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The role of additive manufacturing in industry 4.0: An exploration of different business models

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ABSTRACT

Purpose: The rising interest in the integration of digital advanced manufacturing and production systems in the Industry 4.0 context is one of the main factors in the introduction of Additive Manufacturing (AM). The novel technology might change the way firms operate, and the way they interact with consumers, opening new horizons for an improved profit margin and more sustainable business models. The research presented a comprehensive review on the potent role of AM in adhering to customers' complicated and unique needs using various technologies and techniques, as it discussed the role of AM in introducing new business models that increase the business competitiveness and profitability through an optimisation of production processes. In addition, AM is grasping with innovative solutions varying from waste reduction to shorter supply chains to longer products lifecycle, incentivising firms to adopt it for the economies realised on materials, energy, and costs. Notwithstanding, AM implementation is still in its infancy and faces technical challenges of capability, IT integration, and outcomes.
Design/Methodology/approach: This research is based on a quantitative approach that was administered online by means of a highly structured online survey, which aim was to collect primary data that fills the gaps of the research hypotheses due to the lacking nature of research papers exploring them. Therefore, the literature review was a paramount phase in acquiring empirical knowledge about the problem background and concept boundaries that shaped the topic's core objectives and research questions from the lacking nature of explored areas.
Findings: This research investigated the role of AM in industry 4.0 by exploring its impact and intersection with AM firms' business models while exposing the limitations and challenges to its adoption within industrial contexts. The study highlighted that the AM positive impacts on companies' business models on the value chain and turnover. This study also revealed the eco-design prospect of AM that will be helpful for different firms to rethink their business models shaping them to be more cost-efficient.
Originality: This research gave insight on AM technology through a quantitative survey that mainly aimed to classify knowledge and to investigate the role of AM as a lever in improving firms' value chains through an exploration of possible intersections with business models and impacts of implementation, possible sustainability scenarios and challenges it may face within Industry 4.0 context.

Introduction

Until the last decades, production and crafting systems relied crucially on few main techniques to create parts and objects, and this was either by subtracting little by little the material from the initial input matter until it forms the desired object (also called sculpting or drilling), or by deforming materials to obtain the desired shape (moulding or folding), or through the combination or the gluing of several materials [1], or through the use of two or more of these processes which implied the use of various tools, equipment, and manpower.

In response, the interest in adopting more up-to-date technologies has highly increased in recent years within the framework of the fourth industrial revolution [2]. Thus, the urgency to adapt more production systems to the highly growing complicated production demands besides improving the capability of business models, has become a necessity to cope with the market pace and competitiveness [3]. Additive manufacturing (AM), therefore, came offering diverse possibilities to the smart manufacturing industry, allowing firms and organisations to improve their position in the market through the optimisation of labour, energy and material involved in this new way of manufacturing in order to cre-

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ate a product that allies with market's changing and various demands [4].

AM is known for being highly timesaving and cost-effective for small-batch complex geometries products, through its advanced characteristics of non-traditional mass customisation, shortening the entire product development cycle, allowing companies to replace and improve their tooling more frequently and quickly [5]. This article is going to address how AM tends to facilitate the customers and market needs in order to be more adopted by companies at some point [6] through an online survey led on active professionals in AM related companies within the UK, Europe, and the United States. The rising interest in using this novel technology has resulted from the numerous advantages giving the possibility to stand out in the market for the environmental and social virtues. The high demand for efficient industries and production facilities from the consumers and environment control agencies is pushing firms in the 4th industrial revolution to adapt more their structures and value chains [7] which will be discussed in detail in this research.

Moreover, AM has succeeded to captivate the attention of manufacturing industries in the era of industry 4.0 for the sustainable benefits it yields, including what it heralds of possibilities for shorter, more focalised, and collaborative value and supply chains and possibilities to close the loop and recycle, refurbish and repair [8]. In other terms, AM is considered similar to a biological process through the creation of layer-by-layer products, therefore, this technology is considered less wasteful than the traditional methods of production such as the subtractive ones. Besides, AM can overflow with potential sustainability benefits that decouple the impact of the industrial activities on the environment from the social and economic values, such as the extended life of products that can be realised through repairs and refurbishment tools that AM offers, as it can impact the firm's value chains through the shortening of supply chains, the innovative models as well as the possibilities for new collaborations [9].

Impacts of AM technology on sustainable business models

The adoption of AM technologies in firms within the 4th industrial era seems to herald vast opportunities and unlimited sustainable benefits [10]. With additive manufacturing at the centre, different strategies and innovative business models are being shaped in order to advert solutions and technological advanced alternatives to reduce over the entire products lifecycle, the overall environmental impact of it within the context of industry 4.0 [11].

The organizational and economic transformations in companies' business models foster the possibility to develop new environmental perspectives, especially by reducing the use of raw materials and transport due to local cycles development and diminished supply chains. Adopting AM comes with implications, amongst these is the reconsideration of firms' business models. Hence, AM fosters many opportunities for sustainability through the repair, refurbishment, and remanufacturing extending thus products' lifecycle and closing the loop and many other sustainable models.

Different authors tried to approach this impact on business models from many perspectives and sought that in order to evaluate it, they must consider a proper balance to do so. A balanced scorecard (BSC) approach invented by Kaplan and Norton was used to evaluate four common areas (Financial, customer, internal business, and innovation) variating depending on the organisation strategy [7]. Gonzalez-Varona and other authors (2020) investigated the impacts of AM on companies' sustainable business model through a case study for AM spare parts logistics and sought out that AM initiated a digital supply chain that could change business models to the best with clear benefits to SME and customers in general.

Several journal articles support the ability of AM to improve products processes and design, but few relate it to the sustainable impact of this novel technology. Despeisse and Ford (2015) explained that the freedom in shapes and geometry could generate various benefits that occur during the whole product life cycle and its material, ranging from the increased operational efficiency of AM products, their functionality and durability due to convenient material use, and ease of maintenance and manufacturing [12].

Other publications commend that the design of structures for new products could be of increased strength, stiffness, efficiency, and corrosion resistance due to the incorporation and adaptation of materials to the work environment enhancing thus the component attributes and extending products lifecycle [13]. This was the example of an EBM manufactured part that was replaced with an AM open cellular foam one, which resulted in increased efficiency of the part by 40% [14].

Aerospace is one of many sectors that benefit most from the AM technologies and sustainability impacts, due to the sector's high needs and low production scale. Researchers studied a project led by the EU FP7 MERLIN subsequent to waste generated from airline industry manufacturing processes, and which resulted in an improved AM process that is Laser Material Deposition (LMD) used in aero engines Bladed disks or blisks manufacturing. This new process nullified the waste called "swarf" that cannot be recycled arising from the previous process [8]. Additionally, the LMD process was proven to achieve 60% material savings and 30% time within the Fraunhofer ILT.

Another improvement opportunity that AM fosters is the input material, through its vast catalogue of materials and technologies. According to Lubik and Garnsey (2016), a company based in the UK named Metalysis, succeeded in commercialising a new process called "FFC" used to produce titanium powder with lesser energy consumption and lesser toxicity through the use of AM technologies. Besides, recycled materials as inputs in the AM processes have been proven to be an innovative solution studies have found, printers based on the Fused deposition modelling (FDM) process, use recycled plastic filaments that have been created from past misprint, undesired outputs, and other commonly recycled material, thus minimising the waste [14] . Research leverage within companies adopting AM is highly encouraged to develop new innovative solutions. Authors also described that AM fosters different changes in companies' sustainable business models changing their value proposition for the better [15].

On the other hand, AM implementation within industrial environments remains a challenge itself. This novel technology success highly depends on many other factors ranging from technical and social to legal. Therefore, many challenges have arisen with the emergence of this novel technology, such as the lack of understanding and expertise in AM, the quality of printed products, the absence of standardisation and guidelines to its processes which represent the biggest challenges for this new invasion to take place. This also will be reviewed and discussed throughout this article to organise the body of knowledge and surround the topic from all the perspectives to better understand the role of AM technologies in the era of industry 4.0.

Overall, this paper attempts to surround and underline many dimensions of the AM technology for a better understanding of this novel technology role in the frame of industry 4.0, through an exploration and insights on customers satisfaction, impact on business models and business sustainability, outlining the possible challenges that AM implementation may be facing in the industrial context of industry 4.0. Furthermore, the sustainability aspect in additive manufacturing will be also investigated throughout this paper by studying the potential of reducing waste, material consumption optimisation, and shortening the supply chains and thus impacting the companies' sustainable business models. And finally, the research paper will dive into the constraints and challenges this novel technology implementation may face in Industry 4.0.

Methodology

This research is based on a quantitative approach that was administered online by means of a highly structured online survey, which aim was to collect primary data that fills the gaps of the research hypotheses due to the lacking nature of research papers exploring them. Therefore, the literature review was a paramount phase in acquiring empirical knowledge about the problem background and concept boundaries that shaped the topic's core objectives and research questions from the lacking nature of explored areas.

