Additive manufacturing technology integration: an operational capability perspective

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Abstract

Purpose – Manufacturing companies still struggle to integrate additive manufacturing (AM) technologies with existing traditional manufacturing technologies. This paper explores AM technology integration into a global manufacturing company from an operational capability perspective.

Design/methodology/approach – The research was conducted using a single case study in collaboration with a global heavy-duty vehicle manufacturer. Data were collected through a focus group and interviews representing management and engineering roles. Additional data were collected from meetings, company documents, field notes and observations. Subsequently, the collected data were analyzed thematically.

Findings – The findings reveal that, despite the company embarking on its AM technology integration journey, it encountered challenges, including cognitive fixation, manufacturing fixation, situational awareness, ambiguous ownership and the make-or-buy dilemma. Furthermore, the findings showed that the company developed operational capabilities – such as developing proficiency in AM know-how, continuous use of AM technology, operational practices for AM technology, cross-collaboration for AM initiatives and business cases for AM technology – to address these challenges. A facilitation model was developed, outlining essential actions prioritized for the short-term, mid-term and long-term. These actions leverage the operational capabilities to address challenges in AM technology integration.

Originality/value – This paper offers an in-depth exploration of AM technology integration in a global heavy-duty vehicle manufacturer. It introduces a novel application of operational capability theory and proposes a facilitation model for managers and academics in pursuit of achieving AM technology integration.

Keywords 3D printing, Technology integration, Industry 4.0, Industrialization, Product development, Production development, Smart production, Capability theory, Resource-based view

Paper type Research Paper

Quick value overview

Interesting because: This paper explores additive manufacturing (AM) technology integration within a global heavy-duty vehicle manufacturing company from an operational capability perspective. While many prior studies have examined AM technology adoption and implementation across various sectors, there is a need to research the challenges and potential solutions for AM technology integration within the well-established traditional manufacturing industry. This study is unique by developing a facilitation model to overcome challenges using operational capabilities. Unlike previous research that focused on models for adoption and implementation, this study provides strategic and tactical guidance for managers in the manufacturing industry.

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Theoretical value: The study contributes with theoretical insights expanding the discussion around operational capabilities in connection with AM technology integration. Firstly, it identifies both challenges and operational capabilities to support AM technology integration. Secondly, the study presents that operational capabilities were developed differently and prioritized either short, mid, or long term to overcome the challenges. Thirdly, the study presents a facilitation model demonstrating how operational capabilities can be utilized to overcome the challenges.

Practical value: The study proposes that managers should first evaluate their current operational capabilities and then prioritize investments in new AM technologies for the short, medium, and long term. Initially, low-cost and low-risk measures, such as purchasing services from external AM actors, should be pursued. Subsequently, investments should be made in additional AM systems, focusing on similar materials and processes. Finally, long-term and high-risk investments should be directed toward new AM materials and processes.

Introduction

The global market revenue of additive manufacturing (AM), also known as 3D printing, has surged to \$18bn in 2022 and is anticipated to exceed \$100bn by 2032 (Campbell *et al.*, 2023). In recent years, AM has emerged as a disruptive advanced manufacturing technology with the potential to revolutionize traditional manufacturing (Steenhuis and Pretorius, 2017; Kothman and Faber, 2016). Some companies, such as Boeing, Ford, General Electric, Saab, and Siemens, have successfully adopted and implemented AM technology resources and capabilities. Numerous global manufacturing companies face ongoing challenges transitioning from long-established traditional manufacturing technologies, including molding, casting, and machining, to AM technologies (Roscoe *et al.*, 2023; Flores Ituarte *et al.*, 2016).

The AM technology adoption and implementation challenges, along with potential solutions, have been studied across various manufacturing sectors, encompassing companies of all sizes (Chekurov *et al.*, 2021; Chaudhuri *et al.*, 2019; Yi *et al.*, 2019; Martinsuo and Luomaranta, 2018; Dwivedi *et al.*, 2017; Niaki and Nonino, 2017; Mellor *et al.*, 2014). Despite these research efforts on AM technology adoption and implementation, there is a need to research the challenges and potential solutions for AM technology integration in the manufacturing industry. AM technology integration is challenging because of its inherent complexity, cross-functional nature, and criticality. Furthermore, achieving seamless integration is particularly difficult because it requires embedding AM technology into well-established traditional manufacturing resources and capabilities. For instance, global manufacturers have difficulty motivating high-cost investments such as purchasing excellent yet expensive metal AM machines and establishing such production systems because of workforce resistance (Yi *et al.*, 2019; Flores Ituarte *et al.*, 2016). AM technology integration in traditional manufacturing offers diverse values, such as quick design iterations and reduced downtime, and impacts, such as faster time to market and increased cycle time, across the spectrum from new product concepts to final production (Klahn *et al.*, 2020; Fontana *et al.*, 2019). AM technology integration goes beyond adoption and implementation making AM technology important and necessary complementing existing traditional manufacturing resources and capabilities.

Global manufacturing companies exhibited concerns about the uncertainty surrounding AM technology integration and seek ways to enhance overall competitive advantage through AM technology resources and capabilities in both product development (Handfield *et al.*, 2022; Turkcan *et al.*, 2022) and production (Singh *et al.*, 2023; Haug *et al.*, 2023). Previous research underscored that AM technology resources and capabilities could enhance current products and production systems, render certain activities in product development and production obsolete (Holmström *et al.*, 2017; Kothman and Faber, 2016), induce new operating routines (Roscoe *et al.*, 2019), and incrementally or radically improve company performance (Oduro *et al.*, 2023; Niaki *et al.*, 2022). Operational capability theory (Teece, 2019; Wu *et al.*, 2010) is interesting since it concretizes the required resources and capabilities for AM technology integration. Operational capabilities emphasize a global manufacturer's ability to develop and deploy AM technology resources and capabilities, complementing existing traditional manufacturing technology, in maintaining or enhancing competitive advantage in dynamic markets.

