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Development and validation of an instrument to measure the perceived benefits of digitalization in manufacturing

Poonam Garg, Bhumika Gupta, Archana Sar, Gary Graham, and Adam P Shore

Abstract—**Digitalization in manufacturing can help the firm to improve output and reduce costs. This work reports on the development, testing, and validation of an instrument to measure the perceived benefits of digitalization in manufacturing. The item was developed based on a comprehensive literature review and qualitative investigation from practitioners who are actively engaged in taking decisions/implementing digitalization in Indian manufacturing. Exploratory factor analysis of data from 234 practitioners yielded 5 factors of perceived benefits of digitalization in manufacturing: real-time monitoring; data governance; eco-positivity; resiliency and agility; and embedded/automated control. The results of confirmatory factor analysis on a different sample of 235 practitioners supported the stability of this 5-factor structure. The empirical results confirm the high reliability and construct validity of the newly developed instrument by achieving discriminant, convergent, nomological and predictive validity. Furthermore, this research provides a self-diagnostic tool for manufacturing firms to assess the existing capability and prioritize digitalization efforts for maximum benefits over time.**

Index Terms— **Confirmatory factor analysis, Digitalization, Instrument development, Manufacturing sector, Perceived benefits**

I. INTRODUCTION

DIGITALIZATION in manufacturing which is also known as Industry 4.0 or the fourth industrial revolution is the seamless integration of cutting-edge digital technologies such as machine learning, artificial intelligence (AI), big data, co-bots, sensors, blockchain and 3D-printing with manufacturing processes and products [1], [2], [3], [4], [5], [6]. The digital technologies of the Fourth Industrial Revolution have the potential to significantly transform and disrupt conventional manufacturing processes, products, and the workforce[7]. By leveraging these digital technologies, manufacturers can create a more agile and customer-centric manufacturing environment, enabling them to stay competitive and adapt to the changing business landscape[8], [9], [10], [11].

According to Gobble [11], digitalization also refers to the: "… complex technical and organizational processes taking place within and between organizational boundaries, to create value for a specific business process, product, or service. The process is driven by the recognition of the value creation opportunities from digital technological applications by a group of individuals. It can be viewed as the manufacturing organization investing in digital technologies to drive changes in all different types of its business, organizational processes, growth and innovation [12].

Many contributions focus on digitalization having the potential to deliver: "more efficient product development", "more efficient manufacturing", "more sophisticated products and services", "more integrated value chains", "improved production flexibility", "greater output capacity", "improved product quality" and "reduced machine downtime" [13], [14], [15], [16], [17], [18], [19].

The literature has widely recognized the potential of digitalization and its inherent power of disruption to disrupt product and service process models [6], [20], [21], [22], [23]. Few studies have concluded that digitalization can lead to more supply chain complexity which is a major source of risk [24], [25]. "*….Digitalization in the supply chain can, however, also provide unprecedented benefits to supply chains, such as automation, better visibility, coordination, and collaboration among supply chain networks…*" [26], [27].

There has been recent growth in scholarly popularity in digital technologies, particularly in their response to the COVID-19 pandemic[28], [29]. Studies have highlighted how firms scrambled to find ways to better prepare, respond and recover from catastrophic disruption [30], [31]. The studies addressing the perceived benefits of digitalization are, however, fragmented, and inconclusive [5], [32]. Accordingly, few empirical contributions focus on the benefits of digitalization initiatives for manufacturing. Many of the existing studies rely on a limited number of case studies or interviews, which might not adequately represent the broader population [33]. As a result, much of the evidence gathered is exploratory rather than confirmatory or robust in method. Furthermore, in the literature, there is no comprehensive instrument developed to test the perceived benefits of digitalization to the manufacturing sector. The absence of a suitable instrument to test the perceived benefits of digitalization leaves an important gap and opens the opportunity for more robust research on digitalization. The following research questions aim to fill this gap.

RQ1. What are the measurable benefits of implementing digitalization in manufacturing?

RQ2. How can we robustly measure the perceived benefits of digitalization in manufacturing?

The remainder of the paper is organized as follows. The paper begins with a literature review of previous research on the perceived benefits of digitalization in manufacturing, followed by details of our qualitative and extensive quantitative procedures to develop a new instrument for testing the benefits of digitalization. Then in the next section, we present our analysis and results section to determine the instrument's reliability, convergent, discriminant and predictive validity. Finally, the paper concludes with a presentation of our major theoretical contribution, practical implications, its limitations, and finally, suggested directions for further research.

II. Literature review

A. *Industry 4.0 and digitalization*

Industry 4.0 "The Fourth Industrial Revolution… defines a methodology to generate a transformation from machine dominant manufacturing to digital manufacturing" [34]. Industry 4.0 offers a wide range of processing, communication and production capabilities. Industry 4.0 takes over production with robots that communicate with each other, detect the environment with sensors, and realize needs through data analysis; aims to produce better quality, cheaper, faster and less waste production [35]. It enables enterprises, government and the public sector to use innovative digital technologies, smart automation and advanced analytics to transform the operating processes. Industry 4.0 and digital are paving the way for increased revenue through higher productivity while ensuring the quality of the products [36]. Industry 4.0 may be a powerful vehicle to improve efficiency and cost performance; however, as [37] argue, Industry 4.0 implementation may produce more pronounced effects on quality, delivery and flexibility. Digital technologies today include artificial intelligence, robotics, the Internet of Things, autonomous vehicles, 3-D printing, nanotechnology, biotechnology, materials science, energy storage, and quantum computing. Industry 4.0 concepts and technologies can be applied across all types of industrial companies, including discrete and process manufacturing, as well as oil and gas, mining and other industrial segments[38].

Industry 4.0 was initially considered a technological trial; it has now become a requirement to maintain competitiveness in an ever-changing industry environment. It has the potential to improve productivity and competitiveness, increase energy and resource efficiency and effectiveness and hence to protect the environment. Industry 4.0 is anticipated to bring about a surge in computerization, the implementation of software-driven decision-making processes, and the integration of intelligent systems within production [35]. Industry 4.0 is a comprehensive automation, business intelligence, and manufacturing execution architecture designed to enhance the industry by integrating all production and commerce activities across organizational boundaries for increased productivity [39]. Industry 4.0 technologies play a pivotal role for manufacturers by seamlessly connecting previously distinct processes, offering a transparent and comprehensive view throughout the entire organization. This enhanced visibility provides abundant actionable insights [40].

Digitalization refers to the process of converting analogue information or processes into digital form[12]. In the context of manufacturing, digitalization includes the integration of digital technologies such as Artificial Intelligence (AI), Internet of Things (IoT), Blockchain technology, Augmented Reality (AR) and Virtual Reality (VR), Cloud Computing, and digital twin to enhance efficiency, productivity, and overall performance[41]. Digitalization serves as the foundation upon which Industry 4.0 thrives, encompassing the integration of cutting-edge technologies into industrial processes. This amalgamation enables the creation of smart factories, where interconnected systems powered by IoT, AI, machine learning, and data analytics foster unparalleled efficiency, agility, and innovation[42]. Digitalization acts as the catalyst for Industry 4.0, empowering businesses to optimize production, enhance decision-making, and adapt swiftly to market demands[12]. Together, they form a dynamic relationship, revolutionizing industries worldwide by driving automation, connectivity, and the evolution toward intelligent and adaptive manufacturing systems. The digitalization of processes in organizations facilitates the integration of the functions in the firm and of the distinct agents in the supply chain, enabling an integrated and transparent ecosystem for all stakeholders involved, from raw materials suppliers to final consumers[43].

B. *Digitalization in manufacturing*

In recent times, the acceleration of technological progress, resource scarcity, and globalization have forced manufacturing organizations to redefine their manufacturing processes. To remain competitive, the organization should be more flexible and fully integrated across value chains and product life cycle phases[44]. The concept of digitalization in the manufacturing sector integrates different digital technologies into various aspects of the production process and across value chains to improve productivity, adaptability, efficiency, flexibility, and competitiveness [42], [45]. A wide range of digital technologies like cyber-physical systems (CPS), cloud computing, blockchain, 3D printing, artificial intelligence (AI) as well as the Internet of Things (IoT) have aided manufacturers in improving proficiency, reducing downtime, lowering costs, standing out in the market, and enhancing service, delivery, and quality [46]. These digital technologies are considered as set of disruptive Internet technologies. These disruptive technologies have fundamentally changed how organizations manufacture, deliver and service products[47]. These innovative technologies have the advantages of self-learning, security, and anticipating change in an ever-changing environment[46].

