was applied, focusing on organisations that had adopted AM for production of components for assembly and MRO (Curtis et al. 2000). This sample was adopted in order to enhance construct validity and extend theoretical insights on AM's RA for producing end-use components (Voss 2010). Participating organisations were recruited through a range of channels including cold-calling, linkages with academic colleagues in foreign institutions and attending conferences and tradeshows. The largest number of leads was generated by attending tradeshows and workshops in the UK dedicated to AM. Deliberate efforts were made to target suppliers and focal firms adopting AM, to enable exploration of their adoption decisions by discussing with company representatives at presentations and product stands. Furthermore, snowball sampling was applied at these events for links to other manufacturing cluster organisations and AM companies (Bryman 2015; Guba and Lincoln 1994).

Overall, this process generated a sample of 18 applications in 18 organisations. 13 organisations used AM for batch production, 4 for spare parts production and 1 for repair. Their applications were driven by several metal and polymer AM processes which occupy a sizeable portion of the market. The processes include Selective Laser Melting (SLM), Fused Deposition Modelling (FDM), Directed Energy Deposition (DED) and High Speed Sintering (HSS) (Durach, Kurpjuweit, and Wagner 2017). Most organisations in our sample are located in countries that are significantly advanced in AM development (i.e. UK, USA and Germany). Convenience sampling was used to include 2 companies from India as the authors had access through engagements on another research project. These organisations are represented by pseudonyms to mask their identities. Data collection was primarily based on semi-structured interviews with company respondents across organisations. Snowballing was applied from initial interviews to generate additional leads in respective organisations, where possible, to enhance construct validity (Bryman 2015). Triangulation was achieved through interviews with multiple respondents in each organisation and secondary sources including company websites, online brochures and case studies (Langley and Abdallah 2011). Respondents were selected specifically because of their knowledge of AM adoption for respective applications and ranged from top-level, mid-level management and junior level employees (Curtis et al. 2000). The interview protocol was underpinned by an exploratory orientation of technology adoption theory i.e. seeking to uncover RAs of adopting AM without prior specification of theoretical dimensions (Bryman 2015). This protocol was piloted in four organisations that were in early stages of AM adoption, between August and December 2018, after obtaining approval from an ethical review committee. Subsequently, data collection in the 18 organisations, included in our sample, was conducted between January 2019 and March 2022.

A total of 24 interviews, lasting between 1 and 2 hours, were conducted via face-to-face meetings (13), Skype (8) and telephone calls (3). All interviews were voice-recorded after obtaining informed consent from participants. Respondents were asked to explain the background of AM adoption in their organisations and motivations for selecting the technology for a particular component (see Appendix A for a detailed interview protocol). Some organisations provided samples of the subject components, during interviews, providing the opportunity to confirm elements of adoption elicited during interviews to enhance construct validity (Voss, Tsikriktsis, and Frohlich 2002). In addition, company websites, brochures and online case studies were drawn upon as secondary data sources to triangulate interview data (Creswell and Miller 2000). A summary of the organisations, including respective sectors, location, application type, AM process type and data sources are provided in Table 3.

3.3. Data analysis

Interviews were transcribed using QSR NVivo Pro 12, providing an initial opportunity to understand the data and generate tentative themes which supported detailed analysis in subsequent stages (Miles 2019, 74). For example, data transcription enabled detection of RAs and associated contextual factors of applications, which aided generation of initial themes. A database was maintained on NVivo Pro 12 to store interview recordings, transcripts, email communications, online case studies in readiness for data analysis to enhance reliability. Secondary sources were analysed to triangulate interview data in terms of AM's RA, to further enhance construct validity (Eisenhardt 1989). Thematic analysis was conducted on the interview data, to generate the relevant themes that explained the RA dimensions and contextual factors influencing AM adoption decisions (Braun and Clarke 2006). The coding of the interview data was done in two rounds. The first round involved coding of RAs influencing AM adoption decisions, according to the definition of DOI, and contextual factors associated with those decisions (Rogers 2003). These extracts were coded to nodes on NVivo Pro 12 as descriptive codes. This first-order analysis involved compressing data into brief phrases that were salient to answering our RQs. This resulted in the generation of first order codes for RAs and contextual factors. As we coded the RAs and contextual factors, we discovered that some informant terms (e.g. lightweighting for light parts, manufacturing complexity for simpler SCs) were not cited verbatim in the literature, however, they were adopted because they more accurately reflected the purpose of the research questions (Patil et al. 2022). In other cases, informant terms were cited verbatim in literature (e.g. durability, repair) and were adopted. This iterative process enabled us to ground emerging concepts in the literature (Gioia, Corley, and Hamilton 2013). Subsequently, pattern coding was used to categorise related descriptive codes into sub-themes, which represent the different RA sources

Table 3. Study sample.

Company	Employees	Sector	Country	Application Type	AM Process	Interview Duration	No. of Interviewee(s)	Secondary Sources
Aero1	< 500	Aerospace	UK	batch production	SLM	120mins	2 – Head of strategy (HS), Project Engineer (PE)	Company website, online case study
Aero2	< 500	Aerospace	UK	batch production	EBM	131mins	2 – Principal Research Engineer (PRE), Lead Transformation Advisor (LTA)	Company website, online case study
Aero3	< 200	Aerospace	UK	Spare-part production	SLM	105mins	1 – Additive Manufacturing lead (AML)	Company website, project directory
Aero4	< 50	Aerospace	India	batch production	SLM	80mins	2 – CEO, Partner	Company website, online case study
Aero5	< 100	Aerospace	UK	batch production	HSS	90mins	1 – R&D Engineer (R&DE)	Company website
Aero6	< 12,000	Aerospace	USA	batch production	SLM	165mins	3 – Additive Manufacturing Manager (AMM), Director of Advanced Manufacturing (DAM), Senior Engineer (SE)	Company website
Aero7	< 300,000	Aerospace	UK	batch production	EBM	80mins	1 – Lead Materials and Process Engineer (LM&PE)	Company brochure
Aero8	< 10,000	Aerospace	UK	Spares	SLM	97mins	1 – Materials and Process Engineer (M&PE)	Company website
Auto1	< 10,000	Motorsport	UK	batch production	SLM	80mins	1 – Principal Engineer (PE)	Company website
Auto2	< 100	Motorsport	UK	batch production	SLM	160mins	2 – Technology Director (TD), Manufacturing Development Lead (MDL)	Company website
Auto3	< 11	Motorsport	UK	batch production	EBM	80mins	1 – Managing Director (MD)	Company website, manufacturing process brochure
Auto4	< 10,000	Automotive	Germany	batch production	SLM	95mins	1 – Program Manager, Additive Manufacturing (PMAM)	Company website
Auto5	< 10,000	Automotive	UK	Spare-parts production	FDM	80mins	1 – Senior Engineer (SE)	Company website
Power1	< 500	Nuclear Power Generation	UK	Repair	DED	105mins + plant tour	1 – Additive Manufacturing Lead (AML)	Company website
Power2	14,000	Power-Generation	Germany	batch production	SLM	86mins	1 – R&D Engineer (R&DE)	Company website
Power3	< 400,000	Power-Generation	Germany	Spare-parts production	SLM	116mins	2 – VP Additive Manufacturing, (VPAM), Business Development Officer (BDO)	Company website
MarineCo	< 10,000	Marine	Netherlands	Spare-parts production	D.E.D.	120mins	1 – Project Engineer (PE)	Company website, online case study
RailCo	< 1000	Rail	UK	Spare-parts production	FDM	76mins	1 – VP Consulting	Company website

influencing adoption decisions and contextual subfactors (Saldaña 2021). Lastly, axial coding was employed to identify the relationships between contextual subfactors and RA sources. These sub-themes were aggregated into higher-level RA and contextual factors, which represent the focal points of AM adoption decisions. The same process was repeated for all interviews in each organisation. The nodes on NVivo Pro 12 facilitated the clustering of related themes across applications (Miles 2019). In our analysis section, we discuss this RA sources and the contextual factors which generate them on the product and process level. Subsequently, we develop an AM adoption framework, clustering AM applications into seven decisions based on their combination of RAs and supporting contextual factors.

4. Analysis

A theoretical structure emerged from the rounds of data analysis to explain the RAs which influence AM adoption decisions and associated contextual factors. Table 4 displays how the second-order RA dimensions emerged from the interview data. These second-order themes represent the different sources from which AM's RA can be derived, based on the specific production application characteristics. For example, lightweighting and manufacturing complexity represent opportunities for AM to generate RAs compared to TM from a product and process perspective respectively. These RA sources are dependent on the existence of a set of contextual conditions in the TM context to make AM viable for adoption. Table 5 displays how the contextual subfactors were derived from the interview data as second-order themes. Axial coding revealed the linkages between the contextual subfactors and RA sources. The values of these contextual subfactors in the TM context determine its potential to serve as a source of RA for AM. For example, a high part/joint count in a TM component represents an opportunity to generate multiple RAs with AM through lightweighting, durability and manufacturing complexity. These relationships between RA sources and contextual factors, as derived from axial coding in Table 5 and summarised in Table 6.

4.1. Overview of relative advantages and related contextual factors

The RA sources are consolidated into product and process dimensions namely: Product performance, Process Cost and Process Speed. The analysis of 18 low-volume production applications reveals that the primary motivations of managers for adopting AM are associated with these three RAs, which can be generated via a range of sources. They represent the degree to which AM surpasses TM in product and process performance, thereby positively influencing managers towards adopting AM. The potential for AM to generate RAs from these sources is dependent on product/service, demand, supply-side and technological/process conditions (Table 5) which exist in the subject TM context. Product performance was the most dominant RA, making up one of the adoption motivations for 15 out of 18 applications; followed by process cost and process speed, which formed one of the adoption motivations for 10 out of 18 applications each. 11 adoption decisions were influenced by a combination of two RAs, 5 by one RA and 2 applications involving the combination of all three. The following subsections present the findings of the analysis of these product and process RAs and contextual factors.