Based on this background, the purpose is to explore AM technology integration into a global manufacturing company from an operational capability perspective. Therefore, the following research questions are suggested:

(1) What are the perceived challenges and developed operational capabilities in AM technology integration in a global manufacturing company?

(2) Which actions are essential to overcome the challenges with the developed operational capabilities for AM technology integration in a global manufacturing company?

This paper contributes new knowledge in three main areas. First, empirical insights into perceived challenges and developed operational capabilities in AM technology integration. Second, emerging theoretical insights complementing existing frameworks in AM technology integration and indications of strategic and tactical operational capabilities. Third, provides managers with a facilitation model for AM technology integration considering the deployment of essential actions that overcome challenges with developed operational capabilities .

Frame of reference

AM technology capabilities and operational capability theory

AM is referred to as the manufacturing "*process of joining materials to make parts from 3D model data, usually layer upon layer*" (ISO/ASTM 52900, 2021). AM is considered an advanced manufacturing technology (Stentoft *et al.*, 2021; Arvanitis and Hollenstein, 2001), in a similar fashion as drones (Maghazei *et al.*, 2022) and mobile robots (Fattouh *et al.*, 2023), with strengths and weaknesses different from traditional manufacturing, thus requiring new types of knowledge and technological change (Ahlskog *et al.*, 2017). AM technology resources and capabilities can be distinguished based on the added value to a manufacturing company (Klahn *et al.*, 2020; Fontana *et al.*, 2019) and its impact on areas such as product development (Renjith *et al.*, 2020), production (Holmström *et al.*, 2010), and hybrid manufacturing (Gao *et al.*, 2022).

According to Teece (2019), companies have two kinds of capabilities, namely operational capabilities and dynamic capabilities. An operational capability enables a company to conduct an activity efficiently and effectively daily in the development and production of current products and services for the current customer base (Helfat and Winter, 2011). Usually, global companies have access to a lot of operational capabilities. However, operational capabilities are "*hidden in plain view*", meaning that they exist but are often overlooked and often taken for granted and fail to generate attention from the workforce (Wu *et al.*, 2010, p. 742). An operational capability consists of parts referring to company-specific sets of skills, equipment, facilities, processes, routines, administration, and coordination developed by the company and used for efficient and effective problem-solving or fulfilling needs (Teece, 2019; Wu *et al.*, 2010).

(1) *Skills* refer to specific abilities, competence, knowledge, and expertise, used by individuals or teams (Teece, 2019; Wu *et al.*, 2010).

(2) *Equipment and facilities* refer to the required physical and digital resources, used by individuals or teams (Teece, 2019; Wu *et al.*, 2010).

(3) *Processes and routines* refer to the systematic and repetitive activities used by individuals or teams (Teece, 2019; Wu *et al.*, 2010).

(4) *Administration and coordination* refer to the resource management and coordination of efforts, used by individuals or teams (Teece, 2019; Wu *et al.*, 2010).

However, there is "*no one-size-fits-all model*" for operational capability development (Wiengarten *et al.*, 2023, p. 56). Operational capabilities can be developed through a set of mechanisms based on a knowledge-based view (Momeni *et al.*, 2023) or a resource-based view (Teece, 2019) extending a company's existing operational capability base. The resource-based view in operational capability development is crucial for leveraging tangible and intangible resources and capabilities holistically for AM technology integration rather than only focusing on the creation, sharing, and application of knowledge.

(1) *Make* refers to how companies develop operational capabilities in-house (Teece, 2019). For example, developing currently employed people and internal teams.

(2) *Rent* refers to how companies develop operational capabilities from other internal departments or external actors (Teece, 2019). For example, adding new resources or capabilities through temporary contracts and consultancy firms.

(3) *Buy* refers to how companies develop operational capabilities from external actors (Teece, 2019). For example, purchasing new machines or hiring key personnel with required know-how.

Factors affecting AM technology integration

The starting point for AM technology integration begins with adoption and implementation. The literature mainly highlights efforts in AM technology adoption implementation. Rylands *et al.* (2016) explored AM technology adoption in a manufacturing system and its business impact. Mellor *et al.* (2014) developed an AM technology implementation framework consisting of external forces, AM strategy, AM technology, AM supply chain, organizational change, and systems of operations. Deradjat and Minshall (2017) extended the framework by Mellor *et al.* (2014) to explore AM implementation for mass customization in the dental sector. Chaudhuri *et al.* (2019) explored the role of Danish and German service providers in AM technology adoption.

Before starting the journey towards AM technology integration, several factors should be considered. The frameworks by Mellor *et al.* (2014), Priyadarshini *et al.* (2022), and Yeh and Chen (2018) have been widely used in previous AM research. However, these frameworks lack holistic strategic and tactical guidance for managers in the manufacturing industry. Based on this background, five factors have been identified that companies need to consider for AM technology integration, namely:

(1) *Technology* refers to the required AM expertise of a company (Priyadarshini *et al.*, 2022; Yi *et al.*, 2019; Yeh and Chen, 2018; Mellor *et al.*, 2014).

(2) *Organization* refers to the company's characteristics and available AM resources including employees, communication, and company size (Priyadarshini *et al.*, 2022; Yi *et al.*, 2019; Yeh and Chen, 2018; Mellor *et al.*, 2014).

(3) *Environment* refers to the industry structure, the presence/absence of AM technology providers, government support, and market competition (Priyadarshini *et al.*, 2022; Yeh and Chen, 2018; Mellor *et al.*, 2014).

(4) *Value* refers to the performance-to-price offer and other cost-related factors with AM technology (Priyadarshini *et al.*, 2022; Yi *et al.*, 2019; Yeh and Chen, 2018).

(5) *Risk* refers to the resistance due to uncertainties the company encounters or perceives with AM technology (Priyadarshini *et al.*, 2022; Yi *et al.*, 2019; Yeh and Chen, 2018).