Manufacturing organizations integrate IOT devices and sensors in their production lines, machinery, and throughout the factory floor[48]. These devices provide preventive maintenance and operational optimization by gathering data in real-time on performance, machine health, and environmental conditions[49], [50], [51], [52]. Automation by using robotics and automated technologies has completely transformed manufacturing which has resulted in completing tasks quickly and accurately[50]. This reduces mistakes, boosts output, and makes it possible to use resources more effectively[49], [50], [53], [54]. Better customer data collecting and analysis capabilities enabled by the Internet of Things and Big Data analytics capabilities can enhance product and service delivery [53].

Digitalization is an organizational process that is iterative and enabled by several technologies. Its goal is to automate business activities to improve operational efficiency and strengthen a company's competitive advantage [55], [56]. Whatever the technological profile, using a variety of technologies and pushing technological growth within the socio-technical ecosystem are necessary for successful implementation [57]. Mature manufacturing industries are currently experiencing insightful transformation as they are undergoing digitalization which involves the seamless integration of machines, devices, goods, and supply chains to foster flexibility and agility to respond to market change effectively [58]. This organizational shift necessitates the creation of new business models and the application of new business logic to generate and capture value[59].

C. Opportunity/benefits of digitalization in manufacturing

Digitalization isn't just about making things faster; it's about unlocking a new era of agility, resilience, and innovation, reshaping the manufacturing landscape into one that's smarter, greener, and more competitive than ever before. Manufacturers can innovate, and become more agile, efficient, and competitive in a market that is changing quickly by embracing digitalization. Adopting technology isn't enough; we also need to change how things are done and take advantage of new opportunities to spur development and success. The opportunities presented by digitalization in the manufacturing sector are immense. From enhanced efficiency and agility to innovation and sustainability, embracing these technologies is no longer an option, but a necessity for any manufacturer who wants to thrive in the future. Digitalization is a customer-centric mechanism. As a result, the organization undergoing digitalization will pay more attention to the customer's voice in all aspects [69], [70]. Manufacturers can adopt a more customer-centric strategy by utilizing digitalization, offering better after-sales support, tailored experiences, faster response times, and higher-quality products[53], [71]. In the highly competitive manufacturing sector, this ultimately leads to enhanced customer satisfaction and loyalty. Improved customer data collection and analysis capabilities, enabled by the Internet of Things and Big Data analytics, can enhance product and service delivery, and improve resilience[71], [72], [73]. Digitalization makes it easier to gather and analyze feedback and evaluate market trends [18]. By using this information, producers may better match their goods and services to the demands and tastes of their customers [53]. Digitalization fosters innovation by allowing producers to quickly design new products or features that suit consumer tastes [48]. Production lines can be quickly reconfigured by automation systems using digital technology to meet demand or design changes [74]. Customized products that are suited to the specific needs of each customer increase customer happiness. Integrating digital technology into the production environment allows companies to develop new product features, improve reliability and efficiency, and increase the overall value provided to consumers [48]. Digitalization provides the technology infrastructure, connectivity, and data-driven insights required for automated systems to function effectively, laying the foundation for automation in production[75]. Automation and digitization work together to turn traditional manufacturing into intelligent, flexible, and productive processes that stimulate innovation and industry growth [48]. Manufacturing companies are incorporating technology like sensors and IOT into existing machines to make them more "intelligent" and create a network where they can communicate and share data[48]. Since it enables real-time monitoring, control, and coordination of numerous activities on the manufacturing floor, this connectivity is essential for automation.

Data collected from the products enable items to be monitored, optimized, controlled, and, in some cases, autonomously operated [48]. Automation, backed by IoT-ready infrastructure, is expected to generate critical operational data[50]. As a result, manufacturers can reduce human error and boost operational efficiency by streamlining workflows, automating repetitive tasks, and identifying inefficiencies [51], [53], [71], [76], [77]. Using modern digital technologies in manufacturing, such as smart machines and robots, will improve the organization's efficiency [48], [51], [78]. Vertical integration of IoT-embedded equipment, operations management, and energy management systems (EMS) can help enhance machine utilization, energy efficiency, and throughput [50]. Sensor technology reduces errors by providing real-time input, allowing for a better understanding of the manufacturing line and pre-emptive action to address any issues [79]. Factory productivity in terms of improved process and equipment understanding and control can be enhanced by incorporating real-time sensor data analysis[53], [71]. Most industrial companies are working hard to digitalize their operations to increase their competitiveness [51]. By using digital technology, manufacturing organizations can improve throughput and quality, reduce variance, and reduce the frequency of breakdowns and stoppages [72]. Digitalization provides more integrated value chains, which boosts the efficiency of various business tasks, reduces lead times, and improves operational management [71], [72], [73]. Digitalization makes it possible to collect and analyze data in real-time from manufacturing processes [53], [71]. Agile decision-making is made possible by this data-driven strategy, which offers insights into the state of production, the dynamics of the supply chain, and market demand [70]. Transparency is improved by digitalization from raw materials to distribution in the supply chain [80]. Because of this openness, producers may swiftly find substitute suppliers, modify inventory levels, and react to disruptions or shifting market conditions [58]. Agility is increased by the ability of production lines to be quickly adjusted to meet changes in demand or product standards thanks to automation, robotics, and IoT [48], [50], [51], [78].

Based on real-time market feedback, manufacturers are adopting digital technologies to accommodate last-minute modifications and quickly change existing product lines, create new ones, or adjust production volumes[74]. Real-time access to market trends and client input is made possible by digitalization. With the use of this data, manufacturers can locate niche markets, customize goods to meet the needs of certain clients, and develop new items in response to changing consumer tastes [81]. Digitalization makes manufacturing processes more flexible and agile. This flexibility makes it possible for producers to quickly adjust to shifting consumer needs, refine the features of their products, and launch new models more quickly, all of which promote innovation [49], [51], [53], [82], [83]. Digitalization is expected to generate cost advantages by reducing administrative costs, manpower costs, procurement costs and various other operational costs. Digitalization increases revenue for the organization's stakeholders by widening the distribution of sales channels and increasing the productivity of industrial processes by reducing operational expenses or shortening the duration of operations [51], [84]. Manufacturing process optimization through digitalization lowers operational inefficiencies and downtime. This helps in cutting down on errors and rework. Higher customer satisfaction, fewer returns, and more effective asset use are all benefits of improved product quality that boost return on assets (ROA) [85].

Companies operating more efficiently tend to have higher profit margins and attract investor interest, potentially driving up market capitalization [85]. Digitalization provides real-time visibility into inventory levels and demand trends [77]. Because of this transparency, manufacturers can better utilize their assets and increase return on assets (ROA) by optimizing inventories, lowering carrying costs, and matching production to actual demand [51], [84], [86], [87]. Optimizing inventory ensures efficient use of working capital, which positively influences return of sales (ROS)[85]. Businesses are better equipped to adapt to changes in the market thanks to digitalized manufacturing processes. This flexibility increases a company's resilience and appeals to investors who are looking for businesses that can adjust to changing market conditions, which could increase the company's market value. [53]. Innovation always encourage digitalization, which helps businesses create innovative goods and services [51], [82], [83]. Due to their expected future value, innovators frequently draw investors looking for growth prospects, which could increase market capitalization [85]. According to McKinsey Global Institute Research, digitalization and automation might boost productivity growth by 0.8 percent to 1.4 percent annually [88]. Automation of the manufacturing process, as well as access to production and product data throughout the supply chain, may cut delivery times by 120 percent and reduce time to market by 70 percent [89].

Digitalization can help in supply chain innovation by creating an end-to-end supply chain, and minimize unexpected risks through real-time availability of information across diverse phases of the supply chain for improved visibility [53]. Digitalization provides more integrated value chains, which boosts the efficiency of various business tasks, reduces lead times, and improves operational management [71], [72], [73]. Information sharing between systems and functions, such as production and enterprise resource planning, increases process coordination, visualization, and planning [72]. Large volumes of data are gathered via digitalization from sensors, devices, and procedures [90]. Real-time insights into production performance are obtained through data analysis, enabling data-driven decision-making to streamline procedures, boost productivity, and cut expenses [46], [91]. Real-time data availability anticipates probable equipment malfunctions, giving information about when maintenance is required, averting expensive downtime, and enhancing asset performance[71], [83], [92], [93], [94]. This results in continuous improvement of procedures, goods, and services which in turn promotes innovation and operational excellence [49], [52], [53], [79], [92], [93]. Traceability is made possible throughout the production process via digitalization [53], [92]. Manufacturers can monitor and record each stage of the process, from raw materials to final goods, guaranteeing transparency and compliance with regulations related to product safety and quality [53], [92], [93]. The process of digitization also improves quality control methods. Manufacturers can maintain consistent quality standards, meet compliance requirements, and lower the risk of product recalls or non-compliance concerns [95]. Digitalization also aids in environmental compliance by monitoring and optimizing energy usage, waste management, and emissions [96], [97].