4.1.1. Product performance relative advantages

There was a clear rationale for manufacturers to extend the performance frontiers of their products by deploying design and manufacturing capabilities of AM. A common rationale for adopting AM by most manufacturers was its RA in producing complex geometries, which are impossible with TM. With TM, the performance of components is heavily constrained by the manufacturing process, however AM created scope to enhance component performance and by extension, the products they are part of. This view was expressed by respondents from organisations involved in Aerospace, Power-Generation and Motorsport applications (Aero1, Aero2, Aero8, Aero 6, Auto1, Auto2, Auto3, Power1, Power2) which demand high performance and are usually considered high-value. '*With the current manufacturing techniques, you can be quite limited to shape. With 3D printing, you could create very different shapes of your overall heat-exchanger*' (MDL, Auto1). '*Some of those geometries, you can make with additive, it's not possible to do with conventional machining*' (AMM, Aero6). '*In this particular case, the idea was, by additive you can design it in a way you never would be able to do it with conventional*' (VP, Power 2).

By pushing the boundaries of design through AM, our analysis reveals several product-performance RAs, which organisations are able to achieve in comparison to TM, namely: lightweighting, durability, volume maximisation and energy savings. These are discussed in the following subsections.

4.1.1.1. Lightweighting. Through geometric freedoms and part-consolidation, AM is capable of fabricating components that deliver superior performance over the product's lifecycle in service (e.g. aircrafts, vehicles).

Table 4. Illustrative evidence of relative advantage sources.

Illustrative quotes	1st Order Codes	Sub-theme – 2nd Order Categories: Relative Advantage sources	2nd Order Themes: Relative Advantage
'The AM part is lighter and less complex than the original. You don't have the different bits that are put together through honeycomb and metal sheets.' (M&PE, Aero8)	Reduced complexity makes part lighter	Lightweighting	**Product Performance**
'The old design is traditionally made for stamping. The new AM part is topologically optimised and was 75% lighter.' (PMAM, Auto4)	New design made part lighter		
'The AM propeller is harder, stronger, tougher than the casted one, which eventually gives us a longer life.' (Project Engineer, MarineCo)	Stronger part than the former	Durability	
'For life extension, it's a case of using AM. It allows you to take a part that has been in service for a long time and upgrade it.' (AM Lead, Power1)	Extended lifetime		
'The original part was more of a consumable part, so there were lots of spares stored, whereas, the new and the AM one is much more robust, you can keep fewer stored, you need less replacement parts' (M&PE, Aero8)	Durable parts reduce inventory-holding requirements		
'It wasn't maximising the volume, so we used AM to improve the component's size.' (PE, Aero1)	Improved component dimensions to utilise space	Volume maximisation	
'With swirling channels, you can have internal features, which create turbulence and boosts performance leading to a smaller part.' (PE, Auto1)	Complex design to reduce component size		
'AM allows us to design a filter that filters without increasing the pressure drop, optimising energy use.' (R&DE, Power2)	Designs to optimise energy use	Energy savings	
'AM allowed us to generate features that gave us better heat exchange for less pressure drop.' (MDL, Auto2)	Design features for energy optimisation		
'It's quite a number of bits that need to be assembled. It's the labour hours of the assembly really that we are trying to get away from by using AM.. you've got to assemble it by hand which obviously takes quite a lot of labour and labour is quite expensive' (LM&PE, Aero8)	Using AM to reduce assembly, labour and costs	Manufacturing complexity reduction	**Process Cost**
'We improved it with more complex AM designs, fewer components, manufacturing steps, and actually reduced costs.' (R&DE, Power2)	Reduced production complexity reduces cost		
'The interest in using AM was for hard-to-reach places, sections of components that would usually be avoided. You scrap it for that reason.' (AML, Power1)	Overcome inability to repair	Repair	
'There was a high replacement rate of tool sleeves. *In some cases where they can be bought individually, it is prohibitively expensive. They are just plastic hollow cylinders that we print without support material.' (SE, Auto5)*	Repair to reduce cost of replacement		
'It was cheaper with AM. Because there was no tooling investment involved, in the automotive industry, it is often the case that the customer pays for the stamping tools. This was a part for Rolls-Royce in the very low volume segment, a very small number of parts per year.' (PMAM, Auto4)	No tooling enables small volume production and cost reduction.	Tool elimination	
'*You can look at this in various ways; value to our customers through performance improvement, cost savings, repairability, less logistics and maintenance burden, as parts don't get damaged as often.' (M&PE, Aero8)*	Reduced inventory burden and costs	Inventory reduction	
'they are keen on how AM can be used to alleviate some of the issues that they have with massive stock pile of parts. Having a stock pile of parts means you've locked down a lot of real estate, space as well as resources locked down, in those spaces. Obviously the material costs and initial investments to even make those parts in the first place. Is all been tied up, usually for a long time and majority are never used at all. So you have that massive economic impact' *(PR, MarineCo)*	Reduced inventory requirements with AM and costs		
[For Traditional Manufacturing] *'We have issues with pure availability. If it was a casted component and the casting house got burned down, we have a six-month wait to get parts.' (AML, Aero3)*	Overcome risk of unavailability	Supply Risk	**Process Speed**
'AM was considered because there was virtually no stock available for a legacy component. We had a real long legacy product where not only does nobody know where the tool even is, nobody even knows who the original manufacturer was … that's quite common.' (VP AM, RailCo)	No legacy component stock		
'From the supply chain point of view, making the hub will be a lot quicker and easier with AM, because it is smaller than having to make a large propeller by casting.' (PE, MarineCo)	Reducing production lead times with AM compared to casting	Process lead time reduction	
'Trying to make a very complex bracket in traditional methods, e.g. casting, you are probably looking for a six-month lead time, as opposed to a few days.' (CEO, Auto3)	Long process lead times with casting		
[For Traditional Manufacturing] *'If it's an expensive material, it can be tricky to get hold of quickly. You are allowing lead time reduction with AM.' (HS, Aero1)*	Supply lead time reduction	Raw-material lead time reduction	

Table 5. Illustrative evidence of contextual factors.

Illustrative quotes	1st Order codes	2nd Order category – contextual sub-factor	Theme – contextual factor
		Part/Joint Count (High or Low)	**Product/Service Characteristics**
'It's also lighter than the original part. It's less complex because you don't have all the different bits that are put together through honeycomb and metal sheets.' (Aero8, M&PE) 'If you 3D print it as one, then you don't need all that interface to be able to bolt it. It's a single unit, so you reduce all those additional features and that effectively saves weight.' (MDL, Auto2)	Reduced part and joint count reduce weight		
'You can also improve the reliability of a component by reducing the parts count, but that's kind of less tangible than an energy reduction.' (SE, Aero6) 'One of the advantages of additive is that you can design a lot of these joining features out so that you don't have 50,000 brazed joints, you have one big fully welded part effectively.' (TD, Auto2)	Reduced part and joint count increases durability		
'The component had quite a complex assembly of parts, the reduction in part count could sort of offset that change to a slightly more expensive metal.' (LM&PE, Aero7) 'We can actually reduce the costs in the same way. Because as I said, up until now, we have 70 components. Afterwards, we have one component. Fewer manufacturing steps, short process chain and supply chain. Much simpler.' (R&DE, Power2)	Reduced part count reduces manufacturing complexity		
		Design Complexity (High or Low)	
'The problem is how to design a filter that filters all the components but without increasing the pressure drop. Because if we make a filter that only has small holes then we need bigger pumps, we lose energy.' (R&DE, Power2) 'In a perfect world, you want to take as much heat as you can with absolutely no pressure drop, but you can never get that. It's a balance and we felt that with 3D printing, we could generate some features that would give us a better balance, better heat exchange for less pressure drop.' (MDL, Auto2)	Design complexity increases energy savings		
'The longer you want it to operate, if you want 10–20 years operating life, you have to think about the durability of the parts.' (AML, Power1) [For Traditional Manufacturing] 'You bring together loads of parts together and brazing them together and what you find, therefore, is you get a lot of failures of parts, so things have a shorter life.' (TD, Auto2)	Durability drives longer lifetime and vice versa	**Lifetime (Long or Short)**	
[For Traditional Manufacturing] 'Say it's on a plane that was built 25 years ago, and they don't make that part in production. Then they literally need a one-off but the supplier that made it 25 years ago may not even exist. Even if they do, what's the odds that they've got all the stuff that they used to make it the first time, all those sorts of problems. With the age of some of the aircrafts that are flying around and the length of time they are flying around, serious issues arise around parts that are hard to source' (AML, Aero3) '3D Printing was considered because the stock holding of parts was getting to a critical level. There was virtually no stock available for a legacy component, so again, it's a spare parts application, it's an aftermarket application. You've got a real long legacy product where nobody knows where the tool is, nobody even knows who the original manufacturer was.' (VP Consulting, RailCo)	Shorter lifetime reduces supply risk		
'With topological optimisation, you could swap entirely from a metal component to a polymer one, whilst ensuring you have the same mechanical properties that are required of the application.' (R&DE, Aero5) 'Metal handles, they do have a weight penalty on an aircraft, so to turn them into polymer components will reduce the weight substantially and obviously each.' (M&PE, Aero8)	AM's lighter material reduce part's weight	**Material Type**	
'We've found that you can replace many metal components with polymer parts, using the HSS process. HSS is significantly cheaper and simpler than direct metal AM' (R&DE, Aero5)	Change of material reduces manufacturing complexity		
		Power Density (High or Low)	
'There is an increasing trend of increasing power density of aero engines, i.e. maximising space and efficiency of everything within that engine. So, you are generating more heat, and you have got to get rid of more heat, but there is less space so we are exploring ways of downsizing the heat exchanger with additive manufacturing because it allows us that design freedom to create more novel geometries and creating surface area.' (HS, Aero1) 'You can do that with the mixing, and you can do that by swirling the channels. You can have these internal features in there, which then help create a little turbulence or turn it around. That boosts the performance which can then be looking at a smaller part and a lighter part.' (PE, Auto1)	Power density requirements increase the need for volume maximisation		

(*continued*).