AM technology integration challenges and solutions

AM technology integration for manufacturing companies embedded in well-established traditional manufacturing technologies is a formidable undertaking. AM literature has reported a flora of studies highlighting integration challenges related to small and medium-sized enterprises (Stentoft *et al.*, 2021; Martinsuo and Luomaranta, 2018), changes in a traditional manufacturing company (Roscoe *et al.*, 2023; Mellor *et al.*, 2014), mass customization (Deradjat and Minshall, 2017), sustainability (Priyadarshini *et al.*, 2022; Alsaadi, 2021), supply chain and spare parts (Naghshineh and Carvalho, 2022; Chekurov *et al.*, 2021), make-or-buy decisions and AM management (Friedrich *et al.*, 2022; Niaki and Nonino, 2017), manufacturing engineering (Yi *et al.*, 2019), global production environments (Flores Ituarte *et al.*, 2016), and a broader perspective concerning the manufacturing industry and society overall (Yeh and Chen, 2018; Dwivedi *et al.*, 2017; Steenhuis and Pretorius, 2017). Furthermore, AM literature have provided examples of solutions to overcome the challenges. Examples of solutions include participation in non-profit business associations and collaboration with AM knowledge centers (Stentoft *et al.*, 2021; Roscoe *et al.*, 2019; Rylands *et al.*, 2016), involvement of and close collaboration with AM service providers and AM machine providers (Chaudhuri *et al.*, 2019; Deradjat and Minshall, 2017), incorporation of strategic and operative actions (Martinsuo and Luomaranta, 2018), internal and external AM know-how development (Priyadarshini *et al.*, 2022; Alsaadi, 2021; Chaudhuri *et al.*, 2019) through ad hoc problem-solving and learning-by-failing (Roscoe *et al.*, 2019), new product and production innovations (Luomaranta and Martinsuo, 2022; Flores Ituarte *et al.*, 2016; Mellor *et al.*, 2014), and make-or-buy decision strategies (Roscoe *et al.*, 2023; Friedrich *et al.*, 2022).

Research methodology

Research design

This research explores AM technology integration into a global manufacturing company from an operational capability perspective. The research followed the single case study guidelines (Yin, 2018) and took additional inspiration from longitudinal case study guidelines (Pettigrew *et al.*, 2001; Pettigrew, 1985, 1990) and process study guidelines (Langley *et al.*, 2013; Langley and Truax, 1994). Single-case studies are useful when exploring phenomena in-depth compared to superficial multiple-case studies (Yin, 2018). The guidelines from longitudinal case studies and process studies help capture *change* over time, both for the studied technology and its industrial context. Firstly, by understanding the current state by looking into the details of specific technical changes, it was possible to shift to the holistic, multifaceted, and dynamic analysis of *changing* over time (Avital, 2000; Pettigrew, 1990). The literature also requested more case study research since global manufacturing companies still experience challenges with AM technology integration (Niaki and Nonino, 2017; Mellor *et al.*, 2014). One of the main challenges in single-long case study research is to generalize the in-depth findings to other situations, contexts, or populations. To mitigate this, data collection was conducted from multiple sources of data collection, for example, two groups of participants (managers and engineers) of the collaborating manufacturing company (see Table 1). One of the authors had weekly visits to the company and was frequently active in ongoing AM technology integration activities from 2019 to 2024. Furthermore, since 2015, one of the authors developed theoretical and practical knowledge to experientially understand the potential and limitations of industrial AM technology. This was developed through teaching AM technology in mechanical engineering classes at the university, participating in AM technology education and training provided by AM actors, and participating in research and development projects, preceding the commencement of this research.

This research was conducted in collaboration with one global manufacturing company in the heavy-duty vehicle sector with factories located in Sweden and globally. The company has more than 14,000 employees and a turnover of \$5-\$10m. The company was chosen based on opportunistic sampling (Patton, 2002) since the company: (1) develops and manufactures complex products, such as heavy-duty vehicles and most of the parts and components, (2) utilizes AM technology for different operational purposes in product development and

Table 1. Summary of all the participants

Designation	Job role/title	Functional organization	Years of work experience in current role	Geographical location	AM knowledge
Participant A	Head of parts and uptime	Sales	3	Sweden	Low
Participant B	Project manager of parts	Purchasing	7	Sweden	Medium
Participant C	Head of manufacturing technology development and governance	Operations	5	Sweden	Low
Participant D	Head of research engineers	Technology	6	Germany	Low
Participant E	Head of research strategy	Technology	5	Sweden	Low
Participant F	Head of advanced manufacturing engineering and research	Operations	4	Sweden	Low
Participant G	Head of strategic procurement	Purchasing	11	United States	Low
Participant H	Head of virtual product development	Technology	19	Sweden	Low
Participant I	Head of purchasing controls	Purchasing	13	Sweden	Low
Participant J	Head of research strategy and innovation	Technology	5	Sweden	Low
Participant K	Head of business development	Purchasing	1	Sweden	Low
Participant L	Head of research strategy	Technology	1	Sweden	Low
Participant M	Head of advanced manufacturing engineering and research	Operations	1	Brazil	Low
Participant N	Product development engineer	Technology	28	Sweden	Low
Participant O	Design engineer	Technology	16	Sweden	Medium
Participant P	Manufacturing engineer	Operations	25	Sweden	Low
Participant Q	Product development engineer	Technology	35	Sweden	Low
Participant R	Production engineer	Operations	23	Sweden	Low

Source(s): Authors’ own work

production, and (3) has previous experience working with AM technology. The context of the case study focused on AM technology integration and the case focused on the actions for AM technology integration.