D. Challenges of digitalization in the manufacturing sector

Digitalization enables firms to re-imagine new ways of managing their businesses using new digital processes and tools. Digital technologies are the foundation of digital transformation, which affects businesses by enhancing fundamental capabilities such as openness and affordance [60]. However, the adoption of digitalization has presented challenges across industries and platforms. As companies embark on transformation journeys, they encounter obstacles ranging from people-centric concerns to structural issues, technical barriers, and various other factors.

Financial resources and profitability are crucial priorities for numerous organizations. Even though digitalization is capable of lowering costs, it does encounter limitations when dealing with legacy systems [61]. Digitalization requires a large initial investment and infrastructure development. Organizations need to invest in cutting-edge digital technologies, infrastructure, equipment, a skilled workforce, robust data security and organizational capabilities[62]. SMEs frequently lack financial resources or are constrained by budget constraints, which makes successful digital transformation difficult. Despite the necessity of digital transformation to maintain a competitive advantage, most businesses are unwilling to invest in it due to unclear business benefits [61], [62].

With its evident income potential, digitalization is projected to dominate the industry soon, however, security issues arise because "*everything in the entire value chain*" is connected. Cybersecurity is a crucial concern if not one of the most significant challenges in the digital transformation process. When data is collected, data management and security concerns begin. According to [62], many companies do not possess the required tools for automated data collection and security measures. This deficiency can result in data quality problems, including issues related to consistency, completeness, correctness, and redundancy [61], [63].

Also, companies risk losing confidential information and intellectual property when sharing information with partners, and cyber-attacks can cause significant disruptions[14], [61], [62]. The dearth of industry-specific standards that advise organizations on how to undertake this transformation path makes digital transformation appear to be difficult [14]. Many authors cite a lack of standards and rules as an obstacle to digital transformation [61], [64]. According to [65], "*legal and contractual uncertainty barriers are of paramount importance because they influence every other barrier directly or indirectly*." On the other hand, companies have only a limited awareness of the ethical issues surrounding digital change [66].

Technology is a broad term that encompasses a variety of issues. Companies must establish a proper infrastructure for intra-firm and inter-firm communications to support digital transformation [67]. Even industrialized countries like Germany currently lack reliable high-speed internet connectivity for all businesses [61]. A proper infrastructure entails essential components such as efficient communication channels, a universal sensor network and signal coverage, and an uninterrupted energy supply [62], [64], [65]. Infrastructure is even described as a key root challenge [64]. Companies with infrastructure may also encounter issues with unreliable factory connectivity, which impedes real-time communication [68].

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III. Methodology: Scale development process

This study aims to construct and validate a comprehensive instrument for measuring the perceived business benefits of implementing digitalization within the manufacturing sector. The development of a new instrument necessitates a thorough review of existing literature followed by qualitative interviews to identify all relevant domains [98]. As noted by [99], "Qualitative research aims to uncover and explore issues surrounding the problem, especially when little is known about it".

A review of the previous literature through research papers, industry reports, and white papers provided vital information on the benefits of digitalization for the manufacturing sector. Since no conceptual model exists to describe the benefits of digitalization, we supplemented the literature review with qualitative research as an initial phase to develop the items and identify the business benefits associated with implementing digitalization in the manufacturing industry.

Fig. 1 presents the complete steps carried out in the scale development and validation process.

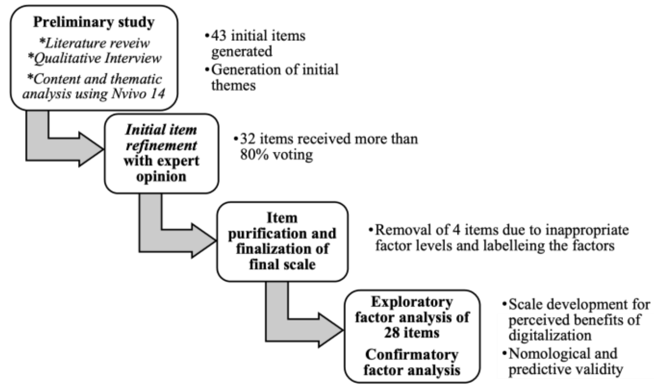

Fig. 1. Instrument development process.

A. Preliminary Study

For the development of an initial item pool, this study began with an in-depth literature review to investigate the concepts, definitions, and initial list of items related to the perceived benefits of digitalization in the manufacturing sector. There was no existing empirical validated literature available on the dimensionality of the digitalization construct. Therefore, open-ended qualitative interviews were conducted face-to-face with key experts. The purpose of these interviews was threefold: firstly, to gain deeper insights into the practical relevance of digitalization in the manufacturing sector; secondly, to solidify the identified benefits of digitalization from the literature review and explore how these items relate to the real world; and finally, to organize these insights into a clear and structured framework of themes and subthemes[100].

Between June 2021 and August 2021, fifteen experts participated in interviews, responding to seven open-ended questions. The objective of this session was to ensure in-depth findings and the richest possible data for scale development. A convenience sampling method was employed to choose the experts who engaged in digital transformation projects within the manufacturing system. The interviewed experts had varied backgrounds vis-à-vis the Chief executive officer, Chief technology officer, Chief information officer, Vice President, Assistant Vice President, Deputy Vice President, Chief Manager, Project Managers and Marketing Managers. These experts held extensive information and expertise regarding the benefits of implementing digitalization in manufacturing and related sectors. All interviews were recorded as audio and transcribed verbatim. The majority of interview sessions took place in person at the convenience of the experts, within their respective offices, while three sessions were conducted over the phone. All discussions were recorded and individually analyzed for further research purposes.

To ensure a comprehensive understanding of our research objectives, we briefed each expert in detail at the interview's outset. We then employed seven open-ended questions to explore specific areas of interest related to our research objectives. These open-ended questions were crafted through collaborative efforts within our research team, ensuring alignment with the study's goals. These open questions also gave the experts the freedom to elaborate on the topic [101]. Among the shortlisted questions, three specifically focused on the benefits of digitalization, such as: "*Describe the five benefits of digitalization in manufacturing?"; "Describe the purpose of digitalization in manufacturing?"; and "Describe how digitalization will revolutionize the manufacturing sector*"? Finally, experts were asked to indicate: "*Why do you think digitalization is so important?"; "Rationale behind the digital technologies implementation"; "challenges faced with the current existing system"; and "what problems does digitalization solve?"* Out of the seven questions, two were focused on the benefits of digitalization. Specifically, the responses to the question (i.e., five benefits of digitalization in the manufacturing sector) provided valuable information in constructing and describing the items. Since the questions were open-ended, the experts shared their experiences about how digitalization is transforming the manufacturing industry, the history of digital technology implementation, its evolution, its impact on the industry, and the benefits and drawbacks of using the technology.

After concluding the interview questions, our experts were asked for input on the identified benefits from the literature. This step is aimed to explore how these items relate to the real world and enhance the credibility of our findings from the literature survey. All experts confirmed that the perceived benefits of digitalization closely match the company's practices. This discussion provided valuable insights into the real-world benefits of digital technology adoption in manufacturing.

The content analysis of the interviews for generating items was a critical phase of this research study. The qualitative content analysis was conducted using N-Vivo 14 software to identify meaningful keywords from the interview discussion. The analysis identified 43 keywords that measure the benefits of digitalization for the manufacturing sector. The exploratory nature of the questions allowed the respondents to share their experiences in the industry and generated valuable information for this study. Further, based on the literature review and qualitative interviews, a thematic analysis was conducted to categorize the multiple items (benefits) into different dimensions for better interpretation. To reduce the bias in the coding process for theme generation, the transcripts of the interviews were analyzed in three steps. First, the coding was undertaken independently by the first two authors of this study using Nvivo 14 software. Second, to reduce the bias in the coding process for theme generation, the first and third authors of the manuscript, meticulously reviewed the interview script and generated a list of initial codes, which were subsequently scrutinized, discussed, and refined by the manuscript's second author. Finally, a discussion was undertaken on the emerging themes by all the authors in collaboration with seven industry experts to ensure the reliability of the findings and presented the final themes to a group of 7 expert researchers to validate the credibility and transferability of our analysis[103]. The perceived benefits of digitalization were divided into economic, environmental, and social indicators and corresponding sub-themes, as listed in Table I.