Table 5. Continued.

Illustrative quotes	1st Order codes	2nd Order category – contextual sub-factor	Theme – contextual factor
'We've done some research into how much a kilogram can save you in terms of space launch, and the figures range anywhere from £80 to £80,000 … Because every kilogram you have to get off the ground, you have to put fuel in to push it up.' (PE, Aero1) 'And it has huge advantages in aerospace where the cost to put an extra kilogram in the air is phenomenal. So, if we can reduce say a few grams off the bracket, we have fantastic cost-saving benefits.' (R&DE, Aero5)	Reduced weight reduces fuel costs	**Fuel Cost**	
[For Traditional Manufacturing] 'Their bill of materials (BOM) is made up of 6,000 components and there are certain 4 or 5 components that they could not produce quickly. So, their BOM gets disrupted and timelines go haywire. They are focusing on maintaining the supply chain for those components for the main subsystem to be realised.' (Partner, Aero4).	Critical parts need rapid production	**Criticality**	
'Airbus gets fined hundreds of thousands of pounds a day if a plane is broken down and their airlines have contracts. If we are not making money from the plane and it's your fault, then you are giving us that money. It's almost a cost is no object. It's about service level and lead time.' (AML, Aer03) 'You've got the situation where if we don't get these parts through manufacture, we will not have this rolling stock on the rails. And it will cost thousands and thousands of pounds a day in either lost revenue or penalties. That's why, in that particular case, the client wanted to investigate additive manufacturing.' (VP Consulting, RailCo)	High downtime costs increase the need to reduce supply risk	**Downtime costs (High or Low)**	
'The original part was more of a consumable part, so there were lots of spares stored, whereas, the AM one is much more robust, you can keep fewer stored, you need less replacement parts, so as well as being more robust and light, it decreases the burden.' (M&PE, Aero8) 'The major, reason why they shifted from 5 assembled components to one was reducing the number of subassemblies and reducing the chances of failure.' (Partner, Aero4)	High failure rate drives the need for durable parts	**Failure Rate (High or low)**	**Demand Characteristics**
'They say we need one of these and you start making one. There is no way, and that's going to be kind of the nature of it, because if you could anticipate it then, they could probably find a cheaper way of getting it done than a rapid spare.' (AML, Aero8)	Rapid production suits parts with uncertain demand	**Demand Uncertainty (High or Low)**	
'Yeah, it's the scarcity of the part and the cost of remanufacturing, using traditional manufacturing. At the end of the day, we can pretty much make anything but it is the economics of do we tool up to make these things or do we want them in relatively small volumes.' (VP Consulting, Railco) 'The component is a very very low volume segment. You can imagine how many parts that would be per year.' (PMAM, Auto4)	Very low volumes drive the need to eliminate tooling	**Volume (Low or extremely Low)**	
'The batch sizes, when we build an aircraft, we obviously, there is probably a bigger batch size. But repair and overhaul-wise, it is extremely small. I would say it depends on the number of aircraft. If it is one aircraft, then there is a handful.' (M&PE, Aero8) 'Low-volume could be repair, you could be repairing a one-off part, it could be multiple parts that came off a production line, but you only need to repair one, that's a low-volume case study, how would you repair it, you can't put it back into the line, so you have to take it out, so DED is quite useful.' (AML, Power1)	Repair demand is associated with very low volumes		
'I guess in terms of there being a lot of different components, different variants, that's a big driver, so if you have to then somehow keep those in stockpile for a long time, that's a massive investment for the company to do. Which has been pretty much the biggest driver.' (PE, MarineCo) 'Realistically, we don't need that, we need 100 sleeves or 1000 sleeves a year, whatever it is. And they might be different sizes, they might be different lengths or diameters. So, we would have to buy an individual tool for each one.' (SE, Auto5)	High variety drives inventory costs	**Variety (High or Low)**	
'Ideally, you want to swap it around, but one of them things could cost you like £100 grand or more, so if you are not able to replace it because obviously you just made this big expenditure, you still have 20 or 18 years to run and this is year 2. Because it costs a lot of money and time to get another one, you would rather repair it, so, how can you repair it.' (AML, Power1) 'They found that they had a high replacement rate of tool sleeves. There are some cases where you buy the individual sleeves, but even then, you pay a premium. They are just hollow cylinders made of plastic. And they go to Daghenam and say we can print these no problem and they don't need support material.' (SE, Auto5)	High part replacement costs drive repair	**Part Replacement Costs (High or Low)**	

'Because it was cheaper in AM. when I put in the design one by one-to-one, without AM design, it was just at the same price. But the big issue that you didn't have any investments for tools.' (PMAM, Auto4) 'At the end of the day, we can pretty much make anything, but it's the economics of do we tool up to make these things or do we want them in relatively small volumes.' (VP Consulting, RailCo)	High tooling investments drive the need to eliminate tools	**Tooling Costs (High or Low)**	
'There are things like forgings that are made in Russia, I don't know if that's a thing at the moment. So, there is political risk involved in the sourcing of parts, there is all sorts.' (AML, Aero3)	High political risk increases supply risk	**Political Risk (High or Low)**	
'Say it's on a plane that was built 25 years ago, and they don't make that part in production. Then they literally need a one-off but the supplier that made it 25 years ago may not even exist.' (AML, Aero3) 'Additive Manufacturing was considered because the stock holding of parts was getting to a critical level. There was virtually no stock available for a legacy component, so it is a spare parts application, it's an aftermarket application. the cost … so again what you've got is you've got real long legacy product where not only does nobody know where the tool even is, nobody even knows who the original manufacturer was.' (VP, RailCo)	Supplier bankruptcy increases supply risk	**Supplier Bankruptcy**	
'You are potentially allowing lead time reduction in terms of. If it's an expensive material, it can be tricky to get hold of that material quickly.' (HS, Aero1) 'One of the interesting things especially when you start looking at materials like Inconel is that you can have a six, eight, ten-month lead time from the supply chain to get the Inconel because again it's supply vs demand and the supply of it is not that high because the demand is not that high.' (AML, Aero3)	Unavailability of raw material increases lead time	**Raw Material Availability**	
'They are keen on how AM can be used to alleviate some of the issues that they have with a massive stockpile of parts, so that's been sort of the main driver.' (PE, MarineCo) 'You can look at this in three ways really, so value to our customers which should be performance improvement, cost savings, decreased delivery time on the aircraft, repairability, so parts need less logistics or less maintenance, burden are ones that are … don't get damaged as much' (M&PE, Aero8)	High inventory management costs drive the need for inventory reduction	**Inventory Management Costs (High or Low)**	
'And they have managed to scan the housing and even though you could cast it, much cheaply … the supplier could easily supply the housings, but they don't want to because of their business model. It is not worth us investing in the tools to cast the stuff, but what we can do on a one-off or two-off basis if they break in individual housing, we could just print them a new one.' (SE, Auto5) 'Using your 3D scanning capability, you can extract enough information about the repair location and issues, using your computer-aided, engineering tools for design, for CAD, CAM.' (AML, Power1)	Reverse engineering enables repair	**Reverse Engineering**	**Technological Characteristics**
'The individual bits of metal by themselves aren't very expensive with sort of simple machining, but then you have got to treat each bit of metal individually and paint it and you've got to assemble it by hand, which obviously takes quite a lot of labour and labour is quite expensive.' (LM&PE, Aero7) 'The actual traditional component is made of metal sheets and honeycomb, which effectively involves a mixture of methods including fastening, welding, additives, that kind of thing. It is also one of those things where there is a mixture of polymer and metal.' (M&PE, Aero8)	High labour intensity and manufacturing complexity	**Labour Intensity (High or Low)**	
'You would say that the full advantage would come from design change. For an actual production solution through AM, but as I said, that was more to look at, you know, as a fast option. If there were issues with lead time through casting, maybe the tooling required, they could just directly just adopt AM were necessary.' (PRE, Aero2) 'From what we've seen, if I want to have a single propeller made, from a time/cost perspective, I don't actually have metrics for you on this one, but it's going to be months vs days in additive. So that's a big step in this case. So, from the point of view, the supply chain has an opportunity to do well. Casting is great when you've got a large batch size.' (PE, MarineCo)	Slow process drives the need for lead time reduction	**Process lead time (High or Low)**	

Table 6. Causal relationships between contextual factors and relative advantage sources.

