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Critical successes factors for the adoption of additive manufacturing: Integrated impact for circular economy model

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ABSTRACT

Additive manufacturing (AM) or three-dimensional (3D) printing is an emerging technology shaping the manufacturing industry, offering performance improvement opportunities for society and the economy. AM supports the circular economy (CE) by enabling sustainable consumption and production. This study identifies factors of performance expectancy, effort expectancy, facilitating conditions, social influence, environmental sustainability, social sustainability, technical efficacy, and government support to determine the adoption of AM with survey data collected from 487 managers of manufacturing enterprises. The study proposed a theoretical framework that integrates the Unified Theory of Acceptance and Use of Technology (UTAUT) and the Technology-Organization-Environment (TOE), providing valuable insight that can guide future research and inform decision-making in the industry. The study revealed that identified critical success factors have significantly influenced AM implementation. Furthermore, how AM adoption supports the implementation of CE, a new production and consumption model promoting sustainable growth. The study guides the managers in the connection between the AM and CE models and suggests implementing CE practices as an integral part of their AM adoption strategy.

1. Introduction

The traditional linear economy model of "take-make-dispose" has led to significant environmental degradation and sustainability challenges (Rashid and Malik, 2023). The circular economy (CE) presents a sustainable alternative that promotes resource efficiency, waste minimization, and product lifecycle extension (Lim et al., 2022; Marsh et al., 2022; Zhu et al., 2010). The CE model focused on reshaping production and manufacturing facilities, emphasizing the importance of redesigning products for sustainability, selecting sustainable materials, and optimizing manufacturing processes to minimize waste (Ellen MacArthur Foundation, 2013; Hina et al., 2022; Kandpal et al., 2024; Stahel, 1982). These efforts are crucial, as they lay the foundation for the initial sustainability of products, focusing on designing for durability, repairability, and recyclability (Bigerna et al., 2021). CE characteristics are based on restorative, regenerative, and disruptive to the economic system and reshaping the manufacturing (Fobbe and Hilletofth, 2023). Digital manufacturing (DM) is crucial in achieving a modern production system, as it optimizes production processes through emerging technologies (Stanko and Rindfleisch, 2023). Industry 4.0 encompasses the advantages of the latest production technologies (Verma et al., 2022), with additive manufacturing (AM) being one of the prominent technologies associated with the CE (Tavares et al. 2023). AM, also known as three-dimensional (3D) printing, is an emerging technology shaping the manufacturing industry, offering potential opportunities for society and the economy (Careri et al. 2023; Gardan, 2017). AM is a disruptive innovation that offers several benefits, such as rapid prototyping, manufacturing flexibility, and print-on-demand. These advantages result in reduced production waste, shorter delivery lead times, and optimized manufacturing capabilities with a cost-effective approach (Behera et al., 2021; Maresch and Gartner, 2020).

AM's flexibility and rapid manufacturing capabilities have allowed firms to adopt rapid manufacturing—also known as direct manufacturing—which is expected to revolutionize the manufacturing industry (Pereira et al., 2019). AM plays a significant role in supporting the CE by enabling a more sustainable approach to consumption and production (Ponis et al., 2021; Sauerwein et al., 2019). AM facilitates the ability to produce goods on demand and decentralized, reducing the need for large-scale mass production and excessive inventory storage (Faludi et al., 2015; H. Khajavi et al., 2018; Peng et al., 2018). This

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approach allows for a shift toward a more localized and distributed manufacturing system, where products can be made closer to the point of consumption, reducing transportation and associated carbon emissions (Mehrpouya et al., 2021; Thomas, 2016). AM enables the creation of complex and customized designs, allowing for product lifespan extension through repair, remanufacturing, and component replacement (Durakovic, 2018). By enabling the more efficient use of materials and reducing waste generation, AM contributes to the CE, where resources are kept in use for as long as possible, creating a more sustainable and resource-efficient manufacturing system (Godina et al., 2020a; Rocha et al., 2020).

Several highly technology-oriented countries, such as the United States, European countries, Japan, and South Korea, have invested significant capital in incentivizing manufacturers to embrace emerging technologies such as Industry 4.0, Artificial Intelligence (AI), and AM (Chauhan et al., 2021; Kuo et al., 2019; Niaki and Nonino, 2017). In response, manufacturing companies are undertaking technological advances and restructuring their business models to integrate these innovative developments (Keränen et al., 2021). Despite the significant efforts and encouragement that have been made, the adoption process of AM in manufacturing industries remains slow (Khorasani et al., 2022; Zhong et al., 2017). Accelerating the process is crucial to fully realize the benefits of AM, such as improved efficiency and sustainability (Laguna et al., 2021). Numerous studies have emphasized the acceptance of AM technology in manufacturing, supported by extensive literature reviews (Bikas et al., 2016; Despeisse and Ford, 2015; Hasanov et al., 2021; Horst et al., 2018; Mehrpouya et al., 2019; Pereira et al., 2019; Tamez and Taha, 2021; Ukobitz, 2020). However, empirical studies addressing the manufacturing sector's adoption or willingness to adopt AM are limited (Schniederjans, 2017).

Despite being in a growth stage within the manufacturing sector, AM holds great potential to shape the future of manufacturing in the long term. Furthermore, over the past decade, researchers have focused on evaluating the technological impact of AM (Böckin and Tillman, 2019; Ferreira et al. 2023b; Godina et al., 2020b). While a few studies have examined AM's value creation in achieving CE practices (Angioletti et al., 2016; Hettiarachchi et al., 2022; Tavares et al., 2020), the implementation of AM within the context of the CE needs to be addressed. Moreover, the factors influencing the adoption of AM need to be highlighted. The study aims to fill the research gap by providing empirical evidence and insights into the acceptance and integration of AM into the manufacturing sector. By understanding the potential of AM in achieving CE practices and identifying the factors that hinder or facilitate its adoption, this study seeks to contribute knowledge and provide recommendations for manufacturers considering the implementation of AM technologies. Specifically, it investigates the intention of Korean manufacturing industries to adopt AM technologies and how this adoption aligns with the principles of CE.

The study integrates the Unified Theory of Acceptance and Use of Technology (UTAUT) and the Technology-Organization-Environment (TOE) framework theories. These theories are widely recognized for predicting technology adoption in organizational contexts (Akinnuwesi et al., 2021; Batara et al., 2017; Hewavitharana et al., 2021; Holzmann et al., 2020; Jayawardena et al. 2023; Mukherjee et al. 2023; Ukobitz, 2020; Wang et al., 2017). The UTAUT model considers factors such as social influence (SI), effort expectancy (EE), performance expectancy (PE), and facilitating conditions (FC) in determining the intention to adopt AM. In this study, the TOE framework explicitly focuses on environmental context and the study also examines the role of sustainability in terms of environmental and social factors in adopting AM (Hegab et al. 2023a; Jayawardane et al. 2023). Government support (GS) is critical to achieving sustainability (Kurniawan et al. 2023). The study, therefore, proposes that GS acts as a moderator among environmental sustainability (ES), social sustainability (SS), and AM adoption (Top et al. 2023). However, this study proposes the inclusion of technical efficacy (TE) as a moderating variable between EE and PE, as it is important to understand how employees' perception of their competence in using the technology adoption.