Institutional indicators describe the benefits of operational excellence and regulatory compliance in manufacturing. Digitalization emphasizes decision-making, collaboration, and communication by enabling real-time and seamless data. In addition to these benefits, digitalization fosters knowledge sharing, and data accessibility, empowering individuals to retrieve information from anywhere at any time. Digitalization offers a responsive environment that enables actionable alerts and notifications, and strengthens safety measures, sustainability, and regulatory adherence. Digitalization offers numerous market-based benefits related to performance, growth, and customer satisfaction. Key factors such as reducing inventory costs, energy expenses, and maintenance costs notably enhance manufacturing performance. Additionally, smarter resource allocation and the reduction of resource, material, and product waste are crucial aspects to enhance manufacturing. By reducing downtime and cutting maintenance costs, digitalization boosts Return on Sales (ROS) and Return on Assets (ROA). Furthermore, it enhances resilience and agility, speeding up time to market and increasing market value. Digitalization also fosters a better understanding of customer needs, improving customer satisfaction through more direct interfaces, quicker response times to demands, and better alignment of offerings with customer requirements, thus solidifying customer satisfaction.

Digitalization brings comprehensive technical advantages, covering real-time insights, resilience, and automated control across various domains. It significantly enhances end-to-end visibility by bolstering track-and-trace capabilities, offering real-time feedback, and monitoring process performance. Moreover, digitalization streamlines the management of diverse product variants, fostering greater responsiveness to business requirements and creating opportunities for innovation towards more functional products, ultimately enhancing agility and resilience in business operations. Digitalization facilitates automating tasks and processes not only accelerates batch control and reduces changeover times but also minimizes human error, enhances quality control, and amplifies labor productivity. Additionally, digitalization facilitates automated reporting, and improves asset availability and uptime, while reducing lead times. The manufacturing industry encounters various obstacles such as outdated infrastructure, fragmented supply chains, and skill gaps, impeding efficiency and competitiveness. To conquer these challenges and unleash its full potential, the manufacturing sector is actively embracing digitalization. Cutting-edge technologies like Artificial Intelligence (AI), the Internet of Things (IoT), Big Data and Analytics, Additive Manufacturing, and Industrial robots are revolutionizing production lines, refining processes, and yielding valuable data for informed decision-making. Through

TABLE I
SUMMARY OF THEMES AND SUBTHEMES EMERGING FROM THE LITERATURE SURVEY AND QUALITATIVE INTERVIEWS

Indicators	Item code	Perceived benefits	References
Institutional indicators			
Operational Excellence	I1	Improve decision-making	[77], [79], [95], [103]
	I2	Improve collaboration and communication	[103]
	I2	Improve knowledge sharing	[87]
	I4	Real-time tracking and better accountability	[77], [79], [95]
Regulatory Compliance	I5	Improve data accessibility from anywhere and at any time	[79], [103]
	I6	Reduce the environmental impact	[96], [97]
	I7	Compliance with regulations and industry standards	[87], [95]
	I8	Enhance process safety	[77], [91]
	I9	Enable an actionable alert and notification	[70]
Market Indicator			
Performance	I10	Reduce inventory cost	[51], [77], [84], [86], [87]
	I11	Provide better utilization of resources	[48], [49], [50], [51], [53], [54], [78], [82], [103], [104]
	I12	Reduce resource, material, and product waste	[77]
	I13	Reduce the energy cost	[50], [53], [54], [76]
	I14	Reduce the maintenance cost	[51], [54], [71], [83], [84], [92], [93], [94], [104]
Growth	I15	Increased Return on assets (ROA),	[85]
	I16	increased Return on sales (ROS)	[85]
	I17	Improved resilience and time to market	[53]
	I18	Increased Market capitalization	[85]
Customer satisfaction	I19	better understand of customer requirement	[77], [79], [91]
	I20	Improved customer satisfaction	[53], [71], [72], [73]
	I21	More direct interfaces with customers	[51], [53], [74]
	I22	shorter response time to customer requests and market demands	[82], [105]
Technical Indicators			
Real-time Insights	I23	Improve end-to-end visibility	[82], [105]
	I24	Enhance track and trace capabilities	[53], [92]
	I25	Improved deeper understanding of processes	[51][104]
	I26	Provide real-time feedback	[53], [91]
	I27	Improve the monitoring of process performance	[51], [77], [78]
Resilience and agility	I28	Improve operational efficiency	[49], [50], [51], [52], [53], [76], [77], [82], [92], [93], [95], [104], [106]
	I29	Provide agility in manufacturing processes	[74], [82], [103]
	I30	Handle different products variant	[48]
	I31	Enhance responsiveness to business needs	[82]
	I32	Create innovation opportunities	[49], [51], [53], [82], [83]
	I33	Development of more functional products	[51], [53], [92]
Automatic Control	I34	Automate tasks and processes	[48]
	I35	Provide faster batch control	[50], [53], [81], [91]
	I36	Reduce changeover times	[107]
	I37	Minimize human error	[51], [53], [71], [76], [77]
	I38	Improve quality control	[17], [50], [51], [53], [71], [79], [92], [93], [94]
	I39	Increased labor productivity	[48], [51], [52], [78]
	I40	Improve overall equipment effectiveness	[49], [50], [50], [51], [53], [54], [71], [78], [104]
	I41	Provide an automated reporting	[49],[74]
	I42	Improve asset availability and uptime	[87]
	I43	Reduce lead time	[71], [72], [76], [77], [81], [93], [94]

the integration of these tools, manufacturers strive to enhance flexibility and agility, minimize waste, elevate product quality, and secure a competitive advantage in the global market. Digitalization offers a pathway towards a more resilient, sustainable, and future-ready manufacturing sector.

B. Initial item refinement with expert opinion

After a meticulous review of existing literature and expert opinions, a decision was reached to incorporate 43 items aimed at delineating the business benefits derived from implementing digitalization in the manufacturing sector. An initial structured, closed-ended questionnaire was formulated, encompassing the 43 items identified from the literature review supplemented by qualitative research.

Using the technique recommended by Lynn [104], the content validity index (CVI) was calculated for each item (participants rated each item using a 4-point scale. Experts were instructed to rate the importance and necessity of each of the 43 items using a 4-point Likert scale ranging from (1 = "not relevant"; 2 = "somewhat relevant"; 3 = "quite relevant", and 4 = "highly relevant) for assessing the business benefits of implementing digitalization in the manufacturing sector. Additionally, they were asked to provide feedback on clarity, ambiguity, wording, and any concerns regarding the items. While the expert panel initially approached for open-ended interviews comprised of multiple individuals, only 11 experts agreed to participate in refining the scale items. These experts were provided with a direct link to a Google document to complete the questionnaire within a two-week timeframe.

An item's selection for inclusion in the instrument was based on achieving greater than an 80% consensus among the experts (i.e., rated as "highly relevant"). Out of the 43 items, 32 scored above 80%, signifying consensus on their importance for the research study, while 11 items (I6, I15, I16, I18, I19, I20, I21, I25,I35,I37,I39 – refer Table I) received scores below this threshold, prompting suggestions for revision. Following suggested revisions, the 11 items were resubmitted to the experts for appropriateness rating. Items failing to secure an 80% consensus were removed. In the subsequent rating round, experts collectively agreed on the appropriateness and necessity of 32 items (refer Appendix –II), indicating no further revisions were needed in the questionnaire.

Throughout the questionnaire's development stages, input was consistently sought from the experts, facilitating a step-by-step refinement process for the survey instrument. Face and content validity were ensured through multiple rounds of expert review.

C. *Item purification and finalization of final scale*

Dörnyei & Taguchi [105] emphasized the importance of piloting extensively used questions before their application. To further validate the instrument, preceding actual data collection, we conducted a final pilot study with a smaller sample size to assess the business benefits of implementing digitalization in the manufacturing sector. The questionnaire was administered to 50 practitioners who are actively engaged in making decisions/implementing digitalization in Indian manufacturing. Responses were gathered via the questionnaire and processed using the Statistical Package for the Social Sciences (SPSS 26) for factor analysis. The primary aim of employing factor analysis was to refine the item pool. There are diverse methods to conduct factor analysis [106]. Kaiser [106] and Costello & Osborne [107] Suggested the values above 0.5 "*is reliable regardless of sample size*". Following the initial factor analysis, four items were excluded from the measure due to inadequate factor levels as per Kaiser's criteria[107], resulting in a final selection of 28 items outlined in Appendix 1, Part-B.