Contextual Factors	Sub-factors	Linked Relative Advantage sources
Product/Service Characteristics	Part/Joint count	Lightweighting, durability, manufacturing complexity
	Design complexity	Energy savings
	Lifetime	Durability, supply risk reduction
	Material type	Lightweighting, manufacturing complexity
	Power Density	Volume maximisation
	Fuel cost	Lightweighting
	Criticality	Process lead time reduction
	Downtime costs	Supply-risk reduction
Demand Characteristics	Failure rate	Durability
	Demand uncertainty	Process lead time reduction
	Volume	Tool elimination, inventory reduction
	Variety	Inventory reduction
Supply-side characteristics	Part replacement costs	Repair
	Tooling costs	Tool elimination
	Political Risk	Supply-risk reduction
	Supplier bankruptcy	Supply-risk reduction
	Raw material availability	Raw-material lead time reduction
	Inventory management costs	Inventory reduction
Technology/Process Characteristics	Reverse engineering	Repair
	Labour intensity	Manufacturing complexity
	Process Lead time	Process lead time reduction

Lightweighting was the most highly mentioned rationale for adopting AM amongst respondents for mobility-related applications i.e. aerospace, motorsport, automotive and marine (Aero1, Aero2, Aero4, Aero5, Aero6, Aero7, Aero8, Auto1, Auto2, Auto3, Auto4, Trans1). With lightweight components, airlines and space companies are able to reduce fuel consumption on flights and satellite launches, which is important because of expensive jet fuel. '*It's competing with the traditional spherical component. We've radically changed the design … that weight reduction allows them to increase the payload of sensors for experiments or whatever they are doing on the satellites*' (HS, Aero1). '*It's a solid metal part, but it's also lighter than the original part. It's less complex because you don't have all the different bits that are put together through honeycomb and metal sheets' (SE, Aero8).* Similarly, in the marine application, fuel optimisation was also important, therefore lightweighting benefits of AM also informed the adoption decision. '*There has been a massive push to improve efficiency through lightweighting. 1% reduction in efficiency can give you massive savings in fuel costs*' (PE, Trans1). An important application for motorsport companies was the production of heat exchangers (Auto1, Auto2, Auto3), which are high-value components containing hundreds to thousands of parts and internal channels in traditional versions. Through parts-consolidation, AM eliminates the need for joints, which results in lighter components: '*If you've got a series of parts bolted together, if you 3D print it as one, then you don't need all those interfaces. It's a single unit that effectively saves weight*' (MDL, Auto1).

4.1.1.2. Durability. The second most prominent RA under product performance was durability and this was voiced by respondents in applications across all sectors (Aero1, Aero4, Aero8, Auto2, Power1, Power3, Trans1). Here AM's capability in reducing the number of joints and failure points of components through parts consolidation increases the durability of components and their service lifetime. This benefit was realised in applications, where the TM components had high part counts. '*You are brazing loads of parts together and therefore you get lots of failure, and shorter life. With additive, you can design a lot of these joining features out, so that you don't have 50,000 brazed joints' (*MDL, Auto 1). '*The major reason for additive was to shift from 5 assembled components to one, reducing the number of subassemblies and chances of failure*' (Partner, Aero4). Directed Energy Deposition (D.E.D) was used in repairing an already existing damaged and worn-out component, effectively extending its lifetime. '*AM, in this case, is similar to weld repairs. It will allow you to upgrade an aged part that has been in service for a long time, give it additional features and life extension*' (AML, Power1).

4.1.1.3. Volume maximisation. According to Aerospace and Automotive respondents (Aero1, Aero6, Aero8, Auto1, Auto2), manufacturers also sought to exploit AM's RA in creating smaller components which had more optimised geometries for adequate space utilisation in products that they are part of. '*Originally the fuel tank was spherical. But it goes in, one of the 10X10X10 areas and wasn't maximising the volume. So, we used AM to reduce its size' (PE, Aero1). 'The shapes you make with TM are pretty limited and therefore the heat transfer is fairly basic and the part, therefore, has to be bigger' (TD, AMS1).* This volume-maximisation requirement is sought after in aerospace and automotive applications, where there is a demand for increased power density, wherein propulsion systems need to generate more energy per unit volume. '*There is an increasing trend for increasing power density of aero engines, which means, maximising space and efficiency of everything within that engine' (HS, Aero1).*

4.1.1.4. Energy savings. Energy savings was cited as a rationale for AM adoption by respondents of aerospace, automotive and power generation applications (Aero6, Auto1, Auto2, Power 2, Power3). This mainly involved a technical problem of increasing the performance of components (e.g. heat transfer), without increasing the pressure drop. AM's RA in creating complex geometries enables manufacturers to achieve a better balance between these objectives than TM. '*The problem is how to design a filter that filters all particles without increasing the pressure drop. Because if we make a filter that only has small holes, then we need bigger pumps, we lose energy*' (RDE, Power1). '*In a perfect world, you want to take as much heat as you can with absolutely no pressure drop, but you can never get that, it's a balance and we felt that with 3D printing, we could generate some features that would achieve that*' (MDL, Auto1).

4.1.2. Process costs relative advantages

As discussed in the preceding section, the superior product performance benefits which AM generates compared to TM, produce benefits over the product lifecycle in service. That said, several organisations were motivated to adopt AM to reduce process-related costs. Analysis of interviews revealed that organisations were interested in AM's RA in reducing process-related costs via manufacturing complexity, tool elimination for small volumes, repair and inventory cost reduction.

4.1.2.1. Manufacturing complexity reduction. Five applications across aerospace and power generation (Power2, Aero7, Aero2, Aero4, Aero5) were motivated to adopt AM through anticipated cost benefits generated from complexity reduction associated with TM processes. Complex manufacturing processes were typically associated with complex components that consisted of sub-components, which had to be fabricated separately and assembled. The RDE of Power2 described AM's RA in simplifying the production process of a component, which had 70 sub-components: '*We cannot do it with TM for a reasonable cost. We can improve it with more complex designs and actually reduce costs with AM. Formerly, we have 70 components, now we have just one.*' Complexity and increased costs are also generated due to the amount of assembly and labour time required to produce components. AM's RA in reducing the amount of labour time involved in manufacturing translates to direct production cost reduction as expressed by the lead materials and processing engineer of Aero7:

> 'We looked for a complex assembly that has a lot of hands-on skilled assembly time to be done. That adds quite a big cost to the cost of the final component. Anything you can do to get away, that saves a lot of money.'

Opportunities also exist to reduce process-related costs by switching to AM through materials with comparable characteristics to traditional materials, however with a simpler AM production process. Aero5 developed comparable polymer materials, which could be used to replace metal equivalents for Aerospace applications to reduce process costs and fuel costs, via lightweighting. The R&D engineer of Aero5 described AM adoption motivations to realise these benefits:

> 'With improvements in force simulations, we've found that you can replace many metal components with polymer parts, using the HSS process, provided they meet mechanical requirements. HSS is significantly cheaper than direct metal AM and using polymers introduces more weight-savings than an optimised metal bracket.'

4.1.2.2. Repair. An Aerospace and Automotive application (Power1, Auto5) consisted of defective components that needed replacement for the final product. In both cases, however, the cost of replacing the defective component via TM was prohibitive forcing organisations to consider other alternatives. For Auto5, the defective component had a high failure rate and was part of the factory-floor tool. The suppliers insisted on replacing the entire tool anytime there was a defect on a part. Therefore, Auto5 discovered that it could repair the tool by fabricating the defective polymer component with AM and reduce costs. The Senior Engineer of Auto5 explained the repair opportunities created by AM which served as a rationale for adoption: '*There was a high replacement rate of tool sleeves. In some cases where they can be bought individually, it is prohibitively expensive. They are just plastic hollow cylinders that we print without support material.*' For Power1, the cost of replacing the entire metal component was also prohibitively expensive and TM methods lacked the repair capability of a partially damaged component. The unique capabilities of Directed Energy Deposition (D.E.D.) created scope for repair, which was significantly cheaper than outright replacement. Through reverse engineering, damaged sections of components were scanned and reproduced via D.E.D., an AM process similar to welding. The AM Lead of Power1 explained the cost-driven rationale which informed the AM adoption decision for repair

> 'The interest was in hard-to-reach sections, which usually result in scrapping decisions. Rather than scrapping it, because of the value, it might cost you £10,000 to put it back in service. If you discard it, that's £100,000, plus everything else that went into making it. So cost is a big driver.'

4.1.2.3. Tool elimination. All applications in the study's sample were in the low-volume range and there was a general consensus amongst respondents that AM was preferred to TM in this region. High volume applications in mainstream automotive were regarded as bad cases for AM adoption. However, regarding production cost justifications for adopting AM, two respondents (Auto4, Trans2) explicitly specified volume-related considerations. In both cases, the cost of TM tooling was cited as a major obstacle in producing respective components at low volumes and reasonable cost. The components also involved little to no post-processing, further reducing costs. Auto4 made simple, small, low-volume parts for luxury vehicles and the significant cost associated with stamping tools was a motivation to seek toolless AM, as described by the Program Manager of AM

> 'It was cheaper in AM because there was no tooling investment involved … in the automotive industry, is often the case that the customer pays for the stamping tools. This was a part for a luxury car in the very low volume segment.'

Trans2 needed a replacement for a legacy polymer component which was prohibitively expensive via TM due to tooling. The VP of consulting of Trans2 explained how tooling and volume-related issues informed the economic rationale for adopting AM '*It's the scarcity of the part and remanufacturing cost using TM. Ultimately, we can pretty much make anything but it's the economics of do we tool-up or do we want them in relatively small volumes.'*

4.1.2.4. Inventory holding. AM created opportunities for adopters to reduce inventory holding costs, which served as a rationale for adoption for respective applications (Aero8, Tran1). For Aero8, durable AM components generated secondary benefits in reducing failure rates and resulting inventory holding requirements. In this case, production costs via TM are cheaper at high volumes, however this results in higher inventory holding costs. Therefore, AM's RA in producing a comparatively more durable component, at lower volumes, generating inventory cost savings informed the rationale for adoption as explained by the Materials and Processing Engineer of Aero8: '*You can look at this in various ways; value to our customers through performance improvement, cost savings, repairability, less logistics and maintenance, burden as parts don't get damaged as often.'* For Trans1, the subject component was of a high variety, driven by the high varieties of boats in the industry. This high variety causes the boat manufacturers to hold significant inventories, which increases costs, due to long production lead-times. This rationale for AM adoption was explained by the Project Engineer of Trans1:

> 'They make a small number of boats per year. Say they make a dozen boats, which means twice that for propellers and then different configurations depending on the boat class. They would typically have lots of variants of propellers depending on the vessel. So they end up having large stockpiles just in case something goes wrong.'