Ultimately, this research is particularly significant in the Korean manufacturing industry, where staying competitive and sustainable relies heavily on technological advancements and innovation. This study guides policymakers in understanding the adoption of AM technologies for production and its implications for participation in the CE model implementation.

The remainder of the study is structured as follows: Section 2 provides a comprehensive review of the existing literature, leading to the development of study hypotheses and conceptual model. Section 3 describes the methodology employed in the study. Section 4 presents the results with data analysis. Finally, Section 5 summarizes the key findings of the research with a detailed discussion of the practical and managerial implications, study limitations, and future work.

2. Literature review, hypotheses development, and conceptual model

This section provides a comprehensive review of the existing literature on AM and CE, followed by developing hypotheses based on the UTAUT. This concludes with the presentation of the conceptual model, which integrates the reviewed literature and the formulated hypotheses to illustrate the proposed relationships among the key constructs in this study.

2.1. Additive manufacturing and industry 4.0

AM is gaining popularity and disrupting the traditional manufacturing industry. It differs from traditional manufacturing methods involving removing material from a block or volume, leading to significant waste and increased production costs. In contrast, AM adopts a "bottom-up" additive approach, reducing waste and increasing efficiency (Despeisse and Ford, 2015). AM technologies can produce complex geometries and shapes, falling into seven categories: vat photopolymerization, material extrusion, powder bed fusion (PBF), directed energy deposition (DED), material jetting, binder jetting, and sheet lamination (Horst et al., 2018; Vafadar et al., 2021). AM is gradually becoming popular and revolutionizing conventional manufacturing platforms. AM builds products layer by layer, drastically reducing material waste and improving cost efficiency (Mellor et al., 2014). This shift is disruptive, offering manufacturers a more sustainable alternative while aligning seamlessly with the goals of Industry 4.0.

The fundamental concepts of Industry 4.0 within the virtual environment include the Internet of Things (IoT), Big Data, Blockchain, Cloud Computing, Artificial Intelligence (AI), and Machine Learning (ML) (Aslam et al., 2023b, 2023a, 2022, 2021; Dilberoglu et al., 2017). In the physical realm, it encompasses Autonomous Robots, AM, and advanced sensor technologies. The physical capabilities of smart factories are currently limited by the existing manufacturing systems, making AM one of the vital components of Industry 4.0 (Parvanda and Kala, 2023; Saleem et al., 2024). Due to the increasing demand for mass customization in Industry 4.0, the development of non-traditional manufacturing methods is essential. AM, also known as 3D printing, is poised to become a key technology for fabricating customized products. This is due to its ability to create sophisticated objects with advanced attributes, such as new materials and complex shapes (Berman, 2012a). AM offers a digital manufacturing platform that is highly effective for sustainable manufacturing. It is widely utilized in various industries, including art, architecture, energy, dental, medical, aerospace, and the military (Dzogbewu and de Beer, 2023; Lakkala et al., 2023; Mobarak et al., 2023; Valtonen et al., 2023; Wang et al., 2023). AM is commonly employed for product development and prototyping. Table 1 outlines some of the advantages of AM in manufacturing industries:

Table 1
AM benefits in manufacturing.

Benefits	Reference
Flexibility in the design of products	(Berman, 2012b; Frazier, 2014; Peng, 2016)
Production of customized products	(Ford and Despeisse, 2016)
Reduced waste and material saving	(Weller et al., 2015)
Decreased the dependency on high-energy production activities, e.g., casting and forging.	(Peng, 2016)
Effective quality control	(Durakovic, 2018)
Shorter lead time and improved supply chain performance	(Attaran, 2017)

2.2. Additive manufacturing and the circular economy model

The CE concept originated in Europe and was embraced by the European Union (EU), which is actively working to shift from a linear to a circular model through initiatives promoting eco-innovation, using non-toxic substances, and the adoption of environmentally friendly raw materials (Sulich and Sołoducho-Pelc, 2022; Zisopoulos et al., 2022). The EU has set an ambitious target to fully implement a CE business model by 2050, aiming for sustainability, carbon neutrality, and a toxic-free environment, supported by robust recycling policies (Chioatto and Sospiro, 2023). Prior research in the CE domain has highlighted the need to transform production and manufacturing processes to align with sustainability goals (Butt et al., 2024; Chauhan et al., 2022; Kristoffersen et al., 2020; Pieroni et al., 2019). This involves redesigning products for greater durability, selecting sustainable materials, and refining manufacturing processes to curtail waste generation (Aljamal et al., 2024; Jayarathna et al., 2023; Neves and Marques, 2022; Tan et al., 2022). Industry 4.0 serves as a bridge, integrating CE with conventional business models through the adoption of cutting-edge technologies that enhance manufacturing flexibility and efficiency (Kazancoglu et al., 2023).

In the manufacturing sector, CE principles such as reuse, recycle, redesign, remanufacture, reduce, and recover, encourage the judicious use of resources, waste reduction, and sustainable production methods (Giannetti et al., 2023; Puntillo, 2023). AM is poised to significantly advance the principles and practices of the CE by enabling on-demand, localized production, diminishing material waste, and enhancing product longevity (Cardeal et al., 2022; Prashar et al., 2023). AM facilitates the creation of intricate and tailored designs, allowing manufacturers to produce products with optimal material utilization. This contrasts with traditional manufacturing methods, which often result in considerable material waste due to subtractive processes (Xiong et al., 2022).

AM constructs objects in a layer-by-layer fashion, using only the necessary material, thereby minimizing waste and reducing environmental impact (Jadhav and Jadhav, 2022; Ngo et al., 2018; Pajonk et al., 2022). Furthermore, AM supports CE practices such as repair, reuse, and remanufacturing by enabling the digital scanning and reproduction of parts that are damaged or out of production, thus extending the life of products and reducing the need for new manufacturing, conserving resources, and decreasing waste (Colorado et al., 2023). DM Lab of Hwacheon Machinery South Korea developed Automative Tracking (AT) technology to repair the damaged parts and sections. AT only needs the coordinates of the damaged section to be repaired. No 3D scan is required. This approach promotes a shift from the linear model toward a closed-loop system emphasizing resource conservation and product durability (Leino et al., 2016; Nascimento et al., 2019; Singhal et al., 2020). Table 2 highlights how AM technologies align with the principles of the CE through their properties and capabilities.

Table 2
AM benefits and CE.