3.4 Sample size

In an instrument development process, exploratory factor analysis and confirmatory factor analysis should be run using a different data set. In the present study, the sample was randomly divided in two, so that mutually independent samples were obtained for the EFA and CFA. According to Hair et al. [109] (2010), the suggested sample size should be five to ten times greater than the number of variables. The initial scale included 28 items and required a minimum of 140-280 respondents. In addition, a minimum of 200 sample sizes were recommended for confirmatory factor analysis. Thus, a total of 340-480 sample sizes was required for the study.

First, we reached out to approximately 100 manufacturing companies actively involved in digital transformation, leveraging digital technologies IoT, big data, additive printing, blockchain, and smart embedded devices within their operations. This initial selection ensured the consistency within our sample. During these calls, we assessed the company's interest in participating in the survey and identified the key individuals engaged in leading, planning and implementing the digital transformation project. After receiving consent, we engaged with participants, explaining the survey's purpose and guaranteeing anonymity and confidentiality. We emphasized ethical considerations to encourage open and honest responses. Subsequently, we distributed the questionnaire to 600 respondents, collecting 482 completed questionnaires. Ultimately, 469 responses met the inclusion criteria and were used for analysis. We then Employed random sampling and allocation within SPSS program. Specifically, 234 respondents (50% of the total respondents) were randomly selected for the Exploratory Factor Analysis(EFA) sample, while the remaining respondents were allocated to the Confirmatory Factor Analysis (CFA) sample.

Ultimately, 469 responses met the inclusion criteria and were used for analysis. We then employed random sampling and allocation within the SPSS program. Specifically, 234 respondents (50%) were randomly selected for the Exploratory Factor Analysis (EFA) sample, while the remaining 235 individuals were assigned to the Confirmatory Factor Analysis (CFA) sample**.**

D. *Demographic profile of the sample*

Table II demonstrates the Demographic profiles of respondents. The survey was conducted with a total of 469 respondents consisting of 20.26% female and 79.74% male respondents. Notably, there were no significant differences were observed in the average age and designation of participants between the EFA(Exploratory Factor Analysis) and CFA (Confirmatory Factor Analysis) groups, as depicted in Table II.

E. *Bias Issues*

Non-response bias analysis was done comparing early responders (the first 106 respondents) with the late (the last 106 respondents) responders [110](The results showed that there is no statistical difference at a 0.05 level of significance. Therefore, the sample was not deemed biased.

The most common test used for common method bias (CMB) is Herman's single factor test. In this test, this test involves all the variables of exploratory factor analysis (EFA). If a single factor accounts for a significant portion of variance (above 50 %), it indicates the presence of CMB. Another indication of CMB is when an unrotated factor solution yields only one single factor [111]. In our study, the total variance extracted by one factor is 27.207%, which is below the commonly recommended threshold of 50%. Based on this result we can conclude that there is no problem with common method bias] in the data. Our sample does not exhibit the problem with common method bias in this data since the total variance extracted by one factor is 27.207% and it is less than the recommended threshold of 50%.

TABLE II
DEMOGRAPHIC DATA OF EFA AND CFA GROUPS

Variables	Classifications	EFA samples (n=234)	CFA samples (n =235)	Total (n=469)
Gender	Female	55 (23.50%)	40 (17.02%)	95(20.26%)
	Male	179 (76.50%)	195 (82.97%)	374(79.74%)
Age	30-35	130(55.56%)	120(51.06%)	250(53.30%)
	35-50	79(33.76%)	95(40.43%)	174(37.10%)
	51 and above	25(10.68%)	20(8.51%)	45(9.59%)
Designation	Chief Executive officer chief technology officer chief information officer vice president assistant vice president Deputy Vice President Chief Manager project Managers senior Managers divisional Managers, Process Engineers	92(39.32%)	85(36.17%)	177(37.73%)
	Chief Digital Officer, Digital Project Managers, Data Specialist, Digital Business Analyst AI Architect	82(35.04%)	90(38.29%)	172(36.67%)
	Technology product/ marketing Managers	30(12.82%)	20(8.51%)	50(10.66%)
	Others	30(12.82%)	40(17.02%)	70(14.93f%)

IV. ANALYSIS AND RESULTS

Statistical tools and procedures were used to analyze the primary data. Essential stages and steps were followed to ensure the reliability and validity of the measurement. Two different statistical analysis methods - exploratory factor analysis (EFA) and confirmatory factor analysis (CFA) were used to validate a measurement scale. EFA was used to uncover the underlying pattern and factors within the data, while CFA is used to validate a proposed factor structure with the observed data. The results of the analysis are discussed in the following subsequent subsections. Furthermore, EFA was conducted using SPSS 26 and CFA was performed on AMOS 22.0.

A. Reliability of the scale

Reliability refers to the extent to which the constructions are error-free and produce consistent outputs. Internal consistency of the measurement is estimated using Cronbach's alpha [112]. A reliability coefficient above 0.80 is considered good, indicating a high degree of consistency in the measure or instrument being used. A coefficient between 0.67 and 0.80 is considered fair, indicating some degree of inconsistency or variability, whilst a coefficient below 0.67 is considered poor, indicating substantial inconsistency or unreliability in the measure or instrument. In general, a higher than 0.7 level for alpha was regarded as evidence of a reliable scale [113]. As a result, 4 items I22, I32, I33, I38 were removed (refer Table I). The overall Cronbach's alpha for the 28 items pertaining to the perceived benefits of digitalization was 0.904. The obtained results demonstrate that the instrument exhibits high reliability and internal consistency.

B. Exploratory factor analysis

In this study, the factor analysis was performed at two stages, first the factor analysis was used during scale purification process. While, in the second stage, we wanted to group the remaining 28 items related to the perceived benefits of digitalization into a new smaller set of uncorrelated constructs with minimum loss of information. According to Chatfield and Collins [114], "…the fundamental premise of component analysis is that there are multiple factors that can be used to explain the correlations or interrelationships between variables that have been observed…"

Before conducting EFA, it is recommended to check the suitability of data for factor analysis by using two tests namely Bartlett's test of Sphericity and Kaiser-Meyer-Olkin (KMO). Bartlett's test of sphericity is a statistical test that assesses whether the correlation matrix of the variables in the dataset is significantly different from an identity matrix, indicating that there is sufficient correlation among the variables to proceed with factor analysis.

A significant result (i.e., $p < .05$) indicates that the correlation matrix is not an identity matrix and therefore factor analysis may be appropriate [115]. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy is another method to assess the suitability of the data for factor analysis. It assesses the degree to which each variable in the dataset is correlated with others and indicates whether the dataset has enough variance in common to support factor analysis. According to Kaiser [107], the KMO value should be at least 0.5; values falling between 0.5 and 0.7 are considered mediocre; while those between 0.7 and 0.8 are considered acceptable; values ranging between 0.8 and 0.9 are considered excellent; and values above 0.9 are deemed exceptional [109].

Results of the Bartlett Test of Sphericity and Kaiser-Meyer-Olkin (KMO) are presented in Table III. Bartlett's Test of Sphericity was found to be 5322.285 with significance beyond the 0.000 level which indicates that these samples do not produce an identity matrix and are thus nearly multivariate normal and suitable for further analysis. Also, Table III shows the resulting KMO value is 0.838. The results of both tests conclude that EFA can be applied to sample size = 234. Principal component analysis (PCA) with varimax rotation was used in the study to do a factor analysis until each factor's Eigenvalue was equal to 1 or more. Our results from the EFA revealed that 28 items were grouped into the final five factors with an eigenvalue greater than 1 and these 5 factors accounted for 73.214% of the total variance.

Factor 1 was composed of the following six items: improve end-to-end visibility, enhance track and trace capabilities, provide real-time tracking and better accountability, provide real-time feedback, provide automated reporting, and improve the monitoring of process performance. Factor 1 with an Eigenvalue value 8.326 explains 16.087% of the variance.

Factor 2 comprised the following 7 items: Improve decision-making, improved data accessibility from anywhere and at any time, improved collaboration and communication, enhanced compliance with regulations and industry standards, improved knowledge sharing, enabling an actionable alert and notification and enhanced process safety. The factor 2 with an Eigenvalue of 4.253 explains 15.671% % of the variance.

Factor 3 was composed of the following 5 items: reduce inventory carrying cost, higher utilization of resources, reduce resource, material, and product waste, reduce the energy cost, and reduce the maintenance cost. Factor 3, with the Eigenvalue 3.089 explains 14.064% of the variance.