Hence, with AM being a futuristic lever in manufacturing in the era of industry 4.0, there was a need to explore its role in this industrial revolution through an investigation of its impact on different business models within companies and firms adopting it. In addition to shaping the research core objectives, another result of investigating and evaluating the existing literature was forming a questionnaire utilised to address the research objectives such as in

The data gathering tool consisted of a descriptive online survey that highly assisted in investigating participants opinions, attitudes, and preferences. The questionnaire was structured in Google forms research platform, due to the ease and trustworthiness of its links, making it easier to gather data amongst professionals through an easy interface that requires no software to access it. Besides, Google Forms is endowed with a transparent link property that displays its content, thus negating any suspicious activities doubts amongst the addressed professionals which could have interfered between parties and limited their cooperation.

The survey involved a set of 26 closed type questions, 10 of them were multiple choice questions, 13 Likert scale that participants had to answer with 1 to 5 points, and 3 open-ended text field questions.

Theoretical background

The current paper revealed the role of AM in industry 4.0 through exploring different firms' business models and relied on previous research articles to discuss and explore the literature of this novel technology, that only a few included practical experimentations on the various AM impacts on business models. These gaps orientated more the objectives and the discussion of this research that were explored in order to reap the maximum rewards from AM. Moreover, a few publications explored the role of AM implementation on firms that previously relied on conventional methods, creating an insufficiency on empirical research that supports the results.

At the current time, AM is considered to be a game changer in the different industrial sectors that started to raise interest in using it for rapid prototyping (RP) as well as manufacturing products and research and development (R&D). This research paper predominantly focused on results collected from AM companies located within UK, Europe, and America. Hence, in order to make these findings more applicable generally, it is required to explore the research objectives within other world countries' firms that adopt AM in their industrial environments. Besides, another possible limitation is the size of surveyed companies that consists of small to medium-size ones (SME) and start-ups, which can possibly differ for larger size companies and organisations which implies a need for future search to target larger size companies.

Another serious limitation is the absence of empirical on AM business value creation and its impact on customer related issues, where research is needed to investigate the effects of AM implementation on firms' performance with a focus on structures and decisions made to adapt to this novel technology, which will clear the fog on how AM affects businesses moving from knowledge scenarios into facts. Therefore, researchers are required to explore the role of AM in industry 4.0 from a business models perspective with a focus on the added value and value creation that AM brings to the table. Additionally, a need to realise further conceptual framework research on the sustainable side and benefits that AM holds while investigating the related research areas such as materials, energy, and environmental science.

Future research is suggested to demonstrate how AM complex geometry and choice of material can be more rentable to companies from a sustainable and beneficial point of view, with insight on the complete life cycle data of these AM manufactured products compared to conventionally produced ones. Without neglecting the urgent need for empirical studies to be conducted on how AM firms can tackle the challenges resulting from its implementation such as mechanical properties, standards, and quality challenges while exploring the optimal use of this novel technology within industrial contexts. Besides, research is required on the competencies and skills that are needed to adapt firms to additive manufacturing in order to keep a competitive position in the market.

Results

A qualitative analysis was performed by mean of a questionnaire that consisted of 26 questions subdivided into 4 categories and areas aiming to answer the four objectives of the research scheduled as follows: the role of AM in facilitating customers' needs, the intersection between AM and organisations Business Models, the impact on sustainability, and challenges facing this new technology. (Fig. 1)

The survey was answered by 34 professionals from the AM industry, active in various industrial sectors as in Fig. 2 ranging from: 'Manufacturing and Processing' with 15 respondents (44.1%), 'Engineering' with 8 persons (23.8%), and 'Healthcare' sector with 4 participants (11.8%) and the rest from different other backgrounds such as the electrical and automotive sector.

The majority of respondents were active within small and medium-size firms and businesses located in the United Kingdom, Europe, and America. The oldest of these companies inducted AM into their processes since 1996, and the most recent AM adoption dated in 2019. The survey participants occupied different roles within their firms but shared a common interest and involvement with the AM industry. To give a clear insight of the respondents' occupations, the survey resulted in the participation of 4 Process engineers, 4 Application engineers, 3 CEOs, and other roles such as "Lead photonics engineer", "Rapid prototyping engineer", while AM technicians and R&D staffs also took part in this survey. The survey respondents were asked about years of their experience and involvement within the AM industry, 18 respondents (53%) declared to have from 1 to 5 years' experience, 12 of them (36%) indicated to have more than 5 years of experience, while 4 participants (11%) had less than a year of experience within AM sector.

One of the most crucial assets that formed the selection criteria is the involvement of these companies in the field of AM. Therefore, the questionnaire investigated the degree of implication of these firms with AM through enquiring whether their reliance on AM was partial or total, in order to have more in-depth insights into these firms. Concerning the profile of companies, the investigation resulted in a majority of (61.8%) or 21 companies from 34 which totally relies on AM in their processes while the other 13 companies (38.2%) are involved partially in AM.

Thereafter, respondents were asked to rate on a Likert scale from 1-low to 5-high, the extent to which customers' resort to AM when the geometries of products they want to create are complex and harder to shape by the traditional manufacturing methods. Most of the answers 70.6% (24 answers) pointed out that customers are very likely to choose AM to manufacture highly customised and complex parts and Fig. 3 validates the result.

The next question investigated the degree of satisfaction that customers can get when the mass customisation process that AM fosters is employed to answer their needs and requirements. Based on the qualitative insights in the Likert scale represented in Fig. 4, a majority of 67.6% confirmed that customers within various industrial sectors that implement AM, are highly satisfied with the use of this AM property that enables them to combine flexibility and customisation to create a custom-made product created specifically to satisfy their unique needs and requirements. With mass customisation being highly related to the 3DP world, the work on digital channels allows manufacturers to develop products and services in order to adapt them to the specific needs and expectations of a consumer, without having to change their digital and physical production chain. This method of production is highly existent in the medical and dental industry (specifically hearing aids,

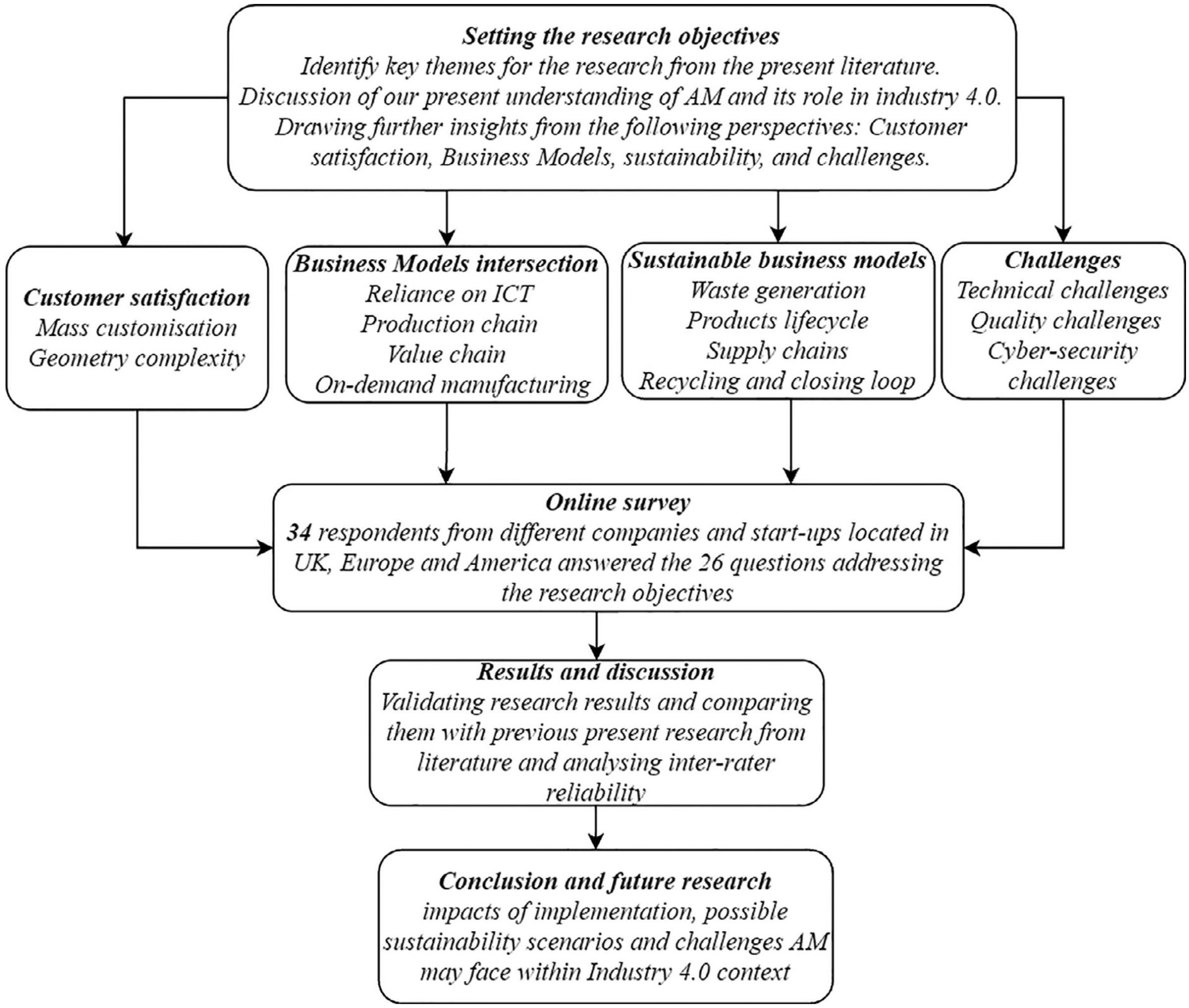

Fig. 1. Research framework diagram.