AM benefits	Support for CE principles	CE principle
Material efficiency (Colorado et al., 2020; Monteiro et al., 2022)	AM enables precise material deposition, reducing waste and material consumption. It facilitates the use of recycled or biodegradable materials, promoting resource circularity. This supports the principles of reuse, recycling, and reducing by minimizing waste and optimizing resource use.	Reuse, recycle, reduce
Design freedom (Fitzsimons et al., 2020; Giurco et al., 2014)	AM allows for complex and optimized designs, which optimize material usage and reduce waste. By enabling the redesign of products for efficiency and sustainability, AM aligns with the principles of redesign and reduce.	Redesign, reduce
Localized production (Ben-Ner and Siemsen, 2017)	AM facilitates decentralized and on-demand production, which minimizes transportation and logistics costs. Thus, it reduces carbon emissions and supports local economies. This approach aligns with the reduce and recover principles by lowering environmental impact and enabling the recovery of value locally.	Reduce, recover
Customization (Lachmayer et al., 2017; Lacroix et al., 2021)	AM enables the production of customized products based on individual requirements, reducing overproduction and waste. By producing only what is needed, AM supports the reduce principle,	Reduce
Waste reduction (Javaid et al., 2021; Walter and Marcham, 2020)	AM reduces the generation of manufacturing waste by using only the necessary material for production. This directly supports the reduce principle by minimizing excess material use.	Reduce
Product lifespan extension (Ford et al., 2015)	AM enables the repair and replacement of specific components, prolonging the overall product lifespan. This enables the resue and remanufacturing of products, aligning with CE principles by extending the life cycle of products and reducing the need for new resources.	Reuse, remanufacturing

2.3. Hypothesis development

2.3.1. Unified theory of acceptance and use of technology, and technology-organization-environment framework

The UTAUT model analyzes users' intentions and actual usage of technology. It was developed by Venkatesh et al. (2003) by reviewing and integrating eight theories and models, namely, TAM, TPB, TRA, DOI, motivation theory, social cognitive theory, a hybrid model of TAM and TPB, and PC utilization model (Venkatesh et al., 2003). Researchers previously used these theories to explain the behavior of information system usage (Ajzen, 1991; Compeau and Higgins, 1995; Davis, 1989; Jebeile and Reeve, 2007; Lee et al., 2003; Thompson et al., 1991). The UTAUT model proposes important constructs such as PE, EE, FC, and SI to understand intention and usage behavior.

The UTAUT model is widely accepted for technology adoption issues in various domains such as smartphone adoption, e-learning software acceptance, self-technology services, and healthcare innovation (Ain et al., 2016; Nordhoff et al., 2020). This study includes four drivers - PE, EE, FC, and SI - to measure the intention to adopt AM. However, this study uses technical efficacy as a moderator for PE and EE. These variables directly influence user acceptance and usage behavior, as the UTAUT model has successfully predicted technology adoption behavior in an organizational context (Ghobakhloo et al., 2011; Oliveira and Martins, 2010; Salimon et al., 2021).

TOE framework helps to understand and analyze the adoption and implementation of technology innovations at the organizational level. TOE framework is based on three key components i.e., technology (readiness, benefits, risk, availability), organization (size, management support, culture, resources), and environments (industry type, regulatory pressure, external support) (Zhang et al., 2020). In this study, the TOE framework emphasizes examining the role of sustainability (environmental and social) in adopting AM. Additionally, TOE helps to understand the role of the government in achieving sustainability (Kurniawan et al., 2023). Thus, this study combines the UTATU and TOE to provide a comprehensive understanding of AM adoption and will lead to behaviors that support the CE model.

2.3.2. Performance expectancy

PE is determined by how much new technology enhances an employee's job performance. When adopting new technology, performance expectancy can be classified into four domains: perceived usefulness, extrinsic motivation, job fit, and relative advantages (Oliveira and Martins, 2010; Venkatesh et al., 2003). In this study, perceived usefulness refers to the employee's belief in the usefulness of AM to enhance their job performance. Extrinsic motivation is based on employees' perception that completing assigned tasks will yield valuable results and improve performance (Yeh and Teng, 2012). The job fit domain examines how new technology can enhance job performance based on its capabilities. Finally, relative advantages focus on the cost benefits of adopting the new technology, considering that AM is highly effective in improving job-related performance through enhanced production flexibility, reduced lead times, minimal waste, and improved resource efficiency (Ford and Despeisse, 2016). Therefore, PE is highly related to the intention to adopt AM, and this study proposes the following hypothesis:

H_1: PE is positively related to the intention to adopt AM.

2.3.3. Effort expectancy

In the context of accepting new technology, EE represents the level of ease associated with using the technology. In the UTATU model, the EE variable combines principles from two theories: the technology acceptance model (TAM) and the diffusion of innovation theory (DOI), specifically drawing from the concepts of perceived ease of use and complexity (Venkatesh et al., 2012). Perceived ease of use refers to an employee's belief that adopting the new technology requires minimal effort. In contrast, complexity refers to the relative difficulty of using the new technology compared to previously adopted technologies (Tahar et al., 2020). Consequently, AM technology offers a reduced production effort as its digital technology is controlled by computer-aided design software. By using AM manufacturing, organizations can produce more intricate products in terms of design and functionality at a higher volume, a capability not attainable through traditional manufacturing methods (Haleem et al., 2023). Thus, EE is highly related to the intention to adopt AM by proposing the following hypothesis:

H_2: EE is positively related to the intention to adopt AM.

2.3.4. Technical efficacy as moderator, performance expectancy, effort expectancy, and intention to adopt additive manufacturing

TE is derived from self-efficacy and refers to an employee's belief in their ability to perform a specific task or behavior successfully. In the context of AM adoption, it pertains to an employee's confidence in their ability to effectively use and implement AM technology within an organization. The employee's intention to use AM technology heavily relies on TE, wherein higher TE- leads to lower resistance and a perception of ease in utilizing the technology. Previous research has demonstrated the indirect effect of TE on various outcomes, including enhanced perceived learning, career satisfaction, and job performance (Duque, 2014; Hmieleski and Corbett, 2008; Jawahar and Liu, 2016). PE and EE capture the perceived benefits and advantages employees associate with using AM technology. It reflects the extent to which employees anticipate that adopting AM will enhance their performance, abilities, productivity, and overall operational outcomes. Thus, this study proposed the following hypotheses.

H_{3a}: TE moderates the relationship between PE and intention to adopt AM.

H_{3b}: TE moderates the relationship between EE and intention to adopt AM.

2.3.5. Facilitating conditions

FC refers to employees believing their organization possesses sufficient technical resources to adapt to and effectively utilize new technology (Mensah, 2019). A firm's intention to adopt new technology carries substantial importance, as it necessitates providing the essential technical support for successful implementation (Benbya et al., 2004; Bollinger and Smith, 2001). In the context of AM, employees must perceive that the firm has the required infrastructure, equipment, and expertise to successfully implement and integrate AM into their operations. The literature underscores the significance of FC as an influential factor in the acceptance and intention to adopt innovative technologies. Studies by Ain et al. (2016) and Venkatesh et al. (2012) highlight the importance of FC in shaping employees' attitudes and behavior toward new technology (Ain et al., 2016; Venkatesh et al., 2012). In the case of AM, employees' perception of FC will manifest in their confidence and readiness to adopt and utilize this technology, ultimately impacting the overall intention to adopt AM within the organization. By addressing FC, organizations can positively influence employees' intention to adopt AM technology and foster a culture of innovation and technological advancement within the company. Thus, this study proposed the following hypothesis.

H_4: FC is positively related to the intention to adopt AM.

2.3.6. Social influence

SI refers to the extent to which a potential adopter believes that influential organizations value the implementation of new technology, similar to subjective norms, image, and social factors in frameworks like TPB, TAM, and TRA (Venkatesh et al., 2003). Previous research has consistently demonstrated that SI significantly impacts the intention to adopt emerging technology (Ahmad and Khalid, 2017; Herath and Rao, 2009; Lewis et al., 2003; Martins et al., 2014). In the context of AM adoption, SI plays a vital role in shaping employees' perceptions and attitudes toward using AM technology in production processes. In this study, social influence expresses that employees are confident about how other important employees (e.g., senior managers, supervisors, and field workers) consider using additive manufacturing technology in production. This study investigates the relationship between SI and the intention to adopt new technology considering the AM environment by proposing the following hypothesis.