Factor 4 was composed of the following 5 items: provide agility in manufacturing processes, handle different product variants, reduce changeover times, enhance responsiveness to Business Needs, and improve resilience and time to market. Factor 4 with an Eigenvalue 2.890 explains 13.840% of the variance.

Factor 5 was composed of the following 5 items: improve operational efficiency, automate tasks and processes, reduce lead time, improve asset availability and uptime, and improve overall equipment effectiveness. The factor 5 with the Eigenvalue 1.842 explains 13.551% of the variance.

These five factors were thematically named: "real-time monitoring"; "data governance "; "eco-positivity"; "resiliency and agility"; and "embedded/automated control", respectively. Table III summarizes the factor analysis results with meaningful factors name, loading, Cronbach alpha, Eigenvalue, and variance explained.

C. *Confirmatory factor analysis*

A confirmatory factor analysis was conducted to validate the findings of the exploratory factor analysis. Using the collected data from 235 samples, a 5-factor measurement model for perceived benefits of digitalization was tested using AMOS 22.0. Several model fit indices and their criteria were used to examine the goodness-of-fit of the model on 235 samples. Confirmatory factor analysis results for standardized results are shown in Table IV. Model fitness indices for the final model were as follows: CMIN/DF=1.595, TLI = 0.957, NFI = 0.903, GFI = 0.860 and CFI = 0.961. According to Table IV, all fit indices are consistent with recommended values except for the GFI which is less than the threshold value of 0.90 but closest to the threshold value. The RMSEA (0.051), RMR (0.041), the CFA results confirmed good model fit.

Fig. 2 and Table V demonstrates the final measurement model of the perceived benefits of digitalization in manufacturing. The model shows a factor loading of 0.68, which confirms that the chosen items for each construct are similar. A low covariance of 0.5 among the constructs indicates that the construct's items are different. The model created the covariance between e27 and e28, e21 and e22. The covariances are formed through the modification indices made by AMOS to improve the goodness-of-fit [116]. After evaluating the model fit, we calculated composite reliability (CR), average variance extracted (AVE) and maximum shared variance (MSV) to ascertain the reliability and validity of the measure. Finally, the reliability of each construct was examined using Cronbach's alpha. Notably, the CFA process retained all 43 items from the initial model developed in the exploratory phase.

The reliability of the measurement model can be determined using two values: composite reliability (CR) and Cronbach's alpha coefficient. Table V indicates that the composite reliability of all the constructs ranges from 0.899-0.933. The result of CR confirms that all the items consistently measure their corresponding constructs. Cronbach (α) of all the constructs ranged between 0.926 – 0.897 confirming that the measures in the study were reliable [117].

In this study, we used content validity, convergent validity, and discriminant validity to evaluate the construct validity. The content validity of this study is primarily based on expert evaluation and target population judgment. As presented in Table V, the standardized outer loading of all indicators in their respective construct is above 0.774. Additionally, the average variance extracted (AVE) of each construct is greater than 0.5. This indicates that all constructs demonstrate good convergent validity. Table VI further supports discriminant validity as the square roots of the AVE of each construct (indicated in bold) are greater than the inter-construct correlation [118].

D. *Nomological and predictive validity*

After examining the evidence of convergent and discriminant validity, a further examination of the causal relationships between the derived construct and conceptually related constructs was performed. Researchers regard this test as a nomological validity of the construct [13], [119]. To assess nomological validity, this study examines the relationship between the newly developed digitalization measurement and organizational performance scales. We adopted standard measures of organizational performance as suggested both by [120], [121].

The statistical results show that the hypothesized model is a good fit to the data (Chi-square value of 719.426 with the degree of freedom(df) = 519). Whilst the other fit indices such as the comparative fit index (CFI) = 0.975, the root mean square error of approximation (RMSEA)=0.037, the normed fit index (NFI)=0.915, the Tucker-Lewis index (TLI)=0.973, and the goodness-of-fit index (GFI)=0.874, all indicate a good fit of the model to the data.

Our results indicate that digitalization is significantly and positively related to organizational performance ($\beta = 0.22$, $p < 0.01$). The predictive power of the model may be considered satisfactory as the model explains a good portion of the variance in organizational performance (R2 = .05). This suggests that the measures of digitalization used in the model are complementary and have nomological validity, meaning they are consistent with existing theories about digitalization.

TABLE III
RESULTS OF EXPLORATORY FACTOR ANALYSIS (N = 234)

Items	Description	Real-time information	Data governance	Eco-positivity	Resiliency and agility	Embedded/ Automated control
RTM1	Digitalization will improve end-to-end visibility	0.762				
RTM2	Digitalization will enhance track and trace capabilities	0.861				
RTM3	Digitalization will provide real-time tracking and better accountability	0.840				
RTM4	Digitalization will provide real-time feedback	0.810				
RTM5	Digitalization will provide an automated reporting	0.869				
RTM6	Digitalization will improve the monitoring of process performance	0.833				
DG1	Digitalization will enhance decision-making		0.833			
DG2	Digitalization will improve data accessibility from anywhere and at any time		0.756			
DG3	Digitalization will improve collaboration and communication		0.806			
DG4	Digitalization will enhance the compliance with regulations and industry standards		0.775			
DG5	Digitalization will improve knowledge sharing		0.834			
DG6	Digitalization will enable an actionable alert and notification		0.809			
DG7	Digitalization will enhance process safety		0.697			
EP1	Digitalization will reduce inventory-carrying cost			0.857		
EP2	Digitalization will provide higher utilization of resources			0.833		
EP3	Digitalization will reduce resource, material, and product waste			0.869		
EP4	Digitalization will reduce the energy cost			0.891		
EP5	Digitalization will reduce the maintenance cost			0.799		
RA1	Digitalization will provide agility in manufacturing processes				0.796	
RA2	Digitalization will handle different products variant				0.834	
RA3	Digitalization will reduce changeover times.				0.815	
RA4	Digitalization will enhance responsiveness to Business Needs				0.856	
RA5	Digitalization will improve resilience and time to market				0.819	
EAC1	Digitalization will improve operational efficiency					0.855
EAC2	Digitalization will Automate tasks and processes					0.817
EAC3	Digitalization will reduce lead time					0.882
EAC4	Digitalization will improve asset availability and uptime					0.838
EAC5	Digitalization will improve overall equipment effectiveness					0.785
Kasier-Meyer-Olkin (KMO) measure of sampling accuracy		0.878				
Bartlett Test of Sphericity		Chi-square = 5322.285 (df = 378 p-value =.000)				
Eigen Value		8.326	4.353	3.089	2.890	1.842
Cumulative Variance explained		16.087	31.758	45.823	59.663	73.214

TABLE IV
FIT INDICES FOR THE CFA

Model fit criteria	Resulting Model value	Acceptable level
CMIN/DF	1.595	3
LI	0.957	0.9
NFI	0.903	0.9
GFI	0.86	0.9
CFI	0.961	0.9
RMSEA	0.051	0.1
RMR	0.041	.01

TABLE V
SCALE ITEMS AND CFA RESULTS (N = 234)

Construct	Variable	Description	Standardized Factor loading	Cronbach (α)	Composite reliability (CR)	Average variance extracted (AVE)	Maximum shared variance (MSV)
Real-time Monitoring	RTM1	Digitalization will improve end-to-end visibility	0.812	0.926	0.915	0.645	0.243
	RTM2	Digitalization will enhance track and trace capabilities	0.946				
	RTM3	Digitalization will provide real-time tracking and better accountability	0.911				
	RTM4	Digitalization will provide real-time feedback	0.707				
	RTM5	Digitalization will provide an automated reporting	0.724				
	RTM6	Digitalization will improve the monitoring of process performance	0.681				
Data governance	DG1	Digitalization will enhance decision-making	0.814	0.897	0.899	0.562	0.008
	DG2	Digitalization will improve data accessibility from anywhere and at any time	0.708				
	DG3	Digitalization will improve collaboration and communication	0.763				
	DG4	Digitalization will enhance compliance with regulations and industry standards	0.730				
	DG5	Digitalization will improve knowledge sharing	0.807				
	DG6	Digitalization will enable an actionable alert and notification	0.772				
	DG7	Digitalization will enhance process safety	0.641				
1) Eco-positivity	EP1	Digitalization will reduce inventory-carrying cost	0.860	0.924	0.926	0.716	0.214
	EP2	Digitalization will provide higher utilization of resources	0.784				
	EP3	Digitalization will reduce resource, material, and product waste	0.898				
	EP4	Digitalization will reduce the energy cost	0.905				
	EP5	Digitalization will reduce the maintenance cost	0.776				
Resiliency and agility	RA1	Digitalization will provide agility in manufacturing processes	0.814	0.910	0.933	0.738	0.243
	RA2	Digitalization will handle different products variant	0.893				
	RA3	Digitalization will reduce changeover times.	0.917				
	RA4	Digitalization will enhance responsiveness to Business Needs	0.839				
	RA5	Digitalization will improve resilience and time to market	0.827				
Embedded /automated control.	EAC1	Digitalization will improve operational efficiency	0.869	0.914	0.915	0.682	0.209
	EAC2	Digitalization will Automate tasks and processes	0.774				
	EAC3	Digitalization will reduce lead time	0.864				
	EAC4	Digitalization will improve asset availability and uptime	0.832				
	EAC5	Digitalization will improve overall equipment effectiveness	0.786				