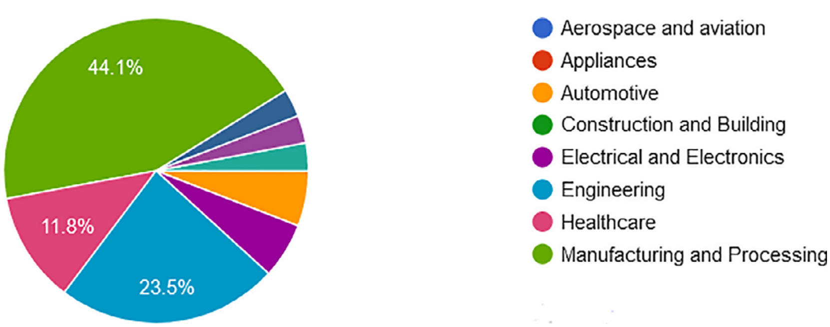

Fig. 2. Survey respondents' industrial sectors background.

dental products, and surgical applications) [16] from which 4 respondents made part in this survey.

In question 8, participants were invited to answer whether their customers were satisfied with the speed that AM offers to deliver their products on a Likert scale 1-Unsatisfied to 5-Very Satisfied. Therefore, 14 persons (41.2%) were neutral about it, while the other majority (41.2%) confirmed the satisfaction of their customers with the delivery speed, and only 6 persons (17.7%) negated the fact. Fig. 5 represents the quantitative data represented with simple colon charts underneath.

Afterward, the survey participants were enquired concerning their firms' reliance on information technology (IT) when AM has been adopted into their processes. However, 20 persons (58.8%) confirmed that AM has forced their business to rely more on IT along with the processes. The quantitative data in Fig. 6 validates the result.

Survey participants were asked about their companies' internal processes, whether they remarked any changes concerning the production machines and chains, tools, and also if they witnessed any changes in the roles of the employees after the AM technology has been inducted into their organisation processes. A prevalence of (78.1%) positive answers were recorded, and only (12.5%) of the answers were negative as is shown in Fig. 7 underneath.

Subsequently, there was a need to investigate whether AM adoption improved the business value chain, in order to explore more the impact of this novel technology on businesses, respondents were asked to approve whether they noticed any changes on the value chain. Hence, the

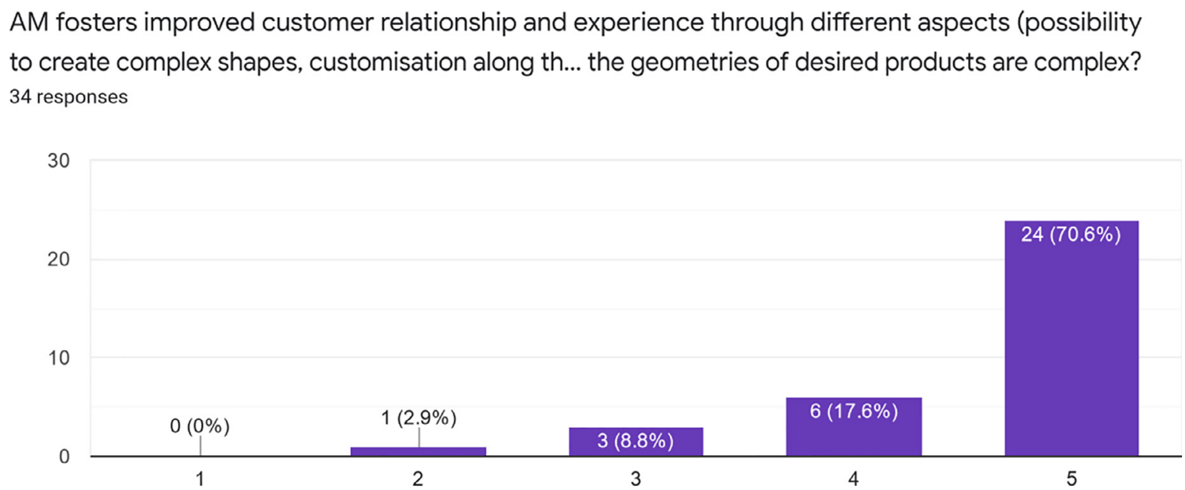

Fig. 3. Percentage of respondents approving AM use in complex shapes.

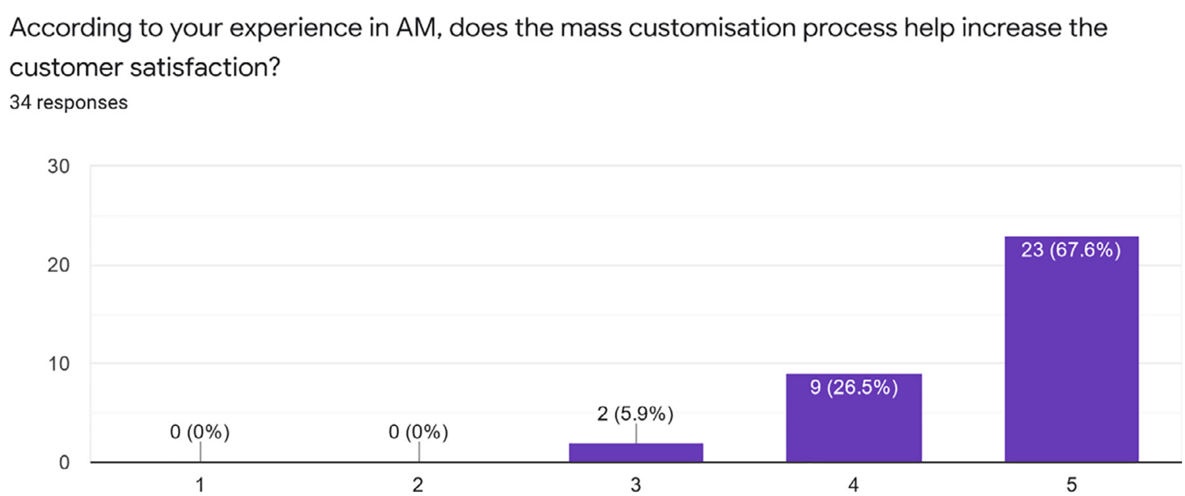

Fig. 4. Percentage of respondents approving customer satisfaction using mass customisation process.

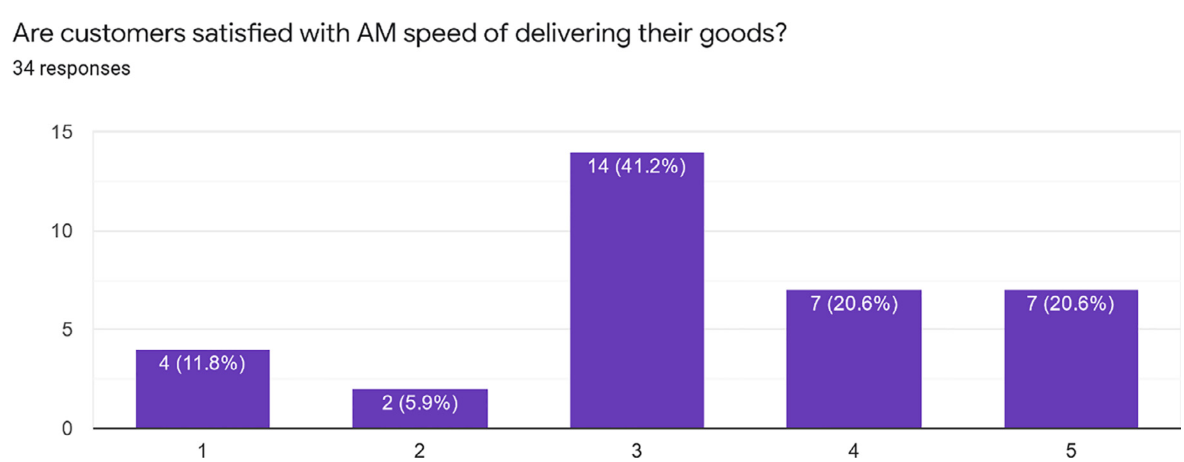

Fig. 5. Percentage of respondents answering customers satisfaction with AM speed of delivering objects.

extreme majority of answers (81.8%) were positive and confirmed the positive change, while only a small portion of the respondents (9.1%) nullified the fact. Fig. 8 illustrates the results of the quantitative data collected.