H_5: SI is positively related to the intention to adopt AM.

2.3.7. Environmental sustainability

ES is a crucial factor influencing the intention to adopt an enabled production system. Organizations increasingly recognize the importance of reducing their environmental footprint and embracing sustainable practices (Asadi et al., 2021, 2019; Yeh and Chen, 2018). AM allows for resource-efficient manufacturing processes, reducing waste and minimizing the use of raw materials. It enables the production of complex and lightweight designs, optimizing material usage. AM can facilitate local production, reducing transportation requirements and associated carbon emissions. These environmental advantages make AM an attractive choice, as organizations aim to align their operations with global efforts to mitigate climate change and promote sustainable development (Despeisse et al., 2017; Javaid et al., 2022; Niaki et al., 2019; Yeh and Chen, 2018). The perceived environmental benefits of AM, such as reduced waste and energy consumption, positively influence organizational attitudes toward adopting this technology. Therefore, this study proposes the following hypothesis.

H_6: ES is positively related to the intention to adopt AM.

2.3.8. Social sustainability

SS includes various factors, such as job creation, worker well-being, and community development (Eizenberg and Jabareen, 2017; Phillips, 2015; Roseland, 2000). By adopting AM, organizations have the potential to create new job opportunities and enhance the skills of their workforce. With advanced manufacturing techniques, organizations can streamline production processes, leading to increased productivity and, in turn, potentially creating more jobs (Calignano and Mercurio, 2023; Soori et al., 2023). AM adoption can improve worker well-being by reducing physical labor and providing a safer working environment. The technology eliminates manual handling, enabling workers to focus on higher-value tasks and reducing the risk of work-related injuries (Ambrogio et al., 2022; Leesakul et al., 2022). Organizations prioritizing employee well-being and seeing the potential to enhance worker safety and job satisfaction through AM are more likely to adopt the technology. Therefore, this study proposes the following hypothesis.

H_7: SS is positively related to the intention to adopt AM.

2.3.9. Government support as moderator, environmental sustainability, social sustainability, and intention to adopt additive manufacturing

AM adoption requires organizations to consider technical factors and broader implications, including environmental and social sustainability. Government support plays a crucial role in promoting the adoption of AM technologies by providing the necessary policies, incentives, and regulations (Kolade et al., 2022). To support sustainability, governments can introduce initiatives that encourage using AM for sustainable manufacturing practices (Guo et al., 2022). By incentivizing and promoting the adoption of AM technology, governments support organizations in reducing their carbon footprint, minimizing waste generation, optimizing resource utilization, and emphasizing job creation, skill development, and community engagement (Hegab et al., 2023b; Martínez-Peláez et al., 2023). Thus, governments play a pivotal role in boosting AM implementation, leading to improved sustainability (ES and SS). Therefore, this study proposes the following hypotheses.

H_{8a}: GS positively moderates the relationship between ES and intention to adopt AM.

H_{8b}: GS positively moderates the relationship between SS and intention to adopt AM.

2.3.10. Additive manufacturing and circular economy

AM is an innovative manufacturing that enables the production of customized and complex products through the layer-by-layer deposition of materials. This technique has gained attention for its ability to optimize material usage, reduce waste generation, and enable local production. These characteristics align well with the CE principles, which aim to minimize resource consumption, promote product reuse and recycling, and shift toward a more sustainable and regenerative economic system (Chowdhury, 2023; Piscicelli, 2023; Priyadarshini et al., 2022). CE promotes the transition from a linear "take-make-dispose" model to a more circular one where materials and resources are used for as long as possible (Rashid and Malik, 2023). AM plays a vital role in this transition by enabling on-demand production and reducing the need for large-scale manufacturing and inventory storage. Organizations can produce items locally and in small quantities by adopting AM, minimizing overproduction and waste. AM supports the principles of the CE by enabling product customization, repair, and remanufacturing. With AM technology, products can be easily modified, repaired, or reconstructed using the same or recycled materials (Ferreira et al., 2023a). This practice extends the lifespan of products, reduces the need for replacement, and contributes to a more resource-efficient and waste-free economy. Thus, the adoption of AM can be positively influenced by the principles of the CE; therefore, this study proposes the following hypothesis.

H_9: The intention to adopt AM is positively related to supporting the CE.

2.4. Conceptual model

The UTAUT and TOE provide a comprehensive framework for understanding the factors that influence both individual and organizational acceptance and use of new technologies (Akinnuwesi et al., 2021; Batara et al., 2017; Hewavitharana et al., 2021; Holzmann et al., 2020; Jayawardena et al., 2023; Mukherjee et al., 2023; Raj and Jeyaraj, 2023; Ukobitz, 2020; Wang et al., 2017). This study aims to understand the intention to adopt AM, which will lead to behaviors that support the CE model in the context of the Korean manufacturing sector. This study utilized the UTATU model to facilitate this understanding, considering factors such as PE, EE, SI, and FC that impact AM adoption. Moreover, the study also examined the moderating effects of TE on PE and EE, which provide insights into employee behavior and confidence in using AM technology. However, the TOE framework explores the sustainability aspect of AM adoption, specifically regarding environmental and social sustainability. This investigation offers a comprehensive view of how AM technology enhances sustainability. Furthermore, the proposed study delves into the role of GS as a moderator in driving ES and SS for AM adoption. Lastly, it examines the relationship between AM adoption and its alignment with the principles of the CE. Fig. 1. presents a conceptual model that illustrates all the variables considered in the study.

3. Methodology

3.1. Data collection

The South Korean government is actively promoting the adoption of Industry 4.0 to boost the economy, and one of the key technologies in this revolution is AM. South Korea relies heavily on manufacturing to maintain a competitive edge in the global market. AM technology enables the development of efficient, streamlined production processes that are cost-effective, reduce waste, and save time. As a result, South Korean manufacturing companies are eager to incorporate AM into their operations. In this study, 487 production foremen from high-tech industrial zones such as Daejeon, Ulsan, Gyeongsan, Suncheon, and Chuncheon, participated in the survey. These zones are critical innovation hubs, driving the advancement of AM, and are strategically important for fostering the technological growth of South Korea. The study ensures that production foremen are directly involved in the day-to-day operations and involve direct interaction with production processes and the use of AM. Regarding the AM adoption, currently, the AM is adopted in serval sectors such as aerospace, automotive, defense, and medical. The survey covered almost three major sectors of the aerospace, automotive, and medical industries of South Korea.