Data collection

Several sources for data collection are available for case study research (Miles *et al.*, 2020). The first group of participants was a focus group (Coghlan and Brydon-Miller, 2014) consisting of 13 managers (Participants A–M). There was a total of three focus group sessions from May 2021 to September 2023 and additional informal focus group sessions for knowledge-sharing opportunities. Each focus group session was between 30min and 1h. Semi-structured interviews were conducted with participants who could not participate in the focus group sessions. The second group of participants was semi-structured interviews with five engineers (Participants N–R) working in product development and production of components in gearboxes. A set of 12 conceptual designs of components in a gearbox was developed through the action design research guidelines (Sein *et al.*, 2011) and used during interviews with the engineers. The interviews were between 1h and 2h and held online. The questions used for the focus group sessions and the interviews aimed at getting insights on perceived challenges, developed operational capabilities, and essential actions to overcome the challenges with the developed operational capabilities for AM technology integration. All focus group sessions with the managers and interviews with the engineers were recorded (video and audio) and transcribed manually. All transcribed data were labeled and listed in spreadsheets sequentially for each participant (e.g. highlighting the perceived origin of the specific transcript as well as the sequential appearance in the list of transcripts). Additional data was collected from informal meetings with several of the participants and other employees, observations (e.g. factory tours, project meetings, online and offline seminars, and workshops), company documents, and extensive field notes. Multiple sources of data collection and reporting of the results back to the participants were used to enhance the validity of the research. Informal meetings with representatives from two AM actors (both actors work with developing metal AM materials and one actor offers services related to design for AM and AM production) located in Sweden that has collaborated with the global heavy-duty vehicle manufacturer were conducted to enhance the reliability of the research.

Data analysis

Several sources for data analysis are available for case study research (Miles *et al.*, 2020). Data analysis was done thematically (Gioia *et al.*, 2012) to locate emerging themes and patterns. First, the data was open-coded using colors by grouping excerpts into first-order concepts. The concepts were initially categorized based on the five factors (technology, organization, environment, value, and risk) of AM technology integration in the frame of reference, and an additional three factors emerged (usage, tradition, and image). Additionally, the concepts were grouped into the four parts (skills, equipment and facilities, processes and routines, and administration and coordination) of operational capabilities in the frame of reference, and an additional part emerged (strategy and tactics). Second, axial coding was used to group the concepts into second-order themes. Third, a higher-level abstraction of the axial coding was used by forming third-order dimensions. The dimensions provided an overview of the challenges and operational capabilities for AM technology integration. Thereafter, mapping of which operational capabilities are required to overcome the challenges for AM technology integration within each part of operational capability theory was analyzed and synthesized based on triangulation. Thereby forming essential actions pinpointing how the operational capabilities were developed and when they were prioritized. These insights became the basis for developing a visualization (Miles *et al.*, 2020) concluding as a facilitation model for AM technology integration.

This helped highlight overlapping or emerging concepts, themes, and dimensions as a contribution of new theoretical insights (Eisenhardt and Graebner, 2007; Eisenhardt, 1989). The data collection and data analysis process was done iteratively through triangulation (Flick, 2018) until reaching data saturation, meaning that additional data or analysis did not add significant new insights (Braun and Clarke, 2021; Langley *et al.*, 2013; Langley and Truax, 1994). Triangulation was performed iteratively between (1) insights from focus group sessions and interviews, (2) observations, company documents, field notes, informal meetings with several participants and other employees, and informal meetings with external AM experts, and (3) reviewing the literature, until reaching theoretical saturation. Meaning there were enough findings to answer the research questions and fulfill the purpose (Braun and Clarke, 2021; Langley *et al.*, 2013; Langley and Truax, 1994).

Results

Challenges in AM technology integration

This section provides insights into the challenges for AM technology integration, as derived fromthe case study findings (Figure 1).

Cognitive fixation. According to the focus group, some parts of the workforce were unwilling to learn a new technology, such as AM, because the learning opportunity would be too time-consuming. Coupled with a hesitant workforce, it made it difficult to combine the resources and capabilities of relatively new AM technology with already-established traditional manufacturing technology. Both the focus group and the engineers emphasized the limited knowledge of AM technology overall such as selecting materials, assuring part and process quality, and available standards. These issues have hindered the workforce from selecting parts and applications suitable for AM technology. This introduces the skills-related challenges:

(1) **Challenge 1:** *Reluctance in bridging the AM knowledge gap*

(2) **Challenge 2:** *Limited know-how of AM technology*

Manufacturing fixation. The focus group and the engineers pointed out the limited understanding of using both industrial and desktop AM technology resources and capabilities. Specifically, which AM machines and materials should be used and when, and the setup of such AM systems in traditional manufacturing environments, as well as whether there will be a need or not for additional post-processing. An observation highlighted an overall reluctance in the workforce to initiate new AM initiatives because of limited success and loss of momentum. Thereby, leaving the people involved with a limited view or negative impression of AM technology. This introduces the equipment and facilities-related challenges:

(1) **Challenge 3:** *Limited grasp of utilizing industrial AM technology*

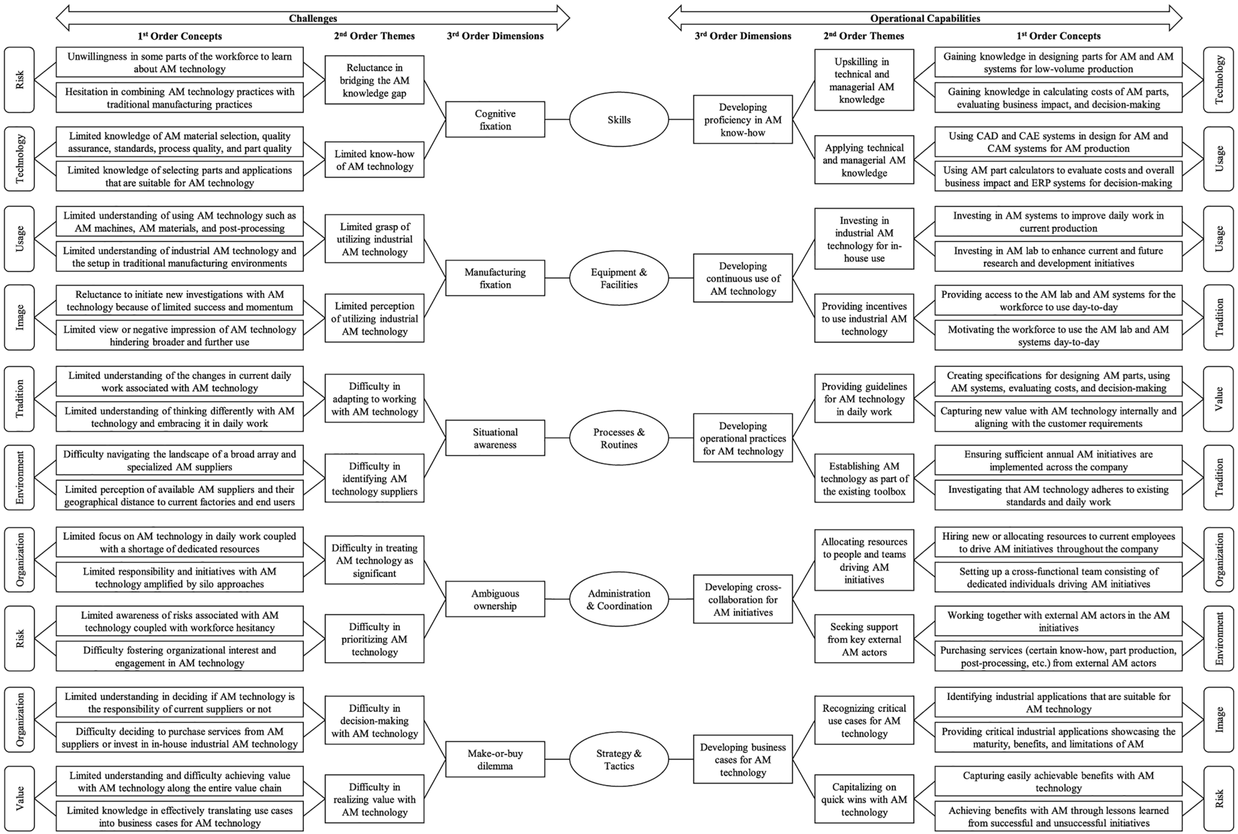
(2) **Challenge 4:** *Limited perception of utilizing industrial AM technology*

Situational awareness. Both the focus group and the engineers mentioned difficulties in thinking differently about AM technology resources and capabilities. Meaning that, for example, design engineers need to embrace design for AM in product development, production engineers need to work with AM systems as part of current traditional manufacturing production systems, and managers need to consider this new way of working with AM technology in planning and conducting future work. An observation highlighted difficulties in selecting AM suppliers due to the broad array and available specialization in specific AM materials, AM processes, and AM machines. This introduces the processes and routines-related challenges:

(1) **Challenge 5:** *Difficulty in adapting to working with AM technology*

(2) **Challenge 6:** *Difficulty in identifying AM technology suppliers*

Ambiguous ownership. According to the focus group, there had been limited focus on AM technology throughout the company in the daily work of the workforce because of limited dedicated resources and capabilities such as allocated time and budget for people. This led to departments pointing fingers regarding who should take responsibility for AM technology. This issue was amplified by individual people or small-sized teams starting AM initiatives by themselves without coordination. On the other hand, the company has had difficulties fostering interest and engagement in AM technology over the years. One main reason for this



Source(s): Authors' own work

Figure 1. Empirical findings highlight challenges (left) and operational capabilities (right) in AM technology integration

issue was the unpredictable risks with AM technology. This introduces the administration and coordination-related challenges:

(1) **Challenge 7:** *Difficulty in treating AM technology as significant*

(2) **Challenge 8:** *Difficulty in prioritizing AM technology*

Make-or-buy dilemma. According to the focus group, there have been questions regarding whether AM technology resources and capabilities should be the responsibility of the current suppliers or not. This led to extensive discussions on deciding economic feasibility through purchasing services from external AM suppliers or investing in in-house industrial AM technology. The focus group and the engineers expressed difficulties in understanding what value, aligning with the company vision, could be achieved in specific use cases with AM technology along the entire value chain. Thereafter, there was limited knowledge in translating the value and use cases into specific business cases because of the existing often low-cost traditional manufacturing production systems. This introduces the administration and coordination-related challenges:

(1) **Challenge 9:** *Difficulty in decision-making with AM technology*

(2) **Challenge 10:** *Difficulty in realizing value with AM technology*

Operational capabilities in AM technology integration

This section provides insights into the operational capabilities for AM technology integration, as derived from the case study findings (Figure 1).

Developing proficiency in AM know-how. The company made efforts to create an internal education and training program on the basics of AM technology. Moreover, certain design engineers and production engineers have gained knowledge and experience by themselves when using available in-house desktop and industrial AM machines focusing on the fused deposition modeling process and plastics such as PLA, PETG, and ABS. The design engineers and production engineers have access to AM-enabled CAD and CAE systems (e.g. CREO, OptiStruct, and Ansys) when designing AM parts and CAM systems and AM systems (e.g. UltiMaker Cura, Autodesk Fusion 360, UltiMaker S-series, Stratasys Fortus-series, and Flashforge Guider-series) for preparing and conducting low-volume production. On the other hand, managers have access to AM part calculators to evaluate costs and business impact and AM-enabled ERP systems (e.g. SAP and open-source calculators) for decision-making. Additionally, several universities, research institutes, and some manufacturing companies in Sweden provide education and training programs both free-of-charge and through payment. This introduces the skills-related operational capabilities:

(1) **Operational Capability 1:** *Upskilling in technical and managerial AM knowledge*

(2) **Operational Capability 2:** *Applying technical and managerial AM knowledge*

Developing continuous use of AM technology. The focus group and the engineers expressed interest in investing in additional polymer (e.g. Onyx and Nylon), composite (e.g. Carbon Fiber), and metal (e.g. Stainless Steel) AM systems for in-house use to improve daily work. Additionally, in the near future, having a dedicated AM lab will enhance current and future research and development. Incentives such as providing access to the AM lab and the AM systems coupled with motivating the workforce will be important for continuous day-to-day use. This introduces the equipment and facilities-related operational capabilities:

(1) **Operational Capability 3:** *Investing in industrial AM technology for in-house use*

(2) **Operational Capability 4:** *Providing incentives to use industrial AM technology*