With the worldwide growing amount of data being generated through businesses relying on technology, and how it could affect the profitability of business solutions when processed and analysed, an investigation on the implementation of Big Data systems was led through the questionnaire. The qualitative insight indicated that a majority of (69.7%) respondents confirmed the use of Big Data in their companies while (30.3%) of the respondents declared that there are no such systems in their firms' processes. Thereafter, the respondents who confirmed

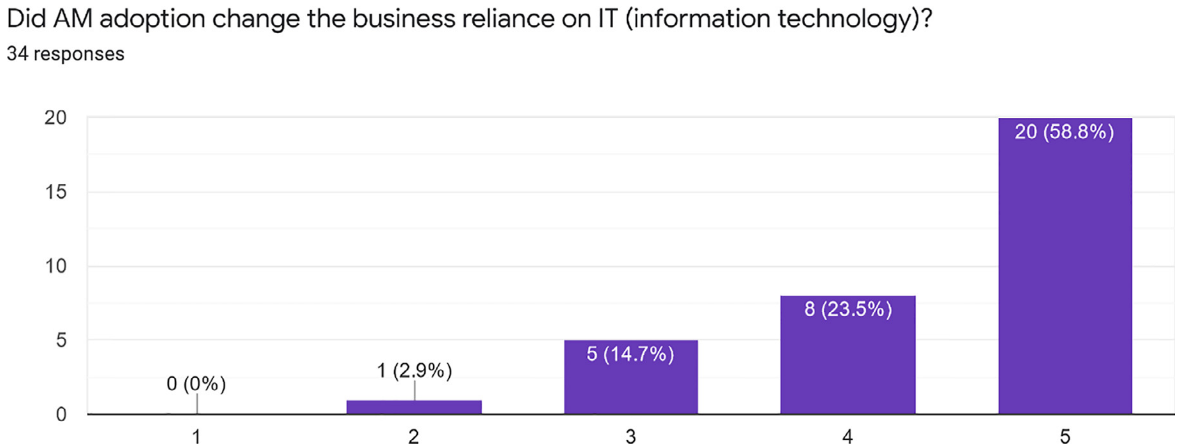

Fig. 6. Percentage of respondents confirming their business reliance on IT after adopting AM.

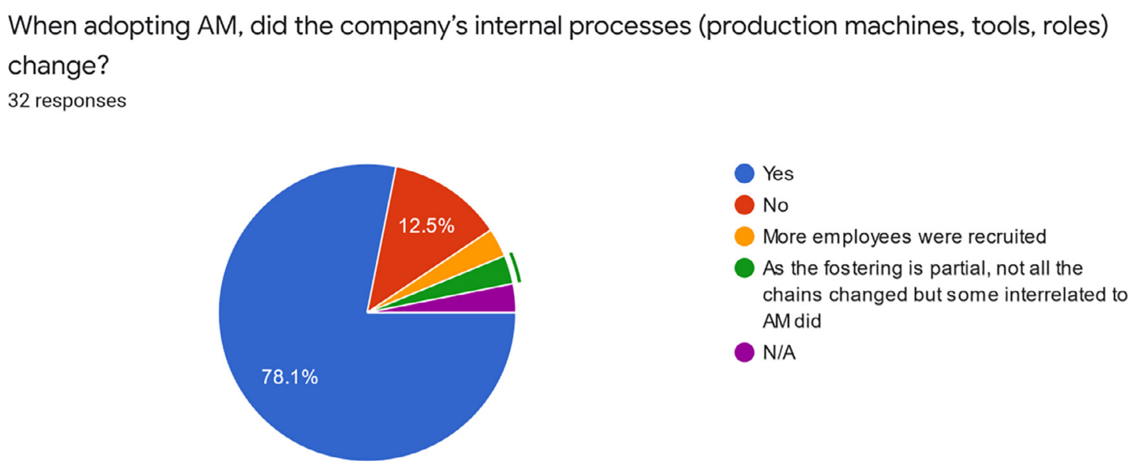

Fig. 7. Percentage of respondents reacting to AM changing internal processes of firms.

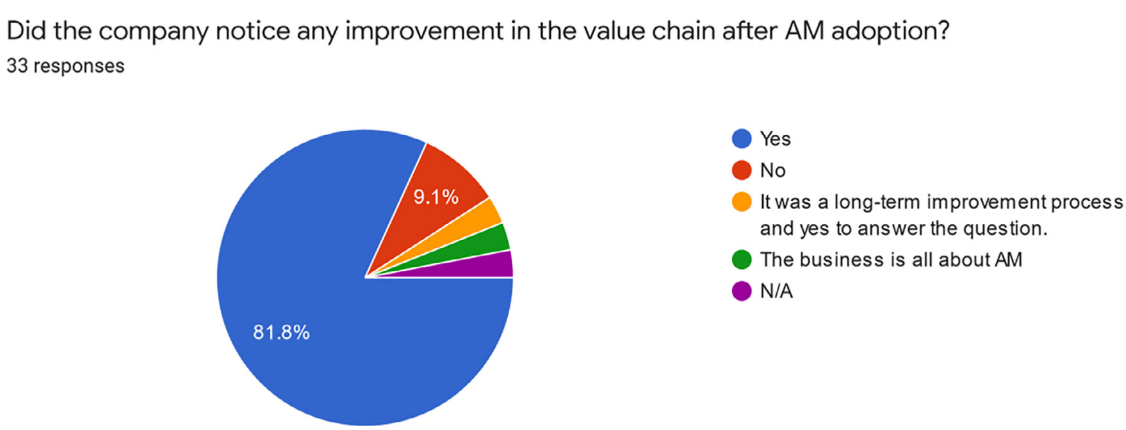

Fig. 8. Percentage of respondents confirming changes in the value chain after AM adoption.

were questioned whether the implementation of this system had any positive impacts on their company's turnover and future product improvements and choices, respondents answered accordingly on a Likert scale 1-low to 5-high. Hence, 17 of the respondents (68%) validated the fact of its positive impact on the firms' performance as shown in Fig. 9 underneath.

Participants were enquired about the use of the bridge manufacturing in their firm's production processes, which is a new term in the industry 4.0 and defines a process used to create individual low costs products and test them to confirm the goal they were set for and apply any necessary cost-efficient changes. Surprisingly, Fig. 10 demonstrated that more than (73.5%) of the respondents confirmed that their companies are using bridge manufacturing in their processes, and only (14.7%) voted for the contradictory while others detailed some of their uses out of the mass production. Furthermore, 67% of those who confirmed the use of bridge manufacturing in their firms' processes approved of the positive impact it has on the overall revenues and production experience in the firm.

The outcome in Fig. 11 is foreseeable and highly expected. Since AM is a technology made to answer the on-demand manufacturing ser-

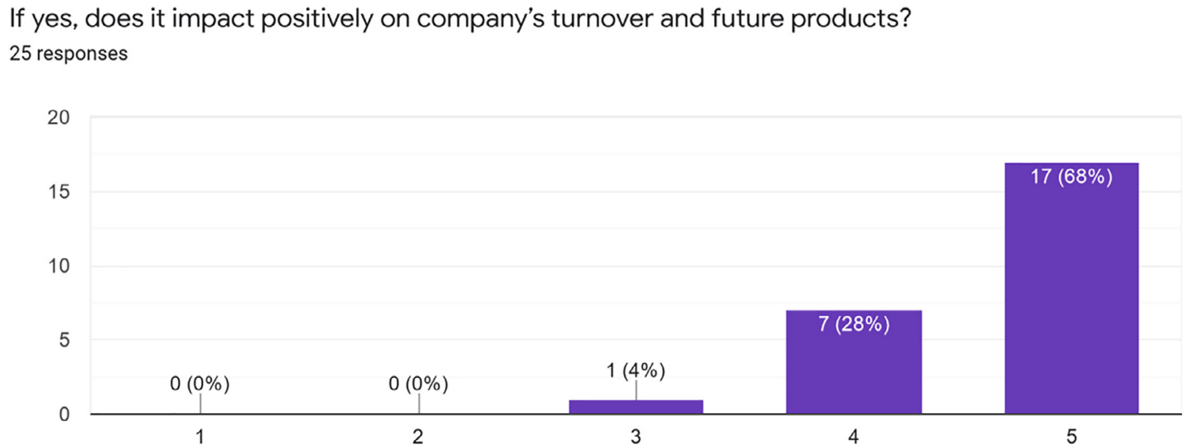

Fig. 9. Percentage of participants confirming the positive impact of Big Data systems on companies' performance on a Likert scale 1-Unlikely to 5-Very likely.