3.2. Construct measurement

The researchers carried out a careful process to develop the survey questionnaires. In this research, we measured items of a construct developed and widely adopted in previous studies. However, we modified the items to the present study context. Survey instruments were first prepared in English and then translated into Korean with the help of specialized Korean translators. Next, to ensure the accuracy and equivalence of the questionnaires, we used the back-translation method by getting the services of two independent translators to translate the Korean version of a survey into English. We asked five qualified researchers to review the final survey to analyze the accuracy and

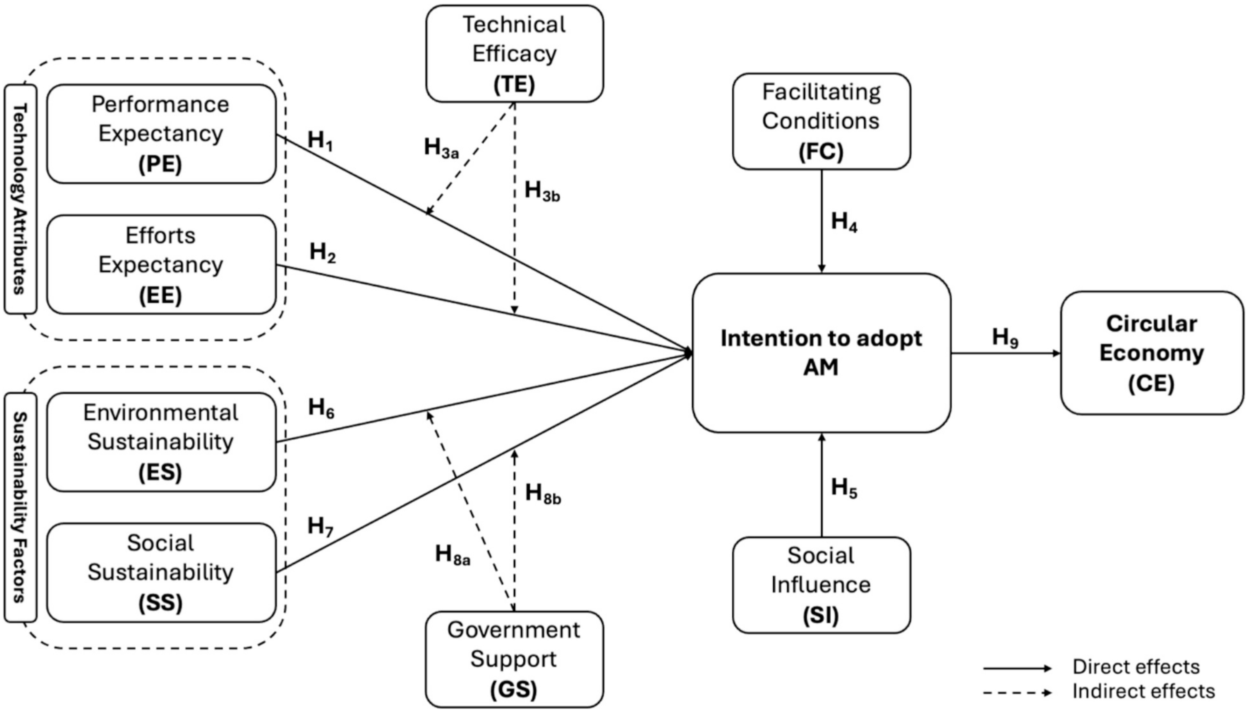

Fig. 1. Conceptual model of study.

consistency of the Korean version of the survey. These researchers had some understanding and experience of AM adoption for manufacturing, which helped us verify the validity of measures and items in the survey. Table 4 presents the variance inflation factor (VIF) value is <3.3, which indicates the study has no collinearity issue related to this research.

According to the conceptual model (Fig. 1), ten variables were used to test the hypotheses. Survey questionnaires were adopted from the literature and were measured on a five-point Likert scale ranging from 1 = strongly disagree to 5 = strongly agree. They were pre-tested to ensure the wording, structure, and format were appropriate for this study. The key factors of adopting AM, such as PE, EE, FC, and SI, were derived from UTAUT2. The PE consists of a four-item scale (Holzmann et al., 2020; Venkatesh et al., 2003), EE was based on a four-item scale (Venkatesh et al., 2003), FC was included on a four-item scale (Popov and Koo, 2020; Wang et al., 2017)), SI was based on a three-item scale (Schniederjans, 2017; Thompson et al., 1991), and intention to adopt AM was based on a three-item scale (Venkatesh et al., 2012, 2003). TE consists of a four-item scale derived from (Guri et al., 2023), SS is based on a four-item scale derived from (Dey et al., 2020; Xiao and Su, 2022), ES leads a three-item scale (Abdul-Rashid et al., 2017; Adebanjo et al., 2016), and GS consists of a three-items scale derived from (Zeng et al., 2017). Lastly, the CE is measured using a ten-item scale (Rodríguez-Espíndola et al., 2022; Zeng et al., 2017). The survey questions are attached in Appendix I.

This study also used demographic information: sector, region, respondent age, working experience in the current company, overall professional experience in the manufacturing sector, and firm size. AM has two key levels of application: i) rapid prototyping (creating various prototypes, test models, and samples) and ii) rapid manufacturing (producing finished products, equipment, tools, or parts). The study asked about the company's representation at these two levels. The response data were coded and input in SMART-PLS4 statistical software. Data were evaluated with statistical analysis in demographic, descriptive, correlation, reliability, factor loading, validity, and regression analysis.

4. Data analysis

4.1. Demographic analysis

This study examines the demographic information to evaluate the respondents' responses. Table 3 expresses the respondent profile.

Table 3
Respondent Profile.

Demographic question		Frequency	Percentage
Industry Sector	Aerospace	25	5.1
	Automotive	357	73.3
	Medical	105	21.6
AM level	Rapid prototyping	362	74
	Rapid Manufacturing	125	26
Region	Deajeon	187	38.4
	Ulsan	120	24.6
	Suncheon	80	16.4
	Chuncheon	40	8.3
	Gyeongsan	60	12.3
Respondent Age (Years)	18–25	0	0
	26–33	39	8
	34–41	108	22
	42–49	170	35
	> 50	170	35
Professional experience in the current firm (Years)	<1	0	0
	1–3	39	8
	3–6	175	36
	>6	273	56
Overall Professional experience in the manufacturing sector (Years)	<2	0	0
	2–5	51	10.5
	6–10	136	28
	>10	300	61.5
Firm Size	Small (<50 employees)	114	23.4
	Medium (50–250 employees)	297	61
	Large (>250 employees)	76	15.6

4.2. Factor loading and reliability analysis

Factor loading reliability analysis was carried out to validate the measurements. Table 4 details the results, where Cronbach's alpha (α) lies in the range (from 0.711 to 0.819), and composite reliability (CR) ranges (from 0.723 to 0.873) (which is >0.7). The factor loading values range (from 0.704 to 0.888) (above 0.7), showing that the measurement showed good internal consistency and reliability. Furthermore, we measured the average variance extracted (AVE) to investigate the converge validity of measurements. The results of AVEs for all constructs are >0.629, which exceeds the threshold of 0.5. thus, we conclude that the result of the reliability and validity of the contract is acceptable and adequate. The variance inflation factor (VIF) value is <3.3, which indicates the study has no collinearity issue related to this research.

4.3. Descriptive and correlation analysis

Table 5 presents the correlation and discriminant validity of the study construct. We examine the discriminant validity by verifying the correlation's hetero-trait-monotrait ratio (HTMT). The result indicates that all HTMT values are under the threshold of 0.85, which is evidence of adequate discriminant validity (Henseler et al., 2015; Kline, 2011).

Table 4
Factor loading and reliability analysis.