4.1.3. Process speed relative advantage

Several organisations were motivated to adopt AM based on its RA in reducing the production lead-time for components. The pressure to reduce lead-time stemmed from the time-sensitive nature of applications, aiming to minimise downtime costs of capital-intensive equipment (aircraft, gas turbines, trains and boats) for MRO (Aero3, Power1, Power3, Trans1, Trans2). In these scenarios, when a defective component puts this equipment out of operation, OEMs are penalised by customers for equipment downtime, with costs that run into tens and hundreds of thousands of pounds. These scenarios were described by different respondents:

> 'We get costs like $200,000 a day as penalties for delays depending on the ship's size and cargo. That's consequential, so obviously, if I am a ship manufacturer or operator, how do I deal with this in the quickest way? (Project Engineer, Trans1)'

> 'Airbus gets fined hundreds of thousands of pounds a day if a plane is broken down. Their airlines have contracts to say if we are not making money from the plane and it's your fault, then you are giving us that money. So, it's almost a cost is no object … it's about service level and lead time. (AM lead, Aero3)'

Lead time reduction pressures for production was also influenced by the nature of demand in the industry. In our sample, two out of three Motorsport applications (Auto2, Auto3) were very time-sensitive and respondents sought to exploit AM's RA to produce newly designed components for Formula-1 races. This was influenced by the unpredictable nature of demand for custom made-to-order components. The respondents characterised this need for speed as the nature of Formula-1 applications, with cost not being a priority. '*Because of the nature of the industry we are working in for formula one, they release their design as late as possible and they want parts as quickly as possible*' (Technical Director, Auto2). '*The standard process is; the customer designs the part, goes out for competitive bids on delivery time. If you can deliver on-time, you can almost name your price*' (Managing Director, Auto3). These factors create suitable conditions for AM to demonstrate its RA and influence adoption decisions of organisations. These RAs were manifested in AM's ability to reduce production lead times via supply risk, process and material characteristics as presented in the following subsections.

4.1.3.1. Supply risk. The most dominant theme associated with lead-time reduction for MRO and assembly applications was the supply risk associated with producing TM components. These concerns were raised by respondents across Aerospace and Rail applications for MRO and batch manufacturing applications alike (Aero2, Aero3, Aero4, Trans2). Supply risk in TM was driven by several factors including political risk arising from location of manufacturing processes, bankruptcy of suppliers, misplaced tooling etc. Attention was drawn to so-called 'long legacy products' that have stayed longer in service than was originally anticipated, making them vulnerable to incidents such as supplier bankruptcy, which cause disruptions. In these instances, AM's RA in reproducing these legacy components via tool-elimination and reverse-engineering are crucial in adoption decisions as described by respondents.

> 'With the age of some aircrafts, serious issues arise around parts that are hard to source. It may have been considered initially, that the plane was only going to fly for 20 years and 40 years later, oh! does anyone know how we made this part? It comes up every now and again.' (AM Lead, Aero3)

> AM was considered because there was virtually no stock available, for a legacy component.. we had a real long legacy product where not only does nobody know where the tool even is, nobody even knows who the original manufacturer was... that's quite common. (VP AM, Trans1)

For batch manufacturing and assembly, reducing supply risk is important for critical components that can halt production lines. Therefore, the RA of AM in reducing supply risk, and consequently, production lead time influenced adoption decisions as expressed by the Partner of Aero4.

> 'Their bill of materials (BOM) is made up of 6000 components and there are certain 4 or 5 components that they could not produce quickly. So their BOM gets disrupted and timelines go hay-wire. They are focusing on maintaining the supply chain for those components for the main subsystem to be realised.' (Partner, Aero4)

4.1.3.2. Process lead-time reduction. The second most dominant theme associated with lead-time reduction was the characteristic of the TM process. Casting was highlighted in two applications (Tran1, Aero2) for its characteristically slow nature involving lengthy tool production, which makes it unsuitable for time-sensitive applications. '*That was more to look at issues with lead-time through casting because of tooling requirements... so they could just directly adopt AM were necessary*' (Principal Research Engineer, Aero2). In the MRO application of Trans1, significant delays were averted with AM as generic aspects of the propeller could be produced with non-casting methods and then differentiated by using D.E.D. to print the blade. This process was described by their Project Engineer:

> 'From the supply chain point of view, making the hub was a lot quicker and easier, because it is smaller than having to make a large propeller by casting. So the business case we see is that I can get the hub quickly made and then spend time depositing the blades for the propeller.'

Significant delays were also identified in procuring legacy parts, which made repair an option. However, there was not an existing repair route via TM. This created opportunities for AM processes such as DED, which works on the welding principle, to repair components and restore them to service quickly, minimising downtime costs. '*The interest was in hard-to-reach places, that would usually be avoided. Rather than scrapping, it can be put back into service via repair. Cost and timeliness are big drivers.*'

4.1.3.3. Raw material lead time reduction. The last theme highlighted by respondents, regarding process-related delays, was the long-lead times associated with sourcing expensive materials such as Titanium and Inconel. The respondents talked about supply problems that could occur when there is sudden demand in the SC, which creates shortages because large stocks are not produced. '*You are allowing lead time reduction with AM. If it's an expensive material, it can be tricky to get hold of quickly' (Head of Strategy, Aero1).*

> 'With materials like Inconel, you can have a six, eight or ten-month lead time from the SC to get it because the supply of it is not that high since demand is not that high. So, when you have a sudden demand, it can be quite difficult to get hold of.' (AM Lead Aero3)

The additional problem with traditional feedstock is customisation, which makes it difficult for large batches to be stocked in inventory as they may not be suited for production demand. With AM, however, some material types, especially powder, can be stocked in their generic form to hedge against supply problems and facilitate delayed differentiation. The AM Lead of Aero 3 explained this RA, which AM has for its material characteristics:

> 'If you are using an exotic material like Inconel, you could have bags of it sat there basically, you don't have to worry about whether you've got the right size billet. If we kept billet in stock that were 200 millimetres long and our customer suddenly said that I want a part that's 205 mill long. Oh, Sorry it might take six months.' (AM lead, Aero 3)

4.2. Synthesis of relative advantages and contextual factors

From the preceding qualitative analysis, we derived four aggregate categories of contextual factors namely:

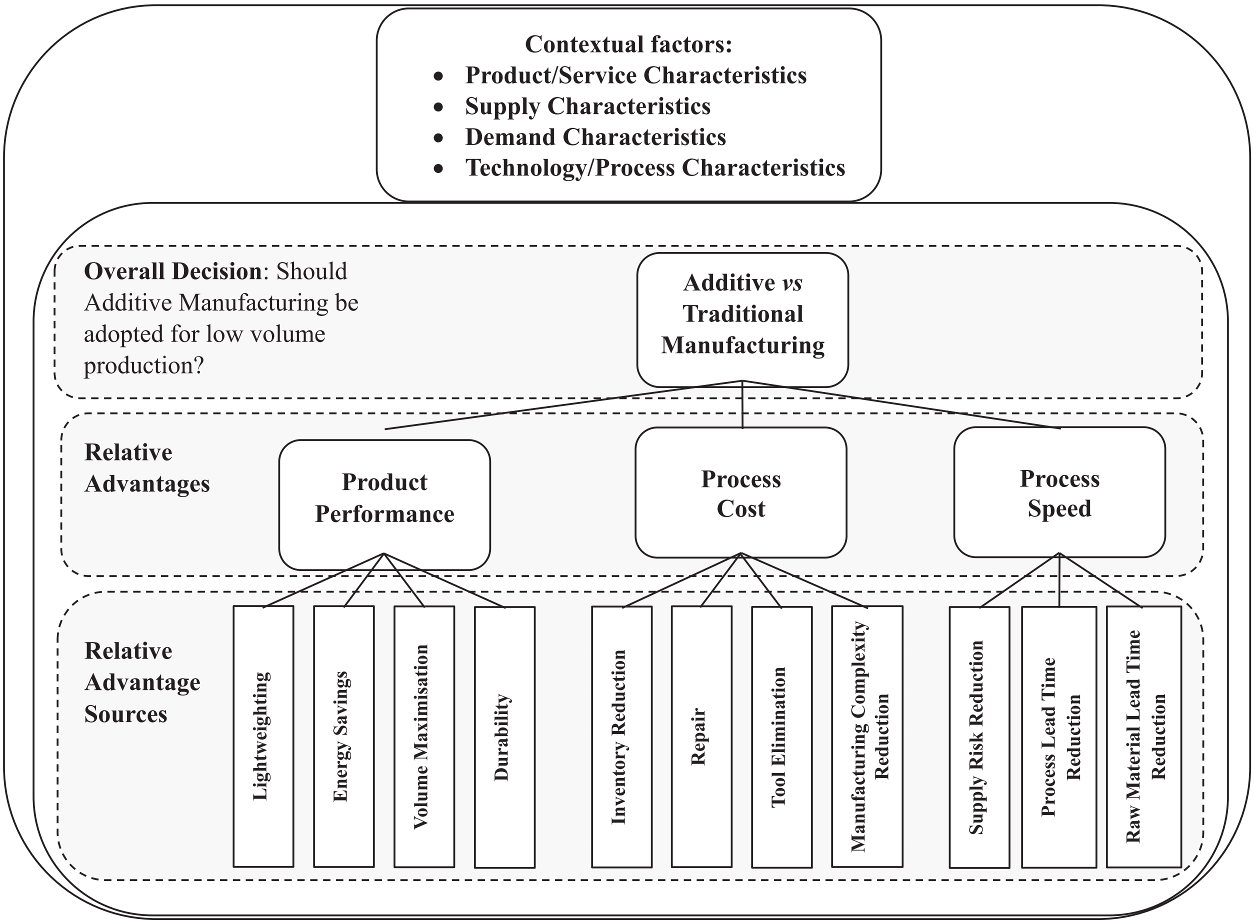

Figure 1. Hierarchical decision framework for evaluating relative advantage of additive manufacturing.

product/service, demand-side, supply-side, and technology/process characteristics, which set the conditions for an array of RA sources that can be exploited with AM. The contextual factors represent decision areas within a TM context, which potential adopters can investigate for opportunities to generate RAs with AM on a product and/or process level compared to existing TM processes. The set of these RA sources represents the strength of AM's RA for a particular low-volume TM component, which influences the likelihood that an organisation will adopt AM. Knowledge of the TM environment and RAs that can be generated as a result are crucial in reducing uncertainty about AM's expected impact on operations performance during the innovation-decision process (Rogers 2003). This decision logic is summarised in the Hierarchical Decision Framework for Evaluating Relative Advantages of Additive Manufacturing (Figure 1), depicting relationships between contextual factors and RA sources summarised in Table 6. The decision logic is as follows:

- The needs/requirements of the subject operation as defined by contextual factors (i.e. product/service, demand-side, supply-side and technological/process characteristics) create an array of sources from which RAs can be generated with AM having the potential to improve product and process.
- An aggregation of RA sources, and their relative strength by comparison to TM determines the strength of AM's RA in relation to product performance, process cost and process speed.
- The aggregation of these product and process RAs determines the strength of AM's overall RA as an option over TM, and, therefore, the likelihood of influencing its adoption decision positively.