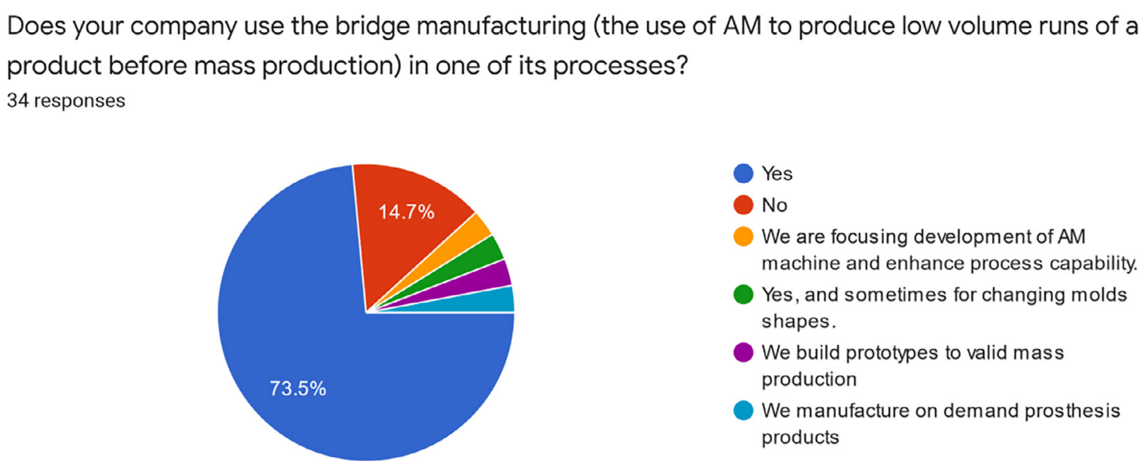

Fig. 10. Percentage of participants confirming their firms using bridge manufacturing.

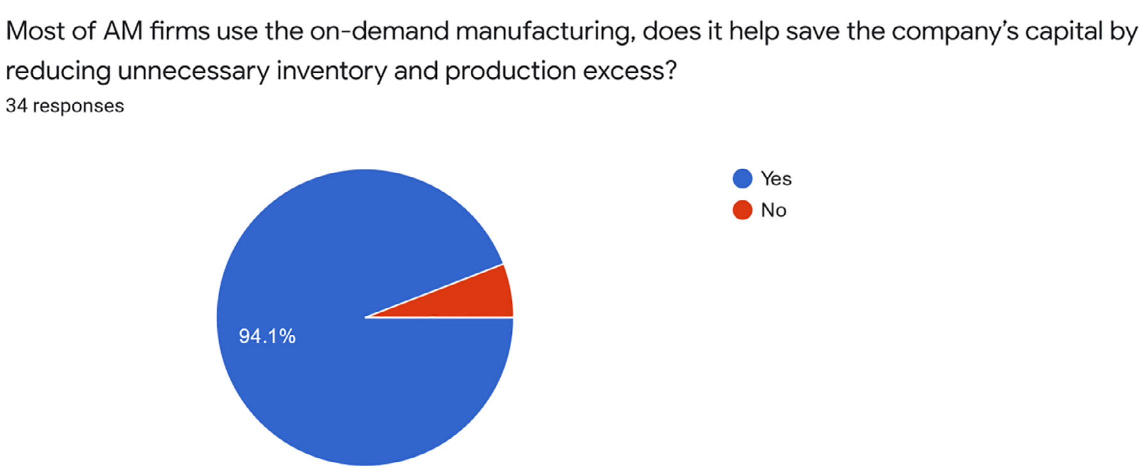

Fig. 11. Percentage of respondents confirming profitability of on-demand manufacturing.

vices, respondents were asked if this manufacturing process helped to save the company from production and inventory excess. The majority (94.1%) allocated on-demand manufacturing with being profitable and cost-effective to the company which was predictable.

Materials processing is a property that AM offers to solve many problems and adapt parts to operational environments, respondents were asked on a Likert scale ranging from 1-unlikely to 5-very likely, whether the vast catalogue of materials choice promotes a longer lifecycle for parts and products compared to the subtractive methods of production. The answers revealed that 13 respondents (38.2%) approved that material choice enhances products' life cycle and 10 others (29.4%) marked 4 out of 5, when 9 of them (26.5%) preferred to stay neutral as Fig. 12 validates the results.

From a supply chain perspective, AM was proven in previous works of literature to create a relative reduction within firms' supply chains. The in-house productions of spare parts and electronic designs reduce

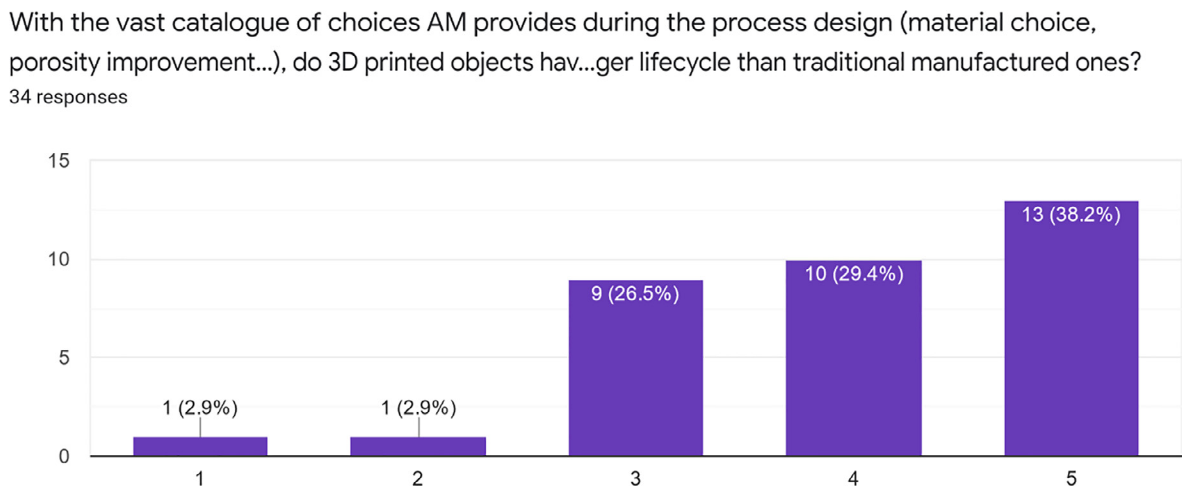

Fig. 12. Percentage of respondents confirming that material choice enhances products lifecycle on a Likert scale 1-Unlikely to 5-Very likely.

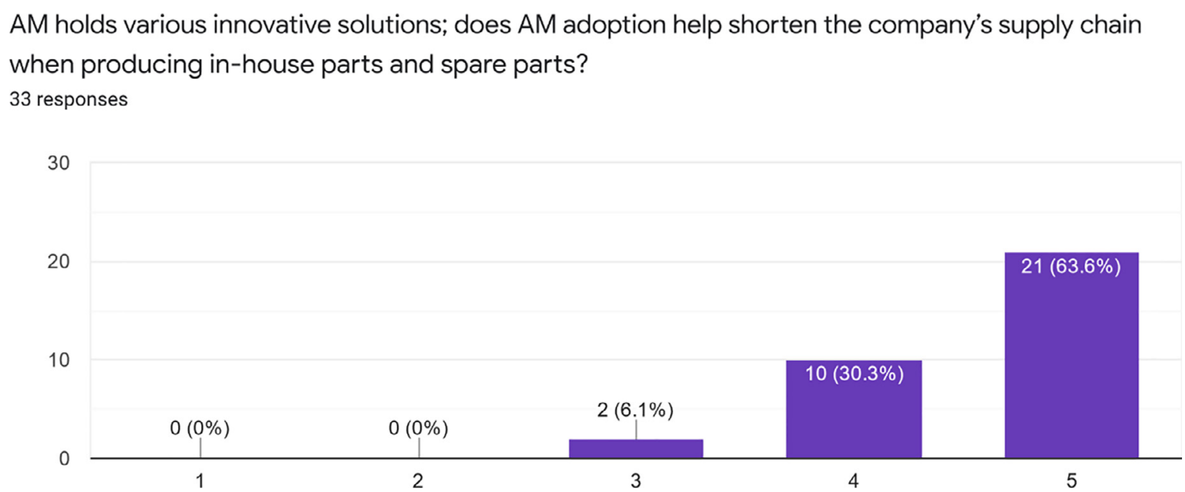

Fig. 13. Percentage of respondents confirming AM minimising supply chain.

logistics and cause some of them to be cancelled, while the materials will be the only remaining and most significant part of the transportation [17].

This can only speak to an intense reduction in businesses logistics activities, especially with the outcomes that could be produced in any location reducing transportation and warehousing costs. Fig. 13 demonstrated the percentage of respondents confirming that AM tends to shorten the supply chain and logistics of a business when producing in house products and spare parts, 21 of them (63.3%) declared that it was very likely to happen, and 10 of survey respondents (30.3%) marked a 4 on 5 in a Likert scale representing 1-unlikely to 5-very likely. Concerning the sustainable side of businesses, respondents were enquired about the implementation of any closed-loop or recycling strategies in their firms, the majority (52.9%) denied the fact, while (47.1%) of the respondents confirmed adopting AM innovative solutions within their businesses. The result is shown underneath in Fig. 14. Respondents that answered yes were questioned whether the recycling process impacted positively on the company's revenues, answers resulted in 61.1% of the respondents approving.