Variable	Item	Factor loading	α	CR	AVE	VIF
Social Influence (SI)	SI1	0.785	0.782	0.873	0.796	1.554
	SI2	0.874				1.924
	SI3	0.841				1.594
Effort Expectancy (EE)	EE1	0.704	0.731	0.783	0.776	1.346
	EE2	0.790				1.353
	EE3	0.763				1.428
	EE4	0.792				1.046
Performance Expectancy (PE)	PE1	0.866	0.722	0.725	0.635	2.238
	PE2	0.884				2.553
	PE3	0.774				1.472
	PE4	0.777				1.199
Facilitating Conditions (FC)	FC1	0.757	0.711	0.723	0.707	1.164
	FC2	0.710				1.026
	FC3	0.785				1.156
	FC4	0.817				1.216
Social Sustainability (SS)	SS1	0.747	0.737	0.738	0.629	1.051
	SS2	0.773				1.382
	SS3	0.819				1.441
	SS4	0.799				1.089
Environmental Sustainability (ES)	ES1	0.785	0.721	0.840	0.630	1.282
	ES2	0.811				1.525
	ES3	0.888				1.586
Technical efficacy (TE)	TE1	0.783	0.771	0.731	0.689	1.179
	TE2	0.768				1.199
	TE3	0.743				1.101
	TE4	0.793				1.013
Governmental Support (GS)	GS1	0.705	0.776	0.737	0.684	1.061
	GS2	0.743				1.131
	GS3	0.737				1.126
Intention to Adopt AM (AM)	AM1	0.750	0.726	0.845	0.646	1.204
	AM2	0.839				1.851
	AM3	0.821				1.805
Circular Economy (CE)	1CE	0.754	0.819	0.858	0.692	1.594
	2CE	0.856				1.367
	3CE	0.799				1.448
	4CE	0.775				1.542
	5CE	0.755				1.473
	6CE	0.710				2.368
	7CE	0.773				2.352
	8CE	0.768				2.608
	9CE	0.799				2.026
	10CE	0.856				2.029

4.4. Regression analysis for hypothesis testing

4.4.1. Direct effects

This study proposed eleven hypotheses from the conceptual model (Fig. 1). PLS-SEM was carried out using SMART-PLS to investigate these hypotheses. The direct and moderating effects are examined in this study. Table 6 presents the direct effects of the proposed hypotheses. The result revealed that the UTATU model elements, i.e., PE ($\beta = 0.624$, $p < 0.005$) and FC ($\beta = 0.292$, $p < 0.005$), are positively and significantly related to the intention to adopt AM, which suggests that the production manager believe that the adoption of AM can help to improve their performance. They have the necessary facilitation to adopt AM for production. Thus, H_1 and H_4 are supported.

In contrast, the remaining two elements of the UTAUT model, EE ($\beta = 0.015$, $p > 0.005$) and SI ($\beta = 0.034$, $p > 0.005$), are found insignificant, which argues that the adoption of AM did not help production managers to overcome their efforts. They think they do not have any social pressure to adopt AM. Therefore, H_2 and H_5 are not supported. In terms of the impact of sustainability attributes, ES ($\beta = 0.369$, $p < 0.005$) and SS ($\beta = 0.296$, $p < 0.005$) both are positively and significantly related to the intention to adopt AM, which reveals that AM has capabilities to enhance the environmental and social sustainable practices. So, H_6 and H_7 are supported in this study. Ultimately, the intention to adopt AM ($\beta = 0.713$, $p < 0.005$) is positively and significantly related to supporting the CE model practices, which shows that H9 is supported. Table 6 presents the results of the direct effects of the hypotheses.

4.4.2. Moderating effects

A PLS-SEM bootstrap re-sampling procedure with 5000 re-samples was conducted to examine the moderating effects. Bootstrap resampling is a non-parametric method that allows for the estimation of the precision of PLS-SEM estimates by generating multiple samples from the original dataset. This technique helps to assess the stability and reliability of the estimated path coefficients. Conducting 5000 resamples provides a robust assessment of the variability in the data, ensuring that the results are not dependent on a single sample but are consistent across numerous resampled datasets. According to the conceptual model, TE is proposed as a moderating variable among PE, EE, and intention to adopt AM (by proposing hypotheses H_{3a} and H_{3b}). Additionally, GS is considered a moderating variable among ES, SS, and intention to adopt AM (by proposing hypotheses H_{8a} and H_{8b}. Table 7 presents that TE insignificantly interacts with the association between PE ($b = 0.029$, $p > 0.05$), EE ($b = 0.031$, $p > 0.05$), and intention to adopt AM; thus, H_{3a} and H_{3b} were not supported. Furthermore, the GS positively and significantly interacted with the association between ES ($b = 0.263$, $p < 0.05$), SS ($b = 0.178$, $p < 0.05$), and intention to adopt AM; thus, H_{8a} and H_{8b} were supported.

Table 8 explains the result of all hypotheses, and Fig. 2 presents the PLS-SEM diagram with the coefficient (β) and p-values of results.

5. Discussion and implications

This study has several key findings, highlighting the UTATU model comprising four elements: PE, EE, SI, and FC. PE and EF are associated with employee perceptions of new technology and their expectations regarding task performance and effort (Rahman et al., 2017). Therefore, understanding the role of TE, derived from self-efficacy, is crucial in comprehending employee confidence and ability to use new technology such as AM (Baumers et al., 2016; Prabhu et al., 2022). This study proposes TE as a moderator between PE, EE, and the intention to adopt AM. The direct effects reveal a positive and significant relationship between PE and AM adoption, suggesting that AM adoption can enhance employees' job performance and elevate the firm's overall performance. For instance, in South Korea, the Hyundai Motor Company has been leveraging AM to produce complex automotive parts with reduced material waste and improved efficiency. Samsung Electronics has also

Table 5
Correlation and discriminant validity.

Variable	SI	EE	PE	FC	SS	ES	TE	GS	AM	CE
SI	1									
EE	0.691	1								
PE	0.637	0.502	1							
FC	0.481	0.561	0.509	1						
SS	0.526	0.542	0.328	0.535	1					
ES	0.505	0.683	0.534	0.409	0.660	1				
TE	0.137	0.148	0.128	0.233	0.250	0.197	1			
GS	0.506	0.685	0.399	0.460	0.687	0.462	0.145	1		
AM	0.672	0.539	0.721	0.613	0.742	0.644	0.103	0.744	1	
CE	0.612	0.764	0.801	0.825	0.805	0.737	0.144	0.594	0.807	1

Table 6
Direct effects.

Hypotheses and path		Coefficient (β)	T-Value	*P*-value
H_1	PE ➔ Intention to adopt AM	0.624	14.970	0.000
H_2	EE ➔ Intention to adopt AM	0.015	0.391	0.696
H_4	FC ➔ Intention to adopt AM	0.292	2.290	0.022
H_5	SI ➔ Intention to adopt AM	0.038	0.807	0.420
H_6	ES ➔ Intention to adopt AM	0.369	4.706	0.000
H_7	SS ➔ Intention to adopt AM	0.296	2.497	0.013
H_9	Intention to adopt AM ➔ to support CE	0.713	31.362	0.000

P-value <0.05 (significant).

Table 7
Moderation effects.

Hypotheses and path		Coefficient (β)	T-Value	P-value
H_{3a}	(PE x TE) ➔ Intention to adopt AM	0.029	0.679	0.497
H_{3b}	(EE x TE ➔ Intention to adopt AM	0.031	0.764	0.445
H_{8a}	(ES x GS) ➔ Intention to adopt AM	0.263	2.906	0.004
H_{8b}	(SS x GS) ➔ Intention to adopt AM	0.178	3.246	0.001

Table 8
Summary of study hypotheses.