Our framework highlights the importance of understanding the fit between AM RA sources and the operations context as a pre-requisite for diffusion of AM in industries (Slack and Lewis 2023). The product/service decision area dominates the list with the largest number of contextual factors, related to product-performance and process-related RA sources. Part/joint count appears significant as it creates 3 RA sources on a product and process level, namely Lightweighting, Durability, and Manufacturing Complexity (Table 6). Whilst the positive product and process effects of parts consolidation have been highlighted separately in the AM adoption literature (Peron et al. 2025; Rylands et al. 2016), they have not drawn attention to the possibility of combined effects and associated influences on decisions. Similar arguments can be made for lifetime and material type, which create multiple RA sources. Our findings also reveal inter-relationships between product and process RAs (e.g. Durability and Inventory Reduction), which suggests layers of RAs which could be realised with AM adoption. Research has also highlighted design complexity as an important area to generate RAs (Mellor, Hao, and Zhang 2014; Rylands et al. 2016), however, energy savings and volume maximisation are lacking in the adoption literature. Energy-savings is particularly crucial for energy-intensive industries given recent mandates for decarbonisation by regional and national governments (Department for Transport 2022). This creates a unique opportunity for AM to demonstrate its RAs.

Supply-side factors are the second most dominant decision area linking to process RA sources alone. The assumption of high-tooling costs appears implicit in the AM adoption literature, due to AM's fundamental capability of tool-elimination. However, there is lack of consensus on the capabilities of AM to rival TM technologies through process cost on the basis of tool-elimination alone, because of post-processing (Jimo et al. 2022). This is important because although AM has been generally regarded as a cheaper alternative to TM at lower volumes, some adopters do not perceive an automatic relative process cost advantage with AM adoption for lower volumes (Patil et al. 2022; Ronchini, Moretto, and Caniato 2023). This could be due to the negative perception of AM process characteristics (high machine and material costs for metal AM) (Di Lorenzo et al. 2023) and industry regulations (FAA regulations that allow one part per build), which impede AM's ability to generate cost efficiencies at lower volumes (Laureijs et al. 2017). For example, current costs of Selective laser melting machines start at 250,000 Euros (3Dnatives 2025). Ti-6Al-4 V for the round bar ranges from \$22.0 to \$31.00, whilst AM powder costs between \$120 and \$150, making the AM powder five times more expensive (Alibaba 2025). Our study revealed two applications (Auto2, MarineCo) that rivalled TM on cost, due to tool-elimination, only because there was no post-processing involved. For the vast majority of applications, post-processing and associated labour demands is likely to diminish AM's effectiveness as a labour-saving technology (Ancarani, Di Mauro, and Mascali 2019). However, research has also shown that learning effects can reduce labour content in AM processes by as much as 58.6% (Baumers and Holweg 2019). Other innovative efforts to increase automation AM and reduce costs are ongoing, however they are in early stages of development (Kanishka and Acherjee 2023).

The literature has identified labour shortages, tooling, inventory burdens and risk-related issues (Adaloudis and Bonnin Roca 2021; Patil et al. 2022; Sandström 2016), however it has not identified niche repair opportunities created by high-replacement costs of entire products. This represents an area where AM clearly provides a distinct advantage, however the size of this opportunity within organisations and industries is unclear. Repair appears to be a budding context, especially in emerging economies, where there a lots of ageing products such as aircrafts (Peron et al. 2025). However, the viability of AM in emerging economy contexts remains an open question because of the associated cost barriers (Patil et al. 2022). In general, repair enabled by AM could be significant in promoting circular economies through the 'right to repair' policies which promote lifetime extension of products (Gebhardt et al. 2022; Roskladka, Jaegler, and Miragliotta 2023). That said, we observed that sustainability dimensions did not surface explicitly as RAs in our analysis, suggesting that such considerations could be secondary, unless AM is adopted in specific sustainability-oriented contexts (Beltagui, Kunz, and Gold 2020). The generic raw-material characteristics of AM and its contribution to shortening production lead times as found in our study, has not been foregrounded in literature (Prataviera, Jazairy, and Abushaikha 2023). This RA could be significant against rival subtractive manufacturing technologies, where raw materials need some form of customisation (e.g. sheet metal, billets). The literature has also emphasised the lead-time reduction RAs of AM (Naghshineh 2024; Priyadarshini et al. 2023), however supply risk reduction represents another avenue for AM to generate RAs in SCs for legacy products which face political and economic risk as highlighted by our research.

The extant research already has a strong demand-side orientation with elements such as market/industry stability and differentiation (Mellor, Hao, and Zhang 2014; Patil et al. 2022; Priyadarshini et al. 2023; Rylands et al. 2016), which our research also emphasises, albeit with novel relationships between failure rates of parts and durability as an RA source. On technological characteristics, existing research highlights how labour shortages can create opportunities for AM to generate RAs in the construction industry (Adaloudis and Bonnin Roca 2021; Sandström 2016). Similar opportunities for RA have been identified in our study, albeit due to labour intensity in engineering-oriented industries involving significant labour and assembly. Repair has also been discussed in the extant literature (Peron et al. 2025), however the role of enabling capabilities such as reverse engineering has not been highlighted in the literature to facilitate AM adoption in the aftermarket domain.

These empirically grounded, constructs and relationships have implications for the shaping of quantitative theory-testing studies. These studies to date have framed the RA construct with generic specifications around speed, productivity, ease, control, cost, and efficiency, reflecting a wide range of AM applications (Table A, Appendix A). Our findings help to bridge this gap by establishing linkages between abstract RAs, constituent dimensions (RA sources) and contextual factors, amounting to construct refinement for the production phase of the manufacturing lifecycle (Delic and Eyers 2020; Fisher and Aguinis 2017). This granular specification of RAs provides a basis to test the specific sets of RAs, which are influencing AM adoption decisions in different industries (Diamantopoulos and Winklhofer 2001). Furthermore, our specification of contextual factors enriches the extant quantitative domain, with an array of variables, which could be used as control variables to test the influence of these factors in different industries. This is an important step to extend the extant control variable domain beyond standard variables such as organisation size, sales volume, age, education, gender, position of employees etc. (Calli and Calli 2020; Schniederjans 2017; Wang et al. 2016). This would help deepen our understanding of the capabilities and boundaries of this emerging innovation and it's potential to diffuse further in the production phase of different manufacturing industries.

4.3. Additive manufacturing adoption framework

The preceding analysis shows that AM adoption decisions are based on one or a combination of RAs. Based on two polar extremes (high and low), a framework (Figure 2) is presented to evaluate adoption decisions for particular applications based on RAs, sources and contextual factors. Each cube edge corresponds to a combination of the three principal RAs (product performance, process cost and process time), their corresponding sources and contextual factors as explained in Figure 1. The cube origin represents the low end of each RA, whilst other edges on the X, Y and Z axis correspond to the high end of each dimension. Altogether, there are seven cube edges, which correspond to a combination of states (high and low) for each RA. Each of these adoption decisions will be discussed in following sections, with reference to relevant sources and contextual factors. The option at the origin is not discussed as it represents a no-go decision, where AM does not provide any RA compared to TM and therefore there is no incentive to adopt. The decisions are labelled 1–7 and are discussed according to the number of RAs they are linked to i.e. one RA (decisions 1-3), 2 RAs (decisions 4–6) and 3 RAs (decision 7). A summary of these decisions, RAs, sources, product types, contextual factors are provided in Table 7.

4.3.1. Decision 1: low value spares (Process cost RA)

In this scenario, process cost alone represents the dominant AM adoption driver. This adoption scenario applied to a low-value spare part with a simple design which was

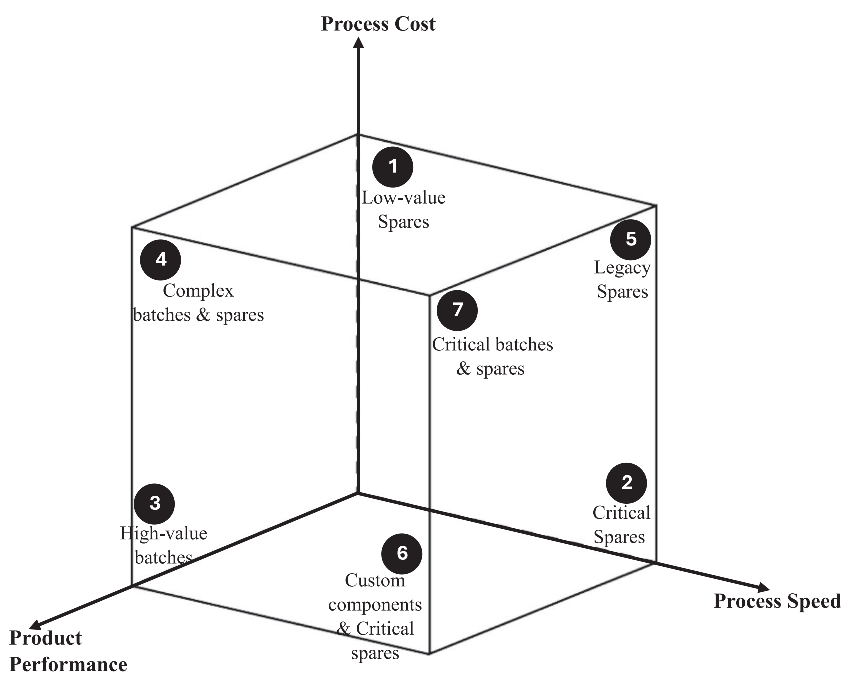

Figure 2. Additive manufacturing adoption framework.