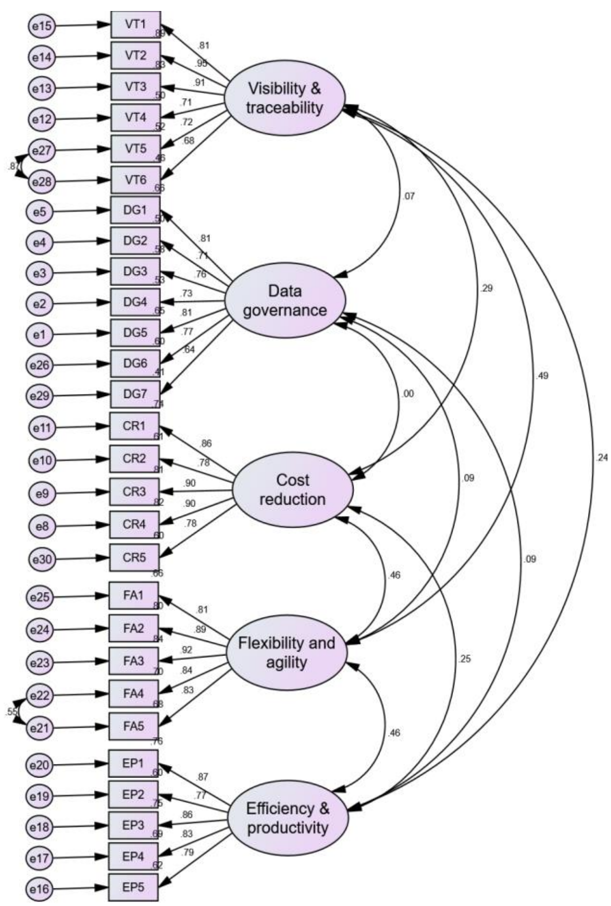

Fig. 2. CFA model of perceived benefits of digitalization.

TABLE VI
DISCRIMINANT VALIDITY OF THE MEASUREMENT MODEL

	RTM	DG	EP	RA	EAC
RTM	**0.803**				
DG	0.066	**0.750**			
EP	0.293	0.001	**0.926**		
RA	0.493	0.091	0.463	**0.859**	
EAC	0.242	0.090	0.249	0.457	**0.826**

V. CONCLUSIONS AND IMPLICATIONS

Digitalization can be beneficial for the success and growth of the manufacturing business through cost savings, improved transparency, productivity, and increased visibility. Following this line of argument and logic, our study, first identified and explored the benefits of digitalization in manufacturing through a structured literature review and validating expert interviews approach, thereby addressing our first research question (RQ1). After that based on the instrument-development process, we developed a valid and reliable measurement for measuring the perceived benefits of digitalization in the manufacturing sector and thus can be used in future research. This led to the authors providing statistical answers to our second research question (RQ2).

Prior research has predominantly explored the significance of digitalization and its associated digital technologies [69], [70], [74]. Additionally, some studies have also examined the barriers and challenges associated to their implementation [61], [122]. However, the scale for measuring the perceived benefits of digitalization in manufacturing has not been rigorously addressed by previous studies.

This study is unique in that it is the first of its kind wherein the perceived benefits of digitalization have been modelled as a second-order five factors construct to provide a more comprehensive understanding of the benefits of digitalization initiatives. Using fragmented and inconclusive findings from previous studies and experts' opinions, we have identified 28 items for scaling that have undergone rigorous validation and reliability testing for measuring the perceived benefits scale in manufacturing organizations. As a result, this study offers a reliable and validated measurement for assessing the benefits of digitalization initiatives.

The findings of this study suggest that perceived benefits of digitalization manifest the interactions among five distinct constructs namely: "real-time monitoring"; "data governance "; "eco-positivity"; " resiliency and agility"; and " embedded/Automated control ". The first construct "real-time monitoring " comprises six items namely end-to-end visibility, track and trace capabilities, real-time tracking and better accountability, real-time feedback, automated reporting, and monitoring of process performance. Real-time monitoring provides real-time visibility into supply chain processes, enabling managers to take informed decisions and optimize operations for maximum efficiency & productivity.

The emergence of this factor reinforces the prominent role of digital technologies like the industrial internet of things (IIoT), radio-frequency identification (RFID), blockchain and cloud computing and is consistent with other scholar's discussions of varying forms of digital technologies in real-time end-to-end monitoring and traceability across the supply chain [111], [123], [124], [125], [126], [127], [128].

RFID tags can capture information in real-time, leading to improved decision-making [124], [129], [130]. The integration of RFID, IIoT and Blockchain technologies significantly enhance supply chain transparency, empowering stakeholders to make better-informed decisions [124]. The utilization of a shared visible ledger in blockchain technology can increase supply chain transparency [124]. The cloud offers a powerful tool for enabling real-time monitoring to access real-time data and analytics from anywhere in the world [131]. Overall, the choice of digital technology for real-time monitoring in manufacturing will depend on the specific needs and goals of the organization.

The second construct comprises seven items representative of "data governance". The items included in this construct are enhanced decision-making, improved data accessibility from anywhere and at any time, improved collaboration and communication, compliance with regulations and industry standards, improved knowledge sharing, enabling an actionable alert and notification and enhance process safety. Studies on digitalization emphasizes the usage of digital technologies in data governance. Cutting-edge digital technologies like and machine learning, deep learning, artificial intelligence, big data analytics, industrial internet of thing and cloud computing offer a robust set of tools and techniques for managing and governing the data throughout its lifecycle and enforcing compliance with regulations and policies[27], [132], [133]. Leveraging these technologies can significantly enhance collaboration and communication, ultimately resulting in more informed and effective decision-making [124], [134]. Furthermore, technologies such as cloud computing enabled businesses to capture and process vast amounts of data in near real-time which will improve data accessibility from anywhere and at any time [124], [129], [130]. Leveraging benefits in a connected, dynamic environment digital twin can enhance process safety [112].

The third construct "eco-positivity" contains five items. The items include using reduced inventory-carrying costs, higher utilization of resources, reduced energy costs and reduced maintenance costs. Digital technologies such as IoT, Big Data Analytics, AI/ML, and cloud computing can provide a powerful set of tools and techniques for managing Eco-positivity. IoT devices can be used to monitor inventory levels in real-time, ensuring that stock levels are optimized and reducing the need for excess inventory. IoT sensors can also be used to track equipment usage and performance, enabling predictive maintenance, and reducing maintenance costs.

With Big data analytics, businesses can analyze large datasets based on IoT data and gain insights. By leveraging the insights provided by big data analytics, businesses can make real-time data-driven decisions that lead to improved efficiency, cost savings, and increased resource utilization [135]. Digital technologies like IoT, AI, and ML can help reduce energy costs and improve overall energy efficiency. Cloud computing has provided a cost-effective, scalable, and secure method for storing the vast quantities of data generated by IoT devices [135].

The fourth construct "resiliency and agility" contains five items. The items include agility in manufacturing processes, different product variants, reducing changeover times, enhancing responsiveness to business needs, improved resilience, and time to market. "Resiliency and agility" refers to a supply chain's capability to respond quickly to fluctuations in demand or supply and handle external disruptions [74]. Bigdata, AI/ML, IOT, Robotic Process Automation (RPA), cloud computing, 3D printing, digital twins, and augmented/virtual reality (AR/VR) can make supply chains more resilient and agile by improving real-time visibility, decision-making, reducing risk, optimizing operations, and responding more quickly to changing market circumstances [6], [136], [137], [138], [144]. Businesses must urgently rethink and reinvent supply chain design and management from the perspective of viable, reconfigurable and data-driven networks, in the context of digital technology, if they are to design end-to-end supply chain visibility that will increase supply chain resilience [139].