Hypotheses and path		Relationship	Result
H_1	PE ➔ Intention to adopt AM	Direct	Supported
H_2	EE ➔ Intention to adopt AM		Not Supported
H_4	FC ➔ Intention to adopt AM		Supported
H_5	SI ➔ Intention to adopt AM		Not Supported
H_6	ES ➔ Intention to adopt AM		Supported
H_7	SS ➔ Intention to adopt AM		Supported
H_9	Intention to adopt AM ➔ to support CE		Supported
H_{3a}	(PE x TE) ➔ Intention to adopt AM	Moderation	Not Supported
H_{3b}	(EE x TE ➔ Intention to adopt AM		Not Supported
H_{8a}	(ES x GS) ➔ Intention to adopt AM		Supported
H_{8b}	(SS x GS) ➔ Intention to adopt AM		Supported

explored AM for prototyping and small-scale production, enhancing their ability to innovate quickly while minimizing environmental impact. General Electric (GE) and Siemens are leading the way in AM adoption. GE uses AM to produce components for jet engines, reducing material usage and weight, which leads to better fuel efficiency and lower emissions. Siemens employs AM in its energy division to manufacture gas turbine parts, significantly cutting down production time and material wastage.

However, EE was found to be insignificant, indicating that employees do not believe AM will reduce their effort. One reason is that adopting new technology requires substantial effort to synchronize the production process and extensive training. Therefore, manufacturers seeking production flexibility and responsiveness should focus on developing customized products or modifying their plants to facilitate customer-based production (Bianco et al., 2023; Ding et al., 2023; Napoleone et al., 2023; Sandra et al., 2020). Regarding TE as a moderator, the results suggest an insignificant relationship between PE, EE, and AM adoption. TE is a critical factor in determining how well employees accept and use technology, and it is also linked to the perceived ease and usefulness of new technology for their tasks (Al-Adwan et al., 2023). This study found that 70 % of the production managers were aged 42 to >50, suggesting that older employees may have lower TE-related to AM (Durst et al., 2023; Medici et al., 2023). To improve TE, employees should be trained to enhance their skills in using AM for their production activities (Jokisch et al., 2020).

The results also indicate that SI is insignificantly related to the adoption of AM. In this study, SI was used to measure how senior employees assist others in using new technology like AM and the differences between one company and its competitors in adopting AM. The implementation of AM in Korean manufacturing is still in its early stages, and employees require extensive training and education related to AM technologies. Therefore, companies should resist adoption pressure from competitors, governmental federations, and customers. As for FC, it was found to be positively and significantly related to AM adoption. This finding suggests that Korean firms are actively upgrading their technological structures to adopt AM technology (Tofail et al., 2018), and the Korean government is also actively promoting the adoption of emerging technologies like 3D printing, Artificial Intelligence, and robotics in manufacturing companies (Bashir et al., 2022; Madhavadas et al., 2022). This study also examines the sustainability factors influencing the intention to adopt AM. AM is recognized not only for its production benefits but also for its potential to promote sustainability (Agnusdei and Del Prete, 2022; Wang et al., 2022). The study results revealed that environmental and social factors positively and significantly impact the intention to adopt AM.

This study investigates the relationship between AM and CE models. The results conclude that AM positively and significantly impacts the implementation of the CE model. By enabling sustainable design practices and eco-friendly materials, AM aligns with the principles of the CE and contributes to a more sustainable and efficient future in production.

5.1. *Theoretical implications*

This study contributes to the literature by developing a framework that incorporates various elements crucial to understanding the adoption of AM in the manufacturing sector and its implication for supporting the CE model. By identifying the elements of the UTAUT model and TOE, sustainability factors (environmental and social), employee TE, and GS, this study provides a robust foundation for analyzing the adoption of AM in manufacturing and supporting the CE model. One significant aspect addressed in this study is identifying key critical factors for successfully implementing and adopting new technologies, especially for manufacturing sectors. Manufacturing processes are central to any economy, and integrating new technologies should enhance the production processes while promoting sustainable practices. By highlighting these factors, the study emphasizes the importance of

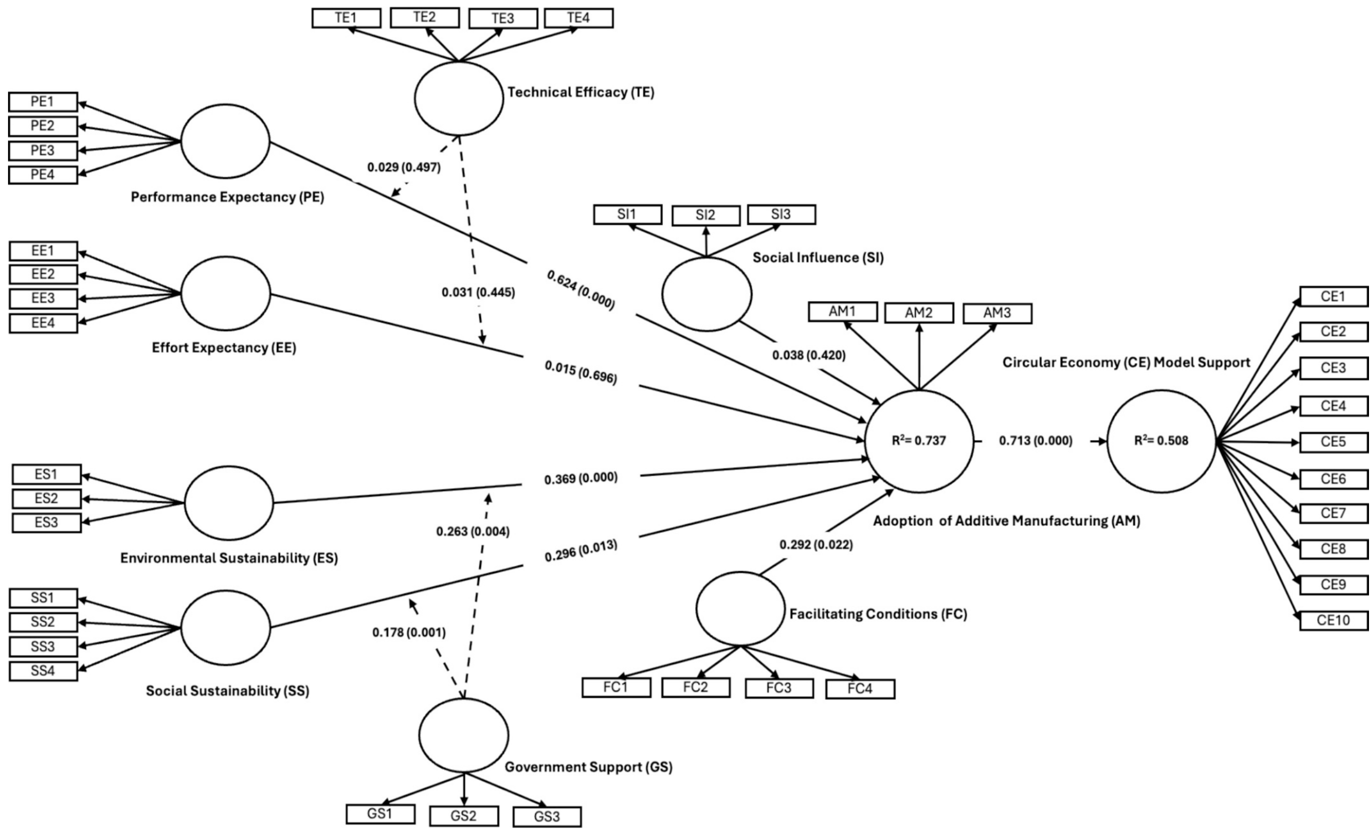

Fig. 2. Research model with result.

considering these elements when adopting AM technologies, as they can greatly impact its effectiveness and long-term sustainability.