Table 7. Relative advantages, sources and contextual factors for AM adoption.

				Contextual factors associated with traditionally manufactured component				
Decision number	Relative Advantage	Component Type	RA Sources	Product	Service	Deman-side	Supply-side	Process/Technological
1	Process cost	Low-value spare parts (Auto5)	Repair, Inventory Reduction	Complexity (L), Value (L)	-	Demand uncertainty (L), Volume (L), Variety (L)	Tooling cost (H), Part replacement cost (H)	Reverse Engineering (Y)
2	Process time	Critical spare parts (Aero3)	Supply risk, TM Process Characteristics, TM Material Characteristics	Complexity (L), Lifetime (H), Criticality (H)	Downtime costs (H)	Demand uncertainty (H), Volume (L), Variety (H)	Supplier bankruptcy (Y), Material availability (N), Raw-material availability (L)	-
3	Product performance	High-value batches (Aero1, Aero6, Auto1)	Lightweighting, Energy Savings, Durability, Volume maximisation	Complexity (H), Part/Joint count (H), Value (H)	Power Density (H)	Demand uncertainty (L), Volume (M to L), Variety (L)	-	-
4	Process cost & product performance	Complex batches and spares (Aero5, Aero7, Aero8, Auto4, Power2)	Lightweighting, Energy Savings, Durability, Volume maximisation, Manufacturing complexity, Volume, Inventory holding	Complexity (H), Part count/joint count (H)	Power Density (L)	Demand uncertainty (L), Volume (L), Variety (L)	Labour intensity (H), Tooling cost (H)	Material Type (N)
5	Process cost & time	Legacy spares (RailCo, Power1)	Volume, Repair, Supply risk, Process Lead time reduction	Complexity (L), Lifetime (H)	Downtime costs (H)	Demand uncertainty (H), Volume (L)	Part replacement cost (H), Supplier bankruptcy (Y)	Reverse engineering (N)
6	Process time & product performance	Custom components and Critical spares (Auto2, Auto3, Power3)	Lightweighting, Durability ,Volume maximisation, Energy savings, Process Lead time reduction	Complexity (H), Part/joint count (H), Criticality (H), Lifetime (L), Value (H)	Downtime costs (H)	Demand uncertainty (H), Volume (L), Variety (H)	-	-
7	Cost, time and product performance	Critical batches and spares (Aero2, Aero4, MarineCo)	Lightweighting, Durability, Manufacturing complexity, Inventory Costs, Supply risk, Process lead time reduction	Complexity (H), Part/joint count (H), Criticality (H)	Downtime costs (H)	Demand uncertainty (L), Volume (L), Variety (H & L)	Labour Intensity (H)	-

Key: H: high; L: low; Y: yes; N: no.

a replica of the TM component (Auto5). The application was not time-sensitive because parts were made to inventory with predictable failure rates. However, replacing the spare part via the existing TM route was prohibitively expensive as suppliers insisted on replacing the entire product rather than the defective part. This would have resulted in excess and high inventory costs for the full product due to the absence of a viable repair route via TM. Thus, AM's RA on process cost was perceived as superior in reproducing the defective part in small batches to repair the product due to the absence of upfront tooling costs and AM's capability to reverse-engineer TM parts.

4.3.2. Decision 2: critical spares (Process time RA)

This AM adoption decision recognises process speed as the dominant RA. This decision was adopted for a critical spare part, with simple design, unpredictable demand and used for aircraft of ground scenarios, with significant downtime costs (Aero3). Here, there is an urgency to reduce lead time by devising the shortest possible manufacturing route. The subject component was prone to supply risk from political factors, misplaced tooling, etc. due to the extended lifetime of the aircraft. Using TM processes such as casting involves lengthy delays due to tooling and shortage of suppliers. AM's RA came from tool elimination and in-house manufacturing, which reduced lead time. In addition, the generic nature of raw material facilitates delayed differentiation, in that AM powder feedstock could be held in advance to avert supply shocks and facilitate rapid production. There was no requirement to enhance product performance, therefore AM's RA on reducing lead time was perceived as superior in reproducing a like-for-like TM design, averting supply risk and expediting delivery.

4.3.3. Decision 3: high-Value components (Product-performance RA)

This adoption decision places a premium on product performance. It applied to high-value batch manufacturing components with predictable demand and high geometric complexity (Aero1, Aero6 and Auto1). Such components also possess a high part/joint count, which can be consolidated with AM. This results in parts, which yield superior lifecycle benefits (e.g. lightweighting, Energy savings, volume-maximisation, etc.) compared to TM and influence adoption decisions. However, process-related benefits, i.e. cost and lead time, were not prioritised in this adoption decision. The adopters were interested in enhancing the technical capabilities of components to be used in the next generation of their products.

4.3.4. Decision 4: complex batches and spares (Process cost and product-performance RA)

In this adoption decision, process cost and product performance are recognised as dominant RAs jointly, while time has the least priority. It applied to complex batch manufacturing and spare components with high-value and predictable demand (Aero5, Aero7, Aero8, Auto4, Power2). TM SCs of these components are complex, which increases production costs. Organisations sought to exploit AM's RA in realising complex designs to enhance product function, whilst reducing production costs simultaneously. AM's RA in reducing production costs was perceived as superior because of parts-consolidation which reduces complex, multistage processes, labour time, machine setups, tooling and inventory co-ordination from multiple suppliers. Opportunities also exist to exploit technology through material substitution (ie. metals to polymer), which reduces the associated manufacturing complexity and process costs. Additionally, AM benefits such as durability reduces inventory costs due to reduced failure rate of components.

4.3.5. Decision 5: legacy spares (Process cost and time RA)

In this decision, reducing process cost and time are high priorities, while product performance is less important. This decision type applied to legacy spare components with long lifetimes, which required replacement or repair. They exhibited unpredictable demand patterns and were deployed in time-sensitive MRO applications where downtime costs are significant (Trans2, Power1). Replacing an entire component was significantly more expensive than repairing a damaged section via AM, therefore cost was a primary consideration. Similarly, replacing legacy components via TM was prohibitively expensive and AM was cheaper. The legacy nature of these components heightens the supply risk in the TM SC due to various factors. Therefore, AM's RA was perceived as superior in reproducing and repairing legacy components through reverse engineering.

4.3.6. Decision 6: custom components and critical spares (Process time and product performance RA)

In this adoption decision, a high priority was placed on product performance and process time. This adoption decision applied to high-value components with complex designs and unpredictable demand (Auto2, Auto3, Power3). These applications belonged predominantly to Motorsport and MRO where there is a high requirement for product and process performance. AM's RA to realise complex components through design freedoms for superior product performance was crucial for adoption decisions. In addition, parts-consolidation provided opportunities to reduce delays associated with multistage TM processes. Time-sensitivity of these applications is heightened by short product lifecycles, short lead times, unpredictable component demand, downtime costs for Motorsport and Power Generation MRO respectively.

4.3.7. Decision 7: critical batches and spares (Cost, time and product performance RA)

In this decision, cost, time and product performance all have equal priorities in the adoption decision. This was evident in a critical batch manufacturing and spare components applications (Aero2, Aero4, Trans1). Technical performance was of high priority, therefore AM's RA for lightweighting and durability, which result in lifecycle benefits, influenced adoption decisions. Cost reduction opportunities existed with AM through reduction of manufacturing complexity and inventory costs. Lead-time reduction is also offered via AM through the reduction of supply risks, and overcoming delays associated with naturally slow processes like casting. These components were critical to the realisation of the overall product and reducing downtime costs, therefore AM's RA was perceived as superior in producing a high-performance component at reduced process cost and time.

5. Discussion

Our study adopted a qualitative approach to investigate the RA sources and contextual factors that govern AM adoption decisions and associated interplays (RQ1). We developed an Additive Manufacturing decision framework to explain how contextual factors in a production environment create opportunities for AM to exhibit its relative advantages and positively influence adoption decisions. We extended the decision framework to create another framework which explains the combination of RAs and contextual factors that influence AM adoption decisions for different classes of end-use components (RQ2). Our findings deepen our understanding of AM RAs in the production phase of the manufacturing lifecycle. Extant research applies RA in a more general sense of AM adoption for various applications (Peron et al. 2025; Schniederjans 2017; Yeh and Chen 2018), thereby limiting insights it can generate about the diffusion of the technology in the production and aftermarket domain. We advance extant research, through our theory development approach, enriching the RA construct with empirically grounded specifications of dimensions and contextual factors to support AM diffusion research (Fisher and Aguinis 2017).