Developing operational practices for AM technology. The company needs to have new guidelines when creating specifications for designing AM parts (moving from only using 2D drawings to also using 3D models), using AM systems (step-by-step, quality assurance, and health and safety), evaluating costs (moving from counting nuts and bolts to evaluating whole parts and assemblies), and decision-making (selecting whether AM or traditional manufacturing is more suitable). Additionally, the focus group emphasized that these guidelines should facilitate the capture of new value with AM technology aligning with customer requirements. Enough AM initiatives annually need to be implemented across the company and AM technology must adhere to existing standards to make AM technology part of the workforce's existing toolbox. This introduces the processes and routines-related operational capabilities:

(1) **Operational Capability 5:** *Providing guidelines for AM technology in daily work*

(2) **Operational Capability 6:** *Establishing AM technology as part of the existing toolbox*

Developing cross-collaboration for AM initiatives. According to the focus group, the company investigated whether hiring new people or allocating resources to current employees would drive AM initiatives. Over the years, this has led to an increased number of cross-functional teams consisting of employees from different departments. For example, one team connected production engineers, operators, and technicians from production sites world-wide to share AM knowledge and experiences monthly with each other. Most AM initiatives conducted by the company have required collaboration with external AM actors in terms of partnerships in research and development projects or through purchasing services such as certain AM know-how, AM part production, and potential post-processing. This introduces the administration and coordination-related operational capabilities:

(1) **Operational Capability 7:** *Allocating resources to people and teams driving AM initiatives*

(2) **Operational Capability 8:** *Seeking support from key external AM actors*

Developing business cases for AM technology. The focus group and the engineers highlighted the need for identifying critical industrial applications suitable for AM technology. Design engineers have used AM technology for rapid prototyping of new design concepts reducing prototyping production time from months to hours. Additionally, production engineers have used AM technology for rapid prototyping of new design concepts to reconfigure certain steps of existing production lines reducing potential future headaches. Production engineers have produced production tools (fixtures, jigs, and other tools) with polymer AM technology that replaced metal material. Furthermore, the benefits of AM technology should be captured easily, focusing on quick wins. Achieving the benefits should be based on lessons learned from successful and unsuccessful AM initiatives. This introduces the strategy and tactics-related operational capabilities:

(1) **Operational Capability 9:** *Recognizing critical use cases for AM technology*

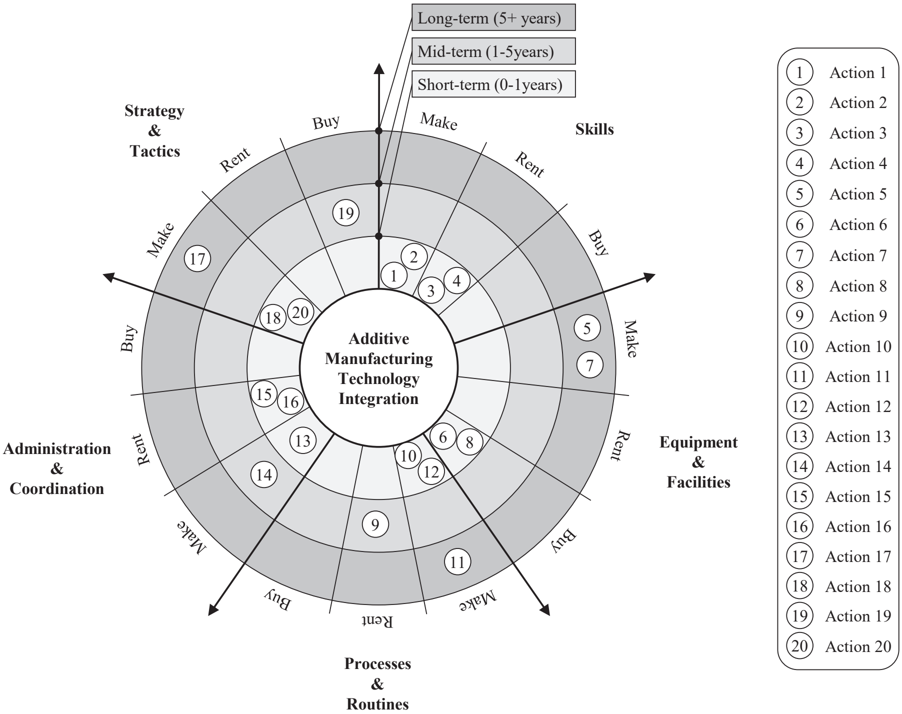
(2) **Operational Capability 10:** *Capitalizing on quick wins with AM technology*

Discussion and implications

Essential actions to overcome the challenges with operational capabilities in AM technology integration

This section discusses the essential actions to overcome the challenges with operational capabilities for AM technology integration, as derived fromthe case study findings (Figure 2).

Skills: essential actions. Although the company has made efforts to develop proficiency in AM know-how, most of the workforce still perceives a cognitive fixation, hindering AM technology integration. A few attempts from the management in providing education and



Source(s): Authors' own work

Figure 2. Facilitation model highlighting essential actions to overcome the challenges with operational capabilities in AM technology integration

training opportunities have been observed and some managers have managed to prioritize AM technology for certain design engineers and production engineers. The upskilling in AM know-how is important and should focus on ad hoc problem-solving and learning-by-failing (Roscoe *et al.*, 2019) by educating and training the existing workforce (make). The company has hired consultants temporarily (rent) to apply AM know-how in exploring the benefits and limitations of new design concepts of parts (e.g. control units) in gearboxes. However, gaining in-depth knowledge and experience in industrial AM technology takes time and should therefore be prioritized by the management as soon as possible (short-term priority for Actions 1–4). This proposes the following skills-related actions:

(1) **Action 1:** *Upskilling in technical and managerial AM knowledge (Operational Capability 1) to overcome reluctance in bridging the AM knowledge gap (Challenge 1)*

(2) **Action 2:** *Upskilling in technical and managerial AM knowledge (Operational Capability 1) to overcome limited know-how of AM technology (Challenge 2)*