For a better understanding and further the examination of barriers that stand between AM implementation within industrial environments, the questionnaire involved 4 questions investigating this research objective. At first, respondents were asked whether the technical knowledge and software skills imposed any problems when implementing AM within a new business, answers were on a Likert scale starting from 1-unlikely to 5-very likely. The highest column of the chart was of respondents agreeing with 14 people (41.2%), the second column was of 11 respondents (32.4%) who also agreed with a 4 on 5 in the Likert scale, when 6 persons (17.6%) preferred to stay neutral and only 3 persons (8.8%) denied the fact. Fig. 15 is validating the presented results.

Secondly, there was an examination amongst the AM professionals about the potential risk that digital threads may be exposed to through the security breaches still unexplored, and if these drawbacks limits AM implementation possibilities. The qualitative answers led on a Likert scale resulted in 13 answers (39.4%) being neutral, 9 respondents (27.3%) confirmed that these cybersecurity threats represent a serious limitation for AM, and only 3 respondents (9.1%) denied the danger of this con. Fig. 16 underneath summarises the findings.

To further examine the challenges AM implementation is facing, there was a need to question if the quality issues that AM outcomes face representing a serious limitation to AM implementation. With that being said, the results of the survey are represented in Fig. 17 revealed that 16 respondents (48.5%) showed a neutral point of view, while 9 respondents (27.3%) marked 4 on 5 in the Likert scale, and 3 (9.1%) expressed that it constitutes a major drawback for AM implementation, and only 4 persons (12.1%) didn't consider it to be a con.

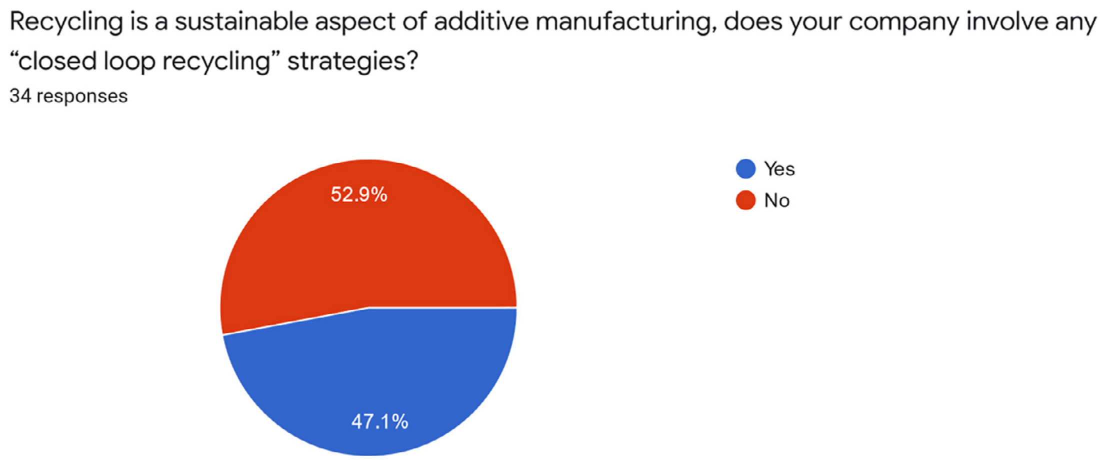

Fig. 14. Percentage of firms using closing loop strategies in their processes.

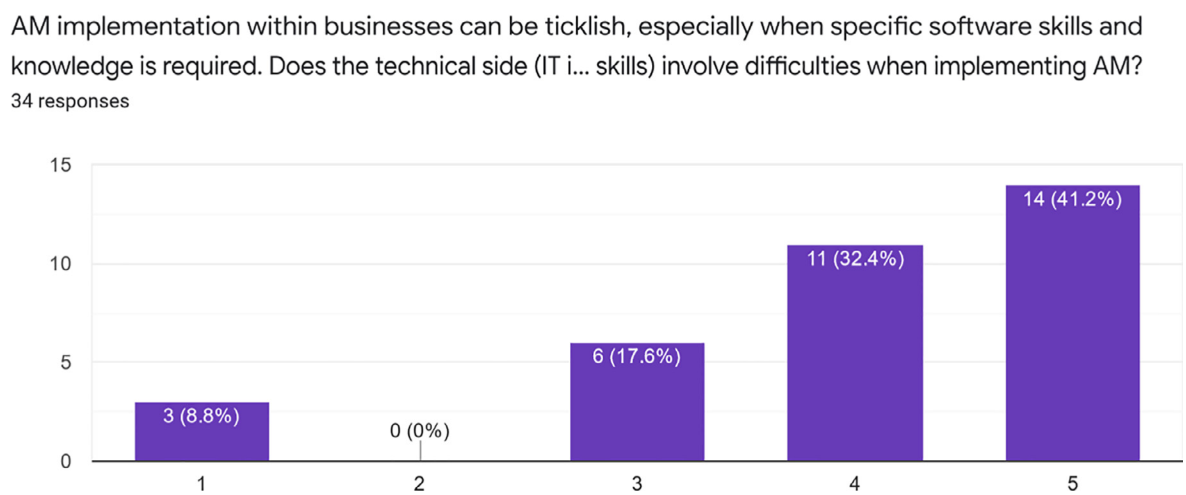

Fig. 15. Percentage of respondents confirming that AM requires technical skills and knowledge on a Likert scale 1-Unlikely to 5-Very likely.

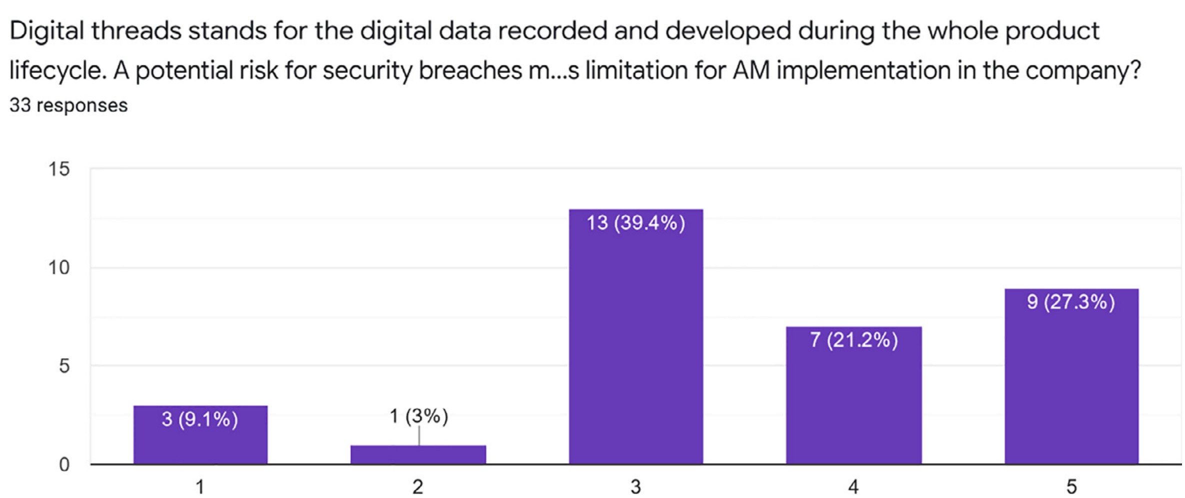

Fig. 16. Percentage of respondents confirming security breaches represent a limitation for AM implementation on a Likert scale 1-Unlikely to 5-Very likely.

And finally, to investigate the gaps in AM standardisation found in the literature, respondents were enquired about the compliance of their firms or businesses with any AM industrial standards. Based on the qualitative insights, the answers revealed that the majority (79.4%) denied it, and only (17.6%) are following AM industrial standards. Fig. 18 underneath summarises the findings.

Discussion on results

AM is defined as the process linking the usage of digital data to the creation of physical objects. The potential of AM technologies is considerable, it allows for example the direct production of complex shaped parts in small series or greater ones, with geometries impossible

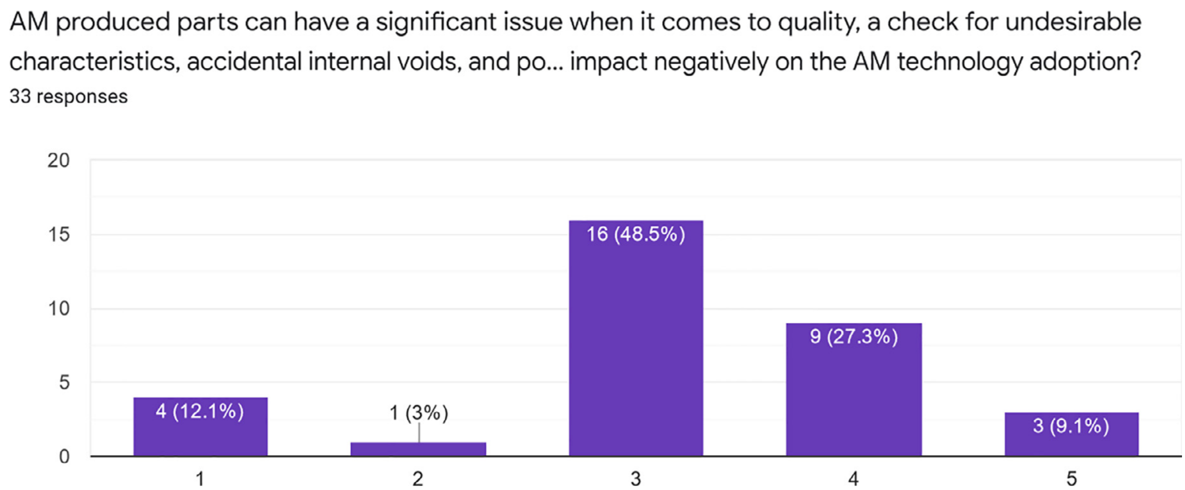

Fig. 17. Percentage of respondents' answers on the quality of AM products being a drawback for its implementation on a Likert scale 1-unlikely to 5-very likely.