This study underscores the significance of employee technical understanding and government involvement in driving the adoption of novel technologies like AM in the manufacturing sectors. To the best of our knowledge, this initial study highlighted the AM adoption factors by extending the UTATU model and TOE framework and the impact of AM adoption to support the CE model. The CE model focuses on minimizing waste, extending product lifecycles, and promoting resource efficiency, and provides an important theoretical lens through which to understand the potential implications and benefits of AM adoption. By examining these aspects, this study sheds light on the relationship between AM adoption and achieving the CE goals, contributing to a deeper understanding of the interplay between technology adoption and sustainable practices. Eventually, this initial study develops the theoretical framework that integrates the UTATU model, TOE, sustainability elements, employee technical understanding, and government involvement to examine AM adoption and its implications for CE implementation. This study provides valuable insight that can guide future research and inform decision-making in the industry.

5.2. Managerial implications

The results of this study offer several critical insights for decision-makers.

Firstly, managers should understand the factors influencing AM adoption from the perspective of PE, EE, SI, and FC (UTATU model). This understanding is crucial as the study reveals that production foremen in Korean manufacturing industries perceive PE and FC as significant contributors to AM adoption. Managers should, therefore, focus on these factors when considering AM adoption, as they believe AM can improve performance and that the necessary resources are available for its implementation. However, the study finds that EE and SI are not significant factors, indicating a potential gap in foremen's understanding of how AM can benefit their tasks and a perceived lack of internal support for AM adoption. To address this, the firm should actively seek to raise awareness of the benefits of AM for employees' job activities and establish a supportive environment. This outcome can be achieved by developing and implementing guidelines, policies, and an AM adoption handbook. This approach should be adopted as soon as possible to improve employees' efficacy in adopting and utilizing AM and enhance their confidence in learning about and applying AM implications.

Secondly, the study provides insights into the sustainability associated with AM adoption. Korean manufacturing firm foremen should understand that AM adoption can contribute to environmental and social sustainability, which are crucial for sustainable manufacturing. They should also recognize the significant role of government policies and regulations in facilitating AM adoption toward achieving sustainable manufacturing. Given that AM adoption can require substantial capital investment, managers should focus on government support and benefits for manufacturing firms that aim to modernize their production processes and adopt eco-friendly approaches. This support will help improve overall employee performance and promote eco-friendly production practices. Lastly, this study guides how AM adoption can support the implementation of CE, a new production and consumption model promoting sustainable growth. Managers should consider implementing CE practices as part of their AM adoption strategy. By doing so, firms can optimize resource use, reduce raw material consumption, and recycle waste.

5.3. Limitations and future work

The study has several limitations which can be addressed in future studies. Firstly, the study was conducted from the perspective of production managers in Korean Manufacturing industries. Including a broad range of industries and different departments would be beneficial to gather a more comprehensive understanding of AM adoption. Secondly, this study highlights the adoption of AM to support CE, but the in-depth study needs to include identifying CE implementation factors. Future research could delve deeper into CE implementation for manufacturing industries. Thirdly, the study focuses on AM technology for supporting the CE. Future studies must address the role of other emerging technologies, such as IoT, AI, and Blockchain, in promoting CE practices and present real-case studies to validate the result. Lastly, the focus of this study is to highlight AM implementation factors without underlining the adoption challenges and barriers so that future work will cover adoption challenges.

CRediT authorship contribution statement

Javed Aslam: Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Conceptualization. **Aqeela Saleem:** Writing – review & editing, Software, Methodology, Investigation, Conceptualization. **Kee-hung Lai:** Writing – review & editing, Validation, Supervision, Project administration, Investigation, Conceptualization. **Yun Bae Kim:** Writing – review & editing, Validation, Supervision, Data curation.

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Appendix. I

Research question (5-point Likert scale ranging from 1 to 5, with 1 = strongly disagree, 2 = Disagree; 3 = neither agree nor disagree, 4 = agree, and 5 = strongly agree.

Construct	Items (questions)	Source
Social influence	Firms that influence our firm behavior think that our firm should use AM. The senior management of our firm is helpful in the use of AM. In general, the organization has supported the use of AM.	(Schniederjans, 2017; Thompson et al., 1991),
Effort Expectancy	Learning how to use AM is easy for me. It would be easy for me to become skillful at using AM. I would find AM easy to use. My interaction with AM is clear and understandable.	(Venkatesh et al., 2003)
Performance Expectancy	I would find AM useful in my job. Using AM technologies would enable me to accomplish the task more quickly. Using AM would increase my productivity. Using AM would increase my job performance.	(Holzmann et al., 2020; Venkatesh et al., 2003)
Facilitating Conditions	Our firm has the resources necessary to use AM. Our firm knows the necessity of using AM. AM technologies are compatible with other systems that our firm uses. Our firm provides help when I have difficulties using AM.	(Popov and Koo, 2020; Wang et al., 2017)
AM adoption	I predict that our firm will use AM on a regular basis in the future. Using AM technologies in manufacturing is a good idea. Our firm will always try to use AM technologies in the future.	(Venkatesh et al., 2012, 2003)
Government support	There are programs and incentives supporting the introduction of sustainability practices using AM. The government defined the sustainability rules and regulations for AM. The government arranged training and workshops to promote AM adoption.	(Zeng et al., 2017)
Social sustainability	Work safety will be increased using AM. The work environment will be improved using AM. The living quality of the surrounding community will be enhanced using AM. Our relationship with the community or stakeholders will be improved using AM.	(Dey et al., 2020; Xiao and Su, 2022)
Environmental sustainability	AM will help to reduce the waste across our manufacturing processes. AM will help to achieve resource efficacy across our manufacturing process. AM will help to improve compliance with environmental standards.	(Abdul-Rashid et al., 2017; Adebanjo et al., 2016)
Technical efficacy	I could use AM technologies easily even though I have not used them before. I could use AM technologies if I have used similar technologies. I could deal with minor problems regarding AM technologies. I feel that I am an expert in using novel technologies like AM.	(Guri Medici Gudela Grote and Hirschi, 2023)
Circular economy	AM helps to reuse the waste in our production process. AM helps to recycle materials as input in our production process. Leftover raw materials can be used again in the AM production process. AM initiatively enhances the energy efficiency of production equipment. AM production has a low environmental impact. AM helps reduce the consumption of raw materials and energy. Waste can be recycled using the AM production process. Waste and garbage can be used to manufacture new products in AM production after reprocessing. AM production help to reduce the consumption of raw material and energy AM focuses on the eco-friendly production process.	(Rodríguez-Espíndola et al., 2022; Zeng et al., 2017)

Data availability

Data will be made available on request.

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