(3) **Action 3:** *Applying technical and managerial AM knowledge (Operational Capability 2) to overcome reluctance in bridging the AM knowledge gap (Challenge 1)*

(4) **Action 4:** *Applying technical and managerial AM knowledge (Operational Capability 2) to overcome limited know-how of AM technology (Challenge 2)*

Equipment and facilities: essential actions. In spite of the company's efforts to develop continuous use of AM technology, the workforce still exhibits a manufacturing fixation, hindering AM technology integration. The identified investments started with purchasing services from external AM actors (buy) to evaluate and test the specific AM materials and AM systems because of the low costs (short-term priority for Actions 6 and 8). Recently, management has considered investing in additional and new in-house industrial polymer-based AM technologies (make) for the workforce to use hands-on, rather than relying on purchasing services, because of a potential positive return on investments over time (long-term priority for Actions 5 and 7). A cautious approach to these investments is a suitable first step that should escalate over time (Friedrich *et al.*, 2022; Luomaranta and Martinsuo, 2022). This proposes the following equipment and facilities-related actions:

(1) **Action 5:** *Investing in industrial AM technology for in-house use (Operational Capability 3) to overcome limited grasp of utilizing industrial AM technology (Challenge 3)*

(2) **Action 6:** *Investing in industrial AM technology for in-house use (Operational Capability 3) to overcome limited perception of utilizing industrial AM technology (Challenge 4)*

(3) **Action 7:** *Providing incentives to use industrial AM technology (Operational Capability 4) to overcome limited grasp of utilizing industrial AM technology (Challenge 3)*

(4) **Action 8:** *Providing incentives to use industrial AM technology (Operational Capability 4) to overcome limited perception of utilizing industrial AM technology (Challenge 4)*

Processes and routines: essential actions. Even with the company's efforts to develop operational practices for AM technology, the workforce shows signs of insufficient situational awareness, hindering AM technology integration. In the past five years, there has been a significant increase in workforce-wide efforts to develop guidelines for both existing and emerging AM technologies. Identifying key AM technology suppliers has been a primary early-stage priority in most AM initiatives (short-term priority for Actions 10 and 12), often driven by current employees (make). Engineers, frequently in collaboration with hired consultants (rent), have initiated the development of guidelines to help the workforce adapt to new ways of thinking with AM technology. Despite these efforts, the guidelines have not yet galvanized the workforce over the past five years (mid-term priority for Action 9). Furthermore, the majority of the workforce has encountered challenges in adapting to AM technology (long-term priority for Action 11), despite the availability of resources and capabilities such as guidelines, education, and training, aimed at AM technology integration into daily work (make). This proposes the following processes and routines-related actions:

(1) **Action 9:** *Providing guidelines for AM technology in daily work (Operational Capability 5) to overcome difficulty in adapting to working with AM technology (Challenge 5)*

(2) **Action 10:** *Providing guidelines for AM technology in daily work (Operational Capability 5) to overcome difficulty in identifying AM technology suppliers (Challenge 6)*

(3) **Action 11:** *Establishing AM technology as part of the existing toolbox (Operational Capability 6) to overcome difficulty in adapting to working with AM technology (Challenge 5)*

(4) **Action 12:** *Establishing AM technology as part of the existing toolbox (Operational Capability 6) to overcome difficulty in identifying AM technology suppliers (Challenge 6)*

Administration and coordination: essential actions. Though the company has worked to develop cross-collaboration for AM initiatives, the workforce still demonstrates ambiguous ownership, hindering AM technology integration. Management has prioritized the allocation of both work time and budgets to current production engineers (make) who were interested in AM technology (short-term priority for Action 13). However, despite these efforts, most of the current production engineers (make) still face difficulty in prioritizing AM technology because of high workloads. Managers might be willing to reduce the workloads of the engineers once the need for AM technology integration increases (mid-term priority for Action 14). Seeking support from external AM actors (rent) has been important in most of the AM initiatives, such as metal AM technology (powder bed fusion with high-strength tool steel) of new design concepts of production tools (gear cutting tool), when existing AM systems and AM know-how were insufficient. Seeking support from external AM actors remains imperative (Stentoft *et al.*, 2021; Chaudhuri *et al.*, 2019; Rylands *et al.*, 2016), especially for AM technology integration (short-term priority for Actions 15 and 16). This proposes the following administration and coordination-related actions:

(1) **Action 13:** *Allocating resources to people and teams driving AM initiatives to overcome difficulty in treating AM technology as significant*

(2) **Action 14:** *Allocating resources to people and teams driving AM initiatives to overcome difficulty in prioritizing AM technology*

(3) **Action 15:** *Seeking support from key external AM actors to overcome difficulty in treating AM technology as significant*

(4) **Action 16:** *Seeking support from key external AM actors to overcome difficulty in prioritizing AM technology*

Strategy and tactics: essential actions. Despite the company's efforts to develop business cases for AM technology, the workforce still faces a make-or-buy dilemma, hindering AM technology integration. The workforce has encountered challenges in identifying critical industrial applications suitable for AM technology, beyond rapid prototyping, production tools, and spare parts. This has impeded management's decision-making (make) regarding whether to purchase services from AM suppliers or invest in in-house industrial AM technology (long-term priority for Action 17). To date, design and production engineers (make) have leveraged AM technology for rapid prototyping, production tools, and spare parts (short-term priority for Action 18). However, additional value-added opportunities, such as custom products, process concentration, and incremental product launches, have remained largely unexplored (Klahn *et al.*, 2020; Fontana *et al.*, 2019). Enhanced designs have only been briefly investigated by the company. Some design and production engineers (make) have managed to adapt the design of certain production tools (jigs and fixtures) using polymer-based AM systems (PLA, Nylon, and fused deposition modeling), as opposed to their metal-based counterparts, within existing production lines (short-term priority for Action 20). These efforts have resulted in cost and time savings when replacing existing production tools. Consequently, management has invested in additional polymer-based industrial AM systems (buy) over the years (mid-term priority for Action 19). This proposes the following strategy and tactics-related actions:

(1) **Action 17:** *Recognizing critical use cases for AM technology to overcome difficulty in decision-making with AM technology*

(2) **Action 18:** *Recognizing critical use cases for AM technology to overcome difficulty in realizing value with AM technology*

(3) **Action 19:** *Capitalizing on quick wins with AM technology to overcome difficulty in decision-making with AM technology*

(4) **Action 20:** *Capitalizing on quick wins with AM technology to overcome difficulty in realizing value with AM technology*

Scientific implications

This research provides novel insights presented as a facilitation model highlighting the essential actions to overcome challenges with operational capabilities for AM technology integration as a response to a call by previous research (Chaudhuri *et al.*, 2019; Martinsuo and Luomaranta, 2018; Deradjat and Minshall, 2017). This research has illustrated short-term, mid-term, and long-term actions, sorted into three operational capability development mechanisms focusing on make, rent, and buy, taken by a global heavy-duty vehicle manufacturer. The presented facilitation model complements existing theoretical models, such as the V-model developed by De Lima *et al.* (2023), focusing on operational capabilities for AM technology integration. This research extended the ongoing discourse on operational capabilities (Teece, 2019; Wu *et al.*, 2010) in the AM technology integration-related literature (Roscoe *et al.*, 2019; Holmström *et al.*, 2017) by focusing on skills, equipment and facilities, processes and routines, and administration and coordination. The findings revealed the emergence of the strategy and tactics part highlighting a potential connection to strategic actions found in dynamic capabilities (Teece, 2019). Additionally, the findings extended the ongoing discourse on operational capability development in the AM technology integration-related literature (Friedrich *et al.*, 2022; Luomaranta and Martinsuo, 2022) by focusing on the resource-based view (Teece, 2019) rather than the knowledge-based view (Momeni *et al.*, 2023). The findings unveil additional factors—usage, tradition, and image—beyond the presented frame of reference (Priyadarshini *et al.*, 2022; Yi *et al.*, 2019; Yeh and Chen, 2018; Mellor *et al.*, 2014). This means that usage refers to AM technology usability and the required changes by the company, tradition refers to the new way of thinking and working with AM technology, and image refers to the positive or negative perception of AM technology. This research suggests that AM technology integration is complex affecting existing operational capabilities of global manufacturing companies (Roscoe *et al.*, 2023; Rylands *et al.*, 2016).

Managerial implications

This research shows that a global heavy-duty vehicle manufacturer still finds AM technology integration challenging despite developing various operational capabilities. These insights have led to the development of a facilitation model for AM technology integration. This model is critical for managers aiming to mitigate challenges with complex manufacturing technologies such as AM technology. Managers should evaluate the current operational capabilities and prioritize investments into new AM technologies based on short-term, mid-term, and long-term strategies, especially if cost is the main driver and of high importance. First, short-term actions are recommended for taking low-cost and low-risk investments (for example, purchasing services from external AM actors). Second, mid-term actions are recommended for taking incremental mid-cost and mid-risk investments (for example, purchasing additional in-house desktop and industrial AM systems focusing on existing and similar AM materials and processes). Third, long-term actions are recommended for taking radical high-cost and high-risk investments (for example, purchasing additional in-house desktop and industrial AM systems focusing on new AM materials and processes). Additionally, managers can further break down the essential actions into detailed activities (see first-order concepts in Figure 1) and re-prioritize the actions in the facilitation model. Managers should proactively evaluate their readiness for AM technology integration, focusing on operational capability development, with the support of the facilitation model in this research.

Conclusion

To summarize, the purpose of this paper was to explore AM technology integration into a global manufacturing company from an operational capability perspective. A single case study was conducted at a global heavy-duty vehicle manufacturing company to investigate this phenomenon. A total of ten challenges and ten operational capabilities for AM technology integration were identified. These were synthesized into essential actions prioritized either short-term, mid-term, and long-term, and further categorized into make, rent, and buy development mechanisms. The actions were presented in a facilitation model that complements existing theoretical models, offering a novel approach to AM technology integration through the development of operational capabilities. The facilitation model presented in this paper can guide manufacturing companies in developing the necessary AM operational capabilities, enabling them to enhance efficiency, reduce costs, and remain competitive in an increasingly digital and innovative manufacturing landscape.

The main limitation of this research focused on one global heavy-duty vehicle manufacturer and a limited number of participating managers and engineers in this single case study, thus limiting the generalizability of the findings. To mitigate the generalizability issue, future research should focus on additional case studies of AM technology integration in different companies, contexts, and scenarios. Additionally, insights from additional manufacturing companies and AM actors could be beneficial for future research. During the case study, several participants in the focus group changed positions within the company or left the company, while new participants were included to fill the gap and add newly employed participants with an interest in AM technology. Another limitation of this research is that the small sample size of involved participants could lead to potential bias. This could be mitigated by including more participants from similar or different departments, mentioned in this research, of a manufacturing company.

The findings represent a global manufacturer's ongoing AM technology integration journey where we were able to continuously observe and involve ourselves in, at times, critical AM initiatives. The facilitation model with an overview of the essential actions for AM technology integration has not been empirically tested and evaluated. This was not intended in this study, but rather to provide new future research directions and practical guidance for academics and industry professionals. The findings can be applied to other contexts, but their suitability should be critically evaluated in relation to the application of the facilitation model.

To gain a clearer picture of AM technology integration, we propose the following recommendations for future research. First, evaluate and test the facilitation model with detailed empirical insights from different functions, departments, or scenarios in a manufacturing company. Second, explore whether certain operational capabilities can overcome certain challenges across parts (for example, administration and coordination-related operational capabilities to overcome skills-related challenges). Third, explore the emergence of dynamic capabilities in AM technology integration.

In conclusion, manufacturing companies should be aware that achieving AM technology integration requires going beyond adoption and implementation, making AM technology an integral part of existing operational capabilities. This strategic shift is not just about adopting new tools, but about rethinking and transforming core operational processes to unlock the full potential of AM technology, driving long-term innovation and competitive advantage in a rapidly evolving industry.

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