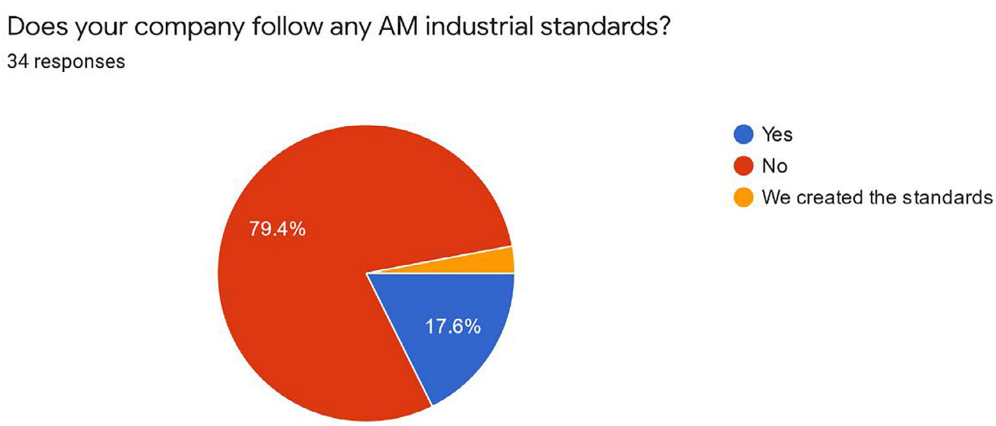

Fig. 18. Percentage of respondents complying with AM industrial standards.

to achieve through conventional processes. In addition, AM holds infinite possibilities for products customisation answering thus the growing complicated customers' and market's needs [18].

The outcomes of the qualitative data collected indicate that 70.6% of the survey respondents confirm that their customers are resorting to AM technologies when the geometries of their desired products are complex and hard to create through traditional subtractive methods. Past research already presented in literature found that AM is highly relied on by aerospace companies to manufacture compound parts and lattices of the engines that can only be produced through AM while maintaining a high performance [19].

Therefore, AM connects between the integration of mechanical functionalities and the eradication of the assembly features when creating internal geometries such as engine cooling channels that were no longer limited to large circular cross-section and instead created optimal channels with the use of DMLS technology [20], honeycomb models and topological structures optimisation that allows a reduction of weight while preserving a high mechanical behaviour [21]. Moreover, the exploitation of AM to manufacture complex shapes is not only limited to aeronautics, in the medical and dental fields, but research papers also identified the interest of these sectors in AM technologies due to the ease of transforming the delicate human body parts from 3D medical imaging data into solid objects [14] which aligns with the results of this study.

In some other applications highlighting the role of AM in facilitating the customers and markets complicated needs, studies have shown how AM is used by electronic leading companies to build complex electronic circuitry inside the printed objects also called embedded systems which is the case of the 3D printed gaming dice with electronic circuitry (microprocessor and accelerometer) detecting motion and identifying the top surface and emit a lightning strike effect through LEDS printed inside [2]. Furthermore, customer satisfaction represents a real stake in the manufacturing world. However, AM is considered to be influential when it comes to customising products. The survey findings indicate that 67.6% of respondents approve that AM mass customisation highly increases customer satisfaction through the features it offers. In this new industrial revolutionary 4th era, the integration of information technologies within the modern manufacturing environments is crucial to realise economic competitiveness, therefore survey respondents were inquired about the technological change AM brought to their business after implementation. Moreover, the outcomes of this study established a majority reaching 81.8% of the respondents noticed an improvement in their firms' value chain after implementing AM, which aligns with multiple past researches. In one of them, Tosello and other co-authors investigated the possible synergies between the conventional manufacturing methods and AM in search for optimisation of operational costs and creation of added value in the value chain production phase, they sought out an economic analysis of AM implementation in firms that it is possible to reduce the manufacturing operational costs in each produced part by 82% when using injection moulding based on AM to create inserts, and a reduction in the production lead time by 66% on tooling when using DLP for low to medium production volumes through increasing the speed of the process chain and making it more flexible [22]. This research highlights the intersection between AM and value chain business model canvas contrasting how AM can be deployed to increase profitability in firms.

From a production-based perspective, it was demonstrated that the big data analytics (BDA) system gave firms a better insight into the quality of their products through feedback data, improved the workshop scheduling decisions through enhancing the management of production equipment (speed of operation and schedule), and increasing the energy efficiency. In the same paper, the role of BDA was explored in the company's Research and development (R&D) department and been demonstrated the cruciality of this system in improving appropriate solutions in the product design phase while achieving innovation in the outcomes. In the context of product development and optimisation, bridge manufacturing can be seen as a traditional method utilised for market testing as well as orienting production of parts towards an efficient design and processing before launching its mass production. This method is commonly used when production and tooling of the part come costly, complex, and time-consuming [23]. Hence, bridge manufacturing through AM was employed by huge manufacturers such as Caterpillar to create a new oil filter and wiring harness assemblies prior to mass production readiness [24]. To investigate the reliance on the bridge manufacturing process in the AM industrial firms, a survey question inquired respondents on the use of this process in their production firms, 73.5% of the answers were positive. Therefore, the same respondents were asked if this process implementation impacted positively on production experience and firms' revenues, 67.9% confirmed that bridge manufacturing experience was very likely to boost the performance of the production and increase the revenues. In a recent research paper led by [24], the use of bridge manufacturing was explored through an investigation of the design and manufacturing process of COVID-19 protective face shields through the use of large-scale AM as a bridge manufacturing. The researchers sought out that the use of LSAM as a bridge manufacturing process helped to achieve 20 times faster production rates through optimising the design and production phases. The bridge manufacturing was firstly used to optimise the design by finding the minimum amount of material that can be used to produce the face masks, reducing the material cost and cancelling out any unrequired material present. Secondly, a toolpath optimisation was realised through bridge manufacturing, making sure that every move that print nozzles do is useful and contributing to material deposit, achieving economies on energy consumption and production time. Additionally, bridge manufacturing was also found beneficial to the production phase by minimising the risk of products being defective and print failures [24]. This paper aligns with the research findings from the survey, spotlighting the benefits and role of bridge manufacturing in AM production processes by realising economies and optimising production processes which impact positively on companies' revenues, and thus value chain business model in firms.

With all the profit possibilities that AM offers a business, on-demand manufacturing represents a crucial game changer that positively impacts firms' business models. When companies often suffer from the production excess and inventories costs implying the costs of occupied and rented physical space, utility costs, insurance, and taxes [25]; there was an urge to investigate through a qualitative analysis whether AM implementation affects this side of the business. Thereupon, 94.1% approved that AM helps to create savings on inventories costs and production excess.

From a sustainable perspective, AM implementation within business environments has the potential to create multiple innovative solutions at the sustainable level, forcing companies to reconsider their business models and change them to be more product orientated. In order to gain more knowledge about the role of AM on sustainable industry 4.0 systems, survey respondents were asked different questions exploring the extent to which AM is having an impact on their sustainable business models. Respondents were asked if AM adoption in production processes created less waste than the conventional methods, the majority of answers (61.8%) approved. The results align with past research findings, that places emphasis on AM nature of the process and studied a project led by the EU FP7 MERLIN subsequent to waste generated from airline industry manufacturing processes, and which resulted in an improved AM process that is Laser Material Deposition (LMD) used in aero engines Bladed disks or blisks (portmanteau of bladed disk) manufacturing. This new process nullified the waste called "swarf" that cannot be recycled arising from the previous process. Additionally, the LMD process was proven to reduce waste generated from the production process thus achieve savings by 60% on materials and 30% on time [8].