5.1. Theoretical implications

Our research contributes to the AM adoption literature in the following ways. First, by identifying key sub-dimensions and attendant links to supporting contextual factors, this research deepens understanding of RAs in the context of AM adoption for end-use components. We identified RA sources that are lacking from the AM adoption literature and discussed their implications for different industries. Secondly, we identified crucial links between contextual factors and RA sources, illustrating the underlying logic behind how RAs influence adoption decisions. We summed up this decision-making logic in the hierarchical framework (Figure 1), representing one of the principal contributions of this research. This contribution fulfils our attempt at theory elaboration by refining the RA construct to better predict AM adoption intentions of managers in different industries and by extension the diffusion potential of this emerging technology. As most constructs in the innovation adoption literature are derived from the information technology domain and applied wholesale in other contexts such as AM, it was necessary to refine the RA construct to reflect the realities of end-use part production accurately. Our theory elaboration approach enriches the RA construct with empirically grounded specifications of RA dimensions on product and process levels to accurately model AM adoption dynamics in a production context and facilitate further theory testing with DOI (Fisher and Aguinis 2017; van Oorschot, Hofman, and Halman 2018). The accurate specification of the RA construct is also crucial to investigate mega-trends such as reshoring and distributed manufacturing, which historically have been associated with AM (Braziotis, Rogers, and Jimo 2019; Fratocchi 2017).

Our second principal contribution involves the development of the Additive Manufacturing Adoption Framework (Figure 2), to explain seven types of adoption decisions according to specific combinations of RAs, sources and contextual factors for low-volume industrial applications. By mapping and focusing on the low-volume domain specifically, our study provides additional contextual depth regarding application and component types suitable for AM, extending previous work, which included high-volume applications (Conner et al. 2014; Patil et al. 2022). This consolidates the disparate factors influencing various applications into seven decisions, which reduces the fragmentation problem in the current literature. These seven decisions could serve as a yardstick for investigating different diffusion paths of AM and prevalence in different sectors.

5.2. Managerial implications

From a practical perspective, our frameworks could serve as a tool for managers to explore their TM context to develop a logic and business case for adopting AM for different applications. The second framework (Figure 2) defines seven AM adoption options and can serve as a decision support tool for selecting candidate AM applications. These adoption decisions demonstrate the wide array of applications, which organisations can exploit with the technology for commercial benefit. Our frameworks could serve as a tool for organisations to systematically investigate AM adoption opportunities through exploration of TM components with supporting contextual factors, RAs and relevant sources. The framework draws attention to unique conditions in TM SCs, such as supply risks and repair opportunities, which create potential application points for AM. Repair opportunities have particularly become significant in light of recent regulatory trends and pressures on organisations to improve their environmental performance (Roskladka, Jaegler, and Miragliotta 2023).

6. Conclusions

Our research adopted a qualitative approach, based on in-depth interviews, to investigate RAs influencing AM adoption decisions for 18 low-volume industrial applications in different sectors. We developed two frameworks to deepen insights into the underlying logic of AM adoption decisions based on RAs. This exploration across contexts supports the creation of a more holistic theoretical explanation around a critical determinant of innovation adoption i.e. relative advantage (van Oorschot, Hofman, and Halman 2018). In relation to RQ1, our study revealed 11 key sources of RA which contribute to product performance, process cost and process speed. Further, the contextual factors identified, namely product/service, supply and demand, and technology/process characteristics, set the conditions in the TM context to make AM viable for adoption. Our hierarchical decision framework (Figure 1) summarises the above and illustrates the relationships between contextual factors and RA sources shaping the AM adoption decisions. Building upon the outcomes of RQ1, to address RQ2, our Additive Manufacturing Adoption Framework (Figure 2) assists in capturing and evaluating adoption decisions for particular applications based on RAs, sources and contextual factors for different low-volume industrial end-use components. Our exploratory approach and outcomes address the lack of contextual depth associated with theory testing approaches (Calli and Calli 2020; Schniederjans and Yalcin 2018; Yeh and Chen 2018) and fragmentation in extant exploratory studies (Mellor, Hao, and Zhang 2014; Ronchini, Moretto, and Caniato 2023; Rylands et al. 2016). The frameworks specify different aspects of AM RAs and contextual factors for industrial production, as well as their potential combinations, and serve to refine the construct and create a basis for further investigation of AM diffusion.

In terms of research gaps (section 1), our findings address the lack of clear identification of the different sources associated with RAs, and contextual factors that create these sources. Our frameworks alleviate fragmentation issues with the AM adoption literature, and illustrate the interplay between combinations of RAs and the relevant contextual factors that define the conditions for adopting AM for low-volume industrial components. Our paper adds clarity and specificity to the product and process RAs and their sources, and identifies four main categories of contextual factors which need to be considered when adopting AM.

Our study, though insightful, has limitations which must be acknowledged in light of future research. We cannot claim statistical generalisability; however, analytical generalisability is achieved through a sample of 18 applications. We acknowledge that our sample could have been biased in favour of certain types of applications due to access considerations. Therefore, future quantitative studies could apply our refinements to the RA construct to test the distribution and relative importance of RAs identified in other industrial contexts such as medical and construction. Additionally, the relationships between RA sources and contextual factors should be tested in various industries to understand different paths to AM adoption. Future studies should also test the contribution of other adoption drivers (e.g. compatibility, triability) on AM adoption decisions for low-volume production, given the strength of RAs identified. Longitudinal case studies could also be conducted to observe the changes in perceptions of managers on the RAs of AM, over its adoption lifecycle where challenges are encountered and implications for implementation success (Rogers 2003). Potential also exists to investigate the effect of trade-offs on the perception of managers about AM RAs. Lastly, future studies should empirically investigate the contribution of RA dimensions, specified in our study, to megatrends such as distributed manufacturing and reshoring given rising geopolitical tensions and concerns about climate change.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary data provided in the appendix.

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Appendices

Appendix A

Table A1. Existing specification of AM performance attributes from innovation theories.

References	Theory	Performance Construct	Sub-dimensions
Schniederjans (2017)	Unified theory of acceptance and use of technology (UTAUT)	Performance Expectancy	'Using 3D printing enables (or would enable) our organisation to accomplish tasks more quickly.' '3D printing allows our organisation (or would allow our organisation) to accomplish activities more quickly.' '3D printing increases (or would increase) our organisation's productivity?'
		Perceived Usefulness	'Our organisation finds 3D printing useful.' 'The use of 3D printing improves (or would improve) our organization's performance.'
	Diffusion of Innovation (DOI)	Relative Advantage	'Using 3D printing improves (or would improve) our organisation's quality of work over traditional methods of manufacturing/prototyping.' 'Using 3D printing makes it easier (or would make it easier) for our organisation's employees to do their job over traditional manufacturing/prototyping.' 'Using 3D printing enhances (or would enhance) our employees' effectiveness on the job over traditional manufacturing/prototyping.' 'Using 3D printing gives (or would give) our employees greater control over their work over traditional manufacturing or prototyping.' 'Using 3D printing has reduced (or would reduce) our organisation's cost structure over traditional manufacturing/prototyping'
Schniederjans and Yalcin (2018)	UTAUT	Performance Expectancy	'3D-printing allows us to validate design work on injection moulded parts before initiating tool manufacturing.'
	DOI	Relative Advantage	'This increases our accuracy while at the same time reducing our expenses.' 'It's important to have 3D-printing through design validation as well as before cutting steel.'
	UTAUT	Perceived Usefulness	'It just works well within our current strategy because we can use 3D printing for rapid prototyping for small plastic parts.' 'It allows us to show objects as sales aids which has helped us enhance sales.'
Wang et al. (2016)	TAM	Perceived usefulness	'The extent to which one person considers whether or not a new technology could increase their productivity and work-related performance.'
		Perceived Enjoyment	'When users perceived a 3D printing system as enjoyable to use.'
Calli and Calli (2020)	TAM	Perceived Enjoyment	'I feel happy when using a 3D printer.' 'I find using 3D Printer to be enjoyable.' 'I think it is pleasant to produce with 3D Printer.'
		Perceived Usefulness	'Using 3D printer enables me to use time more efficiently.' 'Using 3D Printer enables me to accomplish tasks more quickly.'
Handfield et al. (2022)	DOI	Relative advantage	'Product development and prototyping speed at reduced costs.' 'Customised designs.' 'Speed to market.' 'Quality, Production cost reduction, Operating room time.' 'Spare parts no longer in production.'
Ukobitz and Faullant (2022)	TAM/DOI, Institutional theory	Perceived value	'3DPT can provide a competitive advantage for companies in our industry.' '3DPT can provide acceleration of time to market.' '3DPT can provide production of complex structures.' '3DPT can provide improved market positioning.' '3DPT can provide access to new clients.'
Yeh and Chen (2018)	Technology Organisation Environment Cost	Relative advantage	'3D printing, in this case, allows firms to produce customised goods in small quantities.'

Appendix B: interview protocol

Part A – overview of additive manufacturing in the organisation

1. Can you give a general overview of end-use parts applications of Additive Manufacturing at your company?

2a. What product lifecycle stage do these applications belong to? (Series production, legacy and aftermarket (MRO))

2b. Why is your company focusing on this lifecycle stage for the production of AM parts?

3a. What market segments do these end-use applications fall under?

3b. Why is your company focusing on these segments for AM end-use parts?

4a. What kind of Additive Manufacturing technologies does your organisation use for these applications?

4b. Why where these technologies selected?

4c. Are all AM build jobs carried out in-house or outsourced?

4d. If not, why and in what circumstances are build jobs outsourced?

Part B – drivers of additive manufacturing for a particular application

5. Focusing on an end-use part application (for e.g. bracket, heat exchanger), can you give a general overview of the development of this AM component in terms of (Objectives, milestones and outcomes)?

6. Why did your firm consider AM for this component?

7. What specific customer requirements were in view to be addressed by switching production of this component from TM to AM?

8. Were there any other factors or developments that influenced the decision to consider AM for this component?

9. Apart from the technical requirements, were there any operational characteristics of this part that made it suitable for AM? (e.g. demand uncertainty, inventory cost, profit margins, lifecycle, throughput volume, manufacturing lead-time, supply process etc.)

10. Are there any specific operational problems associated with the traditional manufacturing process, you were aiming to overcome with AM?