In another question, participants were inquired on the possibility of enhancing the durability and life cycles length of 3D printed objects through AM compared to the conventionally produced products, 67.6% of the answers were positive. These findings align with the research findings led by Ford and Despeisse (2015), through their compilation of examples from different organisations adopting AM finding that AM plays a crucial role in product life extension and durability by offering freedom of shape and geometry along with simpler assemblies that include fewer parts and material than conventional methods. Concerning business supply chains, AM may hold far reaching implications on this side of businesses that affect by itself many others, such as the customer relationship, the order fulfilment, and demand, the development of products and the returns management as well as the environment. An investigation through a qualitative survey resulted in a majority of 63.6% approving that AM helps to shorten the companies supply chains through spare parts and in-house production. Previous research papers highlighted the sustainable impacts of AM introduction in businesses and their preservation of the environment, by localising spare parts produced through AM closer to the assembly point which leads to a drastic reduction of transportation and international trade [21], shifting globalisation into the localisation and leading to shorter supply chains [22]. In another research that emphasises AM impact on sustainable business models, the novel technology is leading a disruptive change by digitising the entire design to the manufacturing chain, reducing the number of firms involved, and optimising the logistics [23]. The shortened supply chains impact positively on the environment due to the reduced CO2 emissions resulting from transportation and logistics, and additionally, the digitalisation of these latter reduce needs for materials and transportation. The findings from these past research papers align with findings from the questionnaire, pointing up the role of AM and its impact on firms' supply chains reducing the challenges these latter face after the globalisation.

Moreover, sustainable changes might impact companies' business models when adopting AM, and the closed loop recycling strategy is one of them. An urge to explore this sustainable side comes from the literature that spotlighted the potential applications of AM techniques to achieve a full closed loop control within industrial environments in order to boost their performance [24]. Therefore, respondents of the survey were interrogated at first on the implementation of any closed loop strategies inside their firms, 47.1% confirmed while 52.9% denied this implementation. Secondly, positive respondents have been inquired whether this strategy affected positively their revenues, 61.1% of the answers highly agreed. Closing the loop in AM can be realised through various phases and scales, the most rentable value recovery is the recycling of the unused material during manufacturing processes, in AM metal powders, the recycled material can go up to 98%. The AM technology has been proven to increase the potential of recovering value derived from waste with the minimum quality loss which is the case of specialised recycling companies such (Plaxica) turning PLA made from cornstarch into recycled material that can be fed back into inputs material enabling a closed loop strategy for material [25].

In addition, AM use for repairing services promotes the adoption of service-based sustainable business models, yielding higher profitability thus revenues, which is the case of Caterpillar company that used AM cold spray in the remanufacturing. According to studies, Caterpillar succeeded in achieving an average of 94% take back of end of life products, the company used this AM technology in remanufacturing its diesel engines by replacing defective parts with a mixture of new and used parts. These AM innovative repair techniques enhanced the company's profit margins by providing only 40% to 25% unused components in each new engine, leading to less scraping and waste [8] which aligns with the findings from the questionnaire, highlighting the role of AM in creating innovative solutions that incentive companies to rethink their business models shaping them to be more sustainable and thus cost-efficient.

With that being said, the implementation of AM digital technologies in industry 4.0 remains challenging and requires new adapted engineering and managerial skills in order to reap the rewards of this novel technology. Therefore, this online survey explored through its questions some of the challenges that may be facing AM in its implementation. Respondents of the survey were asked about the difficulty that their companies faced when implementing AM involving the technical skills and knowledge of the technology, the majority (73.6%) answers were positive. The results are found aligning with findings from exploratory interview-based research led on four SME acting within AM industry, showing that those SMEs find it difficult to integrate AM without new knowledge and technological skills, more know-how and educational training that shapes solutions to the uncertainties in the AM industry [26]. In another paper, Despeisse and Minshall (2017) discussed different technical barriers to AM implementation such as (design and modelling software skills, materials, processes and machines, skills and knowledge, quality, IP, and security…) and proposed recommendations to make better use of this novel technology [27].

Another serious drawback of AM implementation is the quality of the 3D printed objects, which still display defects on the surface finishing, the quality of products that often display undesirable characteristics, and unintentional voids. The questionnaire investigated whether quality defects represent a major challenge to AM implementation, 48.5% of the answers were neutral, while 36.4% were positive. In some previous research papers, quality challenges represent a major drawback after analysis of XCT data, showing that parts are affected by numerous factors such as the design parameters and complexity (height, width…) as well as the machine settings, that if not tackled properly might cause problems to businesses, the paper also proposed recommendations to enhance the quality of printed products through a 6-sigma quality control method.

However, AM relative immaturity speaking to a lack of standardisation sets which represents one of the main barriers for it to go mainstream and be implemented within industrial environments. AM standards are important pillars that can be used to endorse the technical knowledge amongst industrial firms and encourage them to adopt it. The increasing reliance of these latter in highly regulated industrial sectors is a crucial factor for AM manufactured products to meet the tight restrictions in order to build and establish trust amongst the technology adopters [8]. The qualitative results of the survey pointed out that 79.4% of the companies adopting AM do not follow any specific standards. The same findings align with findings from past research, that standardisation is a big challenge for AM implementation within industrial contexts [28], and in another case study on AM, the difficulty of creating guidelines and standards is associated with multiple factors such as applications, materials used and differences in processes. A generalisation of AM standards and guidelines is interrelated with dependencies from various activities and their stakeholders and needs to be tackled in order to encourage the implementation of this novel technology which requires collaboration and alignment from the different parties and innovative dimensions related to AM.

Main findings

The following main findings are drawn from this research.

- The potent role of AM in manufacturing unique customers' needs, enhancing the customer relationship and value creation.
- The role of AM new introduced business models in improving firms' competitiveness and profit margin through optimising production processes and realising economies on supply chains inventories enhancing thus the value chain business model.
- The incentive role of AM in deploying sustainable benefits to firms adopting it.
- AM implementation within business environments has the potential to create multiple innovative solutions at the sustainable level, forcing companies to reconsider their business models and change them to be more product orientated.
- AM enhancing the durability and life cycles length of 3D printed objects compared to the conventionally produced products.
- An investigation concluded that AM helps to shorten the company's supply chains through spare parts and in-house production.
- The implementation of AM digital technologies in industry 4.0 remains challenging and requires new adapted engineering and managerial skills in order to reap the rewards of this novel technology.

The companies adopting AM do not follow any specific standards. AM relative immaturity speaking to a lack of standardisation sets which represents one of the main barriers for it to go mainstream and be implemented within industrial environments.

Conclusions

Additive manufacturing or AM represents a crucial pioneer in leading the 4th industrial revolution through its versatility and future prospects. Despite being in its infancy, AM gained increasing popularity coming from its various benefits to companies adopting it. This research investigated the role of AM in industry 4.0 by exploring its impact and intersection with AM firms' business models while exposing the limitations to its adoption within industrial contexts.

The research spotlighted that 70.6% of the survey respondents confirmed the role of AM in accommodating the customers' growing complicated needs while strengthening their relationship with the business, by way of manufacturing their unconventional complex designs and customising products to their unique needs via mass customisation methods that bring customers closer to the design and production phases provide firms with possibilities to enhance their business models by making products more customer-centric and thus maximising the benefits.

And with AM being gradually injected as an efficient tool in the business industry, its implementation within industrial contexts comes with implications, the emergence of radically new business models or slightly different ones resulted from this adoption and has been explored throughout the paper. The research revealed that 68% respondents validated the fact of its positive impact on the firms' performance and the detailed analysis shed light on the AM different impacts on companies' business models while valorising the positive impact on the value chain and turnover, that all the new development of ICT and IoT technologies and processes such as the on-demand and bridge manufacturing that when coupled with AM tend to offer more efficient outcomes and increased value creation. Moreover, the eco-design prospect that AM holds incentivised firms to rethink their business models shaping them to be more cost-efficient. amongst these benefits, we can cite the reduced resource consumption and waste generated from production as well as the polluting manufacturing processes, the shortened and digitalised supply chains besides extending products life cycles through the vast catalogue of material choices AM provides.

The research also exposed that with all the aforementioned advantages, AM implementation still knows some limitations such as the shortage of skilled and trained AM workers and sensitization about this novel technology, besides the lack of information reliability especially that AM's cyber threats are still unexplored and remain a serious challenge to companies and businesses. Another drawback for AM implementation is the quality of printed products that lack accuracy and resolution in some cases, additionally, with AM technology being in its infancy a lack of standardisation represents another barrier for this novel technology to go mainstream and be implemented within industrial environments. Additionally, a need to realise further conceptual framework research on the sustainable side and benefits that AM holds while investigating the related research areas such as materials, energy, and environmental science. Future research is suggested to demonstrate how AM complex geometry and choice of material can be more rentable to companies from a sustainable and beneficial point of view, with insight on the complete life cycle data of these AM manufactured products compared to conventionally produced ones.

On the whole, AM technology can play the role of a game changer if the main barriers to its implementation can be addressed. It is obvious how this novel technology is highly potent in streamlining and enhancing product developments and manufacturing within shorter times and budgets than conventional methods. Hence, AM will be relied on by various industries in the future as an engineering production route that will take manufacturing to another level of complexity and flexibility at the same time while inflating businesses' value creation and turnover.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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