Overall, digital technologies can enable real-time data analysis, allowing operators to identify and troubleshoot issues quickly. This reduces changeover time times by improving the efficiency and effectiveness of production processes, allowing for faster time to market and increased competitiveness [140], [141]. 3D printing, digital twins, and AR/VR have revolutionized the product development process and made it faster, more cost-effective, and more efficient [142].

The fifth and last construct of the instrument is "embedded /automated control". The items include operational efficiency, automated tasks and processes, reduced lead time, improved asset availability and uptime and improved overall equipment effectiveness. Digital technologies like IoT, big data, augmented Reality (AR), Cloud Computing, and ML help manufacturing firms to improve their operational efficiency, reduce costs, and increase productivity by automating tasks and processes, reducing lead times, improving asset availability and uptime, and improving overall equipment effectiveness[48], [72], [77], [82], [95].

A. *Implication for practice*

Based on semi-structured qualitative interviews and survey-based cross-sectional data, the study developed a valid and reliable set of five second-order constructs measurement instruments to measure the perceived benefits of digitalization in manufacturing. Whilst the second-order instrument offers comprehensive and easily administered measures and gives insights into the measurement items of digitalization benefits.

By measuring the perceived benefits of digitalization, practitioners can first pinpoint areas where digitalization could bring more value. Second, manufacturing firms can use instrument measurement as a self-diagnostic tool to identify areas requiring improvement and prioritize digitalization efforts for maximum impact over time. Third, our instrument can be useful for assisting decision-makers who are debating whether to implement digitalization initiatives because they are unsure of its potential advantages to manufacturing processes or products. In the absence of such an instrument as proposed here, it would be challenging for practitioners to detect areas of concern, and failure as well it would be difficult to have evidenced reasoning of the impact of their interventions. With our instrument, they will be able to make data-driven decisions to specifically address process issues and improve their performance outcomes.

B. *Implication for research*

The results of this research reveal that the field of digitalization is still developing. First, to the best of our knowledge, this is an early attempt to develop and validate an instrument for measuring the perceived benefits of digitalization in manufacturing. This study provides a distinctive and valuable contribution to both theory and practice. first, we focused on the conceptualization, development and validation of an instrument to measure the perceived benefits of digitalization in the manufacturing sector. The examination and analysis of results explained that the instrument to measure the business benefits is highly reliable and demonstrates construct validity by presenting evidence of convergent, discriminant, nomological, and predictive validity.

We believe that researchers initiating future studies on digitalization will find this study beneficial. The developed instrument on perceived benefits of digitalization can be used first, as a dependent or independent variable in testing a theory. In our observation, the development of valid and reliable instruments enables more theory-building empirical research on this important topic. Second, items of perceived benefits of digitalization were categorized into five second-order constructs namely "real-time monitoring"; "data governance"; "eco-positivity"; "resiliency and agility"; and "embedded/automated control". These constructs represent an important contribution to the literature on digitalization, as they have been proven as statistically robust and can be used by researchers in other studies to build our understanding and knowledge regarding the digitalization concept. Third, developing the psychometric measurement scales in emerging concepts is essential to foster robust research and expand the body of knowledge in the field of digitalization [143].

C. *Limitations of the study*

The present study has certain limitations. First, the study sample has been confined to the Indian manufacturing sector. We acknowledge the importance of providing a more demographic understanding of our study participants to enable better judgments on its representation and generalizability. Unfortunately, due to time, costs, and practical resource difficulties during the data collection phase, we could not fully ensure that all sampling details and criteria of selection could be met, such as the full range of firm sizes, industry focuses, and geographic locations, firm age/maturity among others could be covered. Second, cultural biases may arise in the outcome of the study as the cultural differences between the manufacturing sector and IT sector users could affect the way the instrument is perceived and used. Third, the instrument has been empirically tested and validated using the data obtained from a single developing country. This limits the ability to generalize the findings to other developed countries or contexts. To address this limitation, future studies can test the instrument in multiple countries. Therefore, we suggest further avenues for generalizing the findings might be to consider adapting and testing the scale in other large developing/developed country manufacturing settings. We believe that cross-cultural validation would strengthen the case for universality. Finally, we noted the potential common method bias due to the reliance on self-report data. Incorporating objective measures could address this in future research.

Appendix I: Questionnaire benefits of digitalization

We aim to assess your perception and quantify the benefits of digitalization in the manufacturing industry. Kindly indicate your opinion in the questionnaire using the corresponding number scale (1 = 'Disagree'; 2 = 'Somewhat Disagree'; 3 = 'Neither Agree nor Disagree'; 4 = 'Somewhat Agree'; 5 = 'Strongly Agree').

Part A: Demographics

1. Industry/sector of the company?
2. No of employees
3. Position in the company.
4. Age range
5. Qualification

Part B: Perceived benefits of digitalization

Digitalization will improve end-to-end visibility.
Digitalization will enhance track and trace capabilities
Digitalization will provide real-time tracking and better accountability.
Digitalization will provide real-time feedback.
Digitalization will provide automated reporting.
Digitalization will improve the monitoring of process performance.
Digitalization will enhance decision-making.

Digitalization will improve data accessibility from anywhere and at any time.
Digitalization will improve collaboration and communication.
Digitalization will enhance compliance with regulations and industry standards.
Digitalization will improve knowledge sharing.
Digitalization will enable an actionable alert and notification.
Digitalization will enhance process safety.
Digitalization will reduce inventory carrying costs.
Digitalization will provide higher utilization of resources.
Digitalization will reduce resource, material, and product waste.
Digitalization will reduce energy.
Digitalization will reduce the maintenance cost.
Digitalization will provide agility in manufacturing processes.
Digitalization will handle different product variants.
Digitalization will reduce changeover times.
Digitalization will enhance responsiveness to Business Needs
Digitalization will improve resilience and time to market.
Digitalization will improve operational efficiency.
Digitalization will Automate tasks and processes.
Digitalization will reduce lead time.
Digitalization will improve asset availability and uptime.
Digitalization will improve overall equipment effectiveness.

APPENDIX II: I-CVI SCORES

Item No	Items from Literature survey and qualitative interviews	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	No agree	I-CVI
I1	Improve decision-making	4	4	3	4	4	2	4	4	4	4	4	9	0.81
I2	Improve collaboration and communication	4	4	4	4	4	4	3	3	4	4	4	9	0.81
I3	Improve knowledge sharing	4	4	4	4	4	4	3	3	4	4	4	9	0.81
I4	Real-time tracking and better accountability	4	4	4	4	4	4	4	3	4	4	4	10	0.9
I5	Improve data accessibility from anywhere and at any time	4	4	4	4	4	3	3	4	4	4	4	9	0.81
I6	Reduce the environmental impact	3	2	3	3	4	2	4	3	4	3	4	4	0.36
I7	Compliance with regulations and industry standards	4	4	4	4	4	4	4	3	3	4	4	9	0.81
I8	Enhance process safety	4	4	4	4	4	4	4	4	4	3	4	10	0.9
I9	Enable an actionable alert and notification	3	4	4	4	4	4	4	4	4	4	4	10	0.9
I10	Reduce inventory cost	4	4	4	3	4	3	4	4	4	4	4	9	0.81
I11	Provide better utilization of resources	3	4	4	4	4	4	4	4	4	4	4	10	0.9
I12	Reduce resource, material, and product waste	4	4	4	4	4	3	4	4	4	4	4	10	0.9
I13	Reduce the energy cost	4	4	4	4	4	4	4	3	3	4	4	9	0.81
I14	Reduce the maintenance cost	4	4	4	4	4	4	4	4	4	3	4	10	0.9
I15	Increased Return on assets (ROA),	3	3	3	3	3	3	3	4	2	4	2	2	0.18
I16	increased Return on sales (ROS)	4	4	2	3	2	3	3	3	3	4	4	4	0.36
I17	Improved resilience and time to market	4	4	4	4	4	4	4	4	4	3	4	10	0.9
I18	Increased Market capitalization	3	4	4	4	4	2	2	2	4	4	3	6	0.54
I19	better understand of customer requirement	3	3	3	3	3	2	1	4	4	2	3	1	0.09
I20	Improved customer satisfaction	2	2	2	3	3	4	4	4	4	4	3	5	0.45
I21	More direct interfaces with customers	1	1	1	3	3	4	4	4	2	2	3	3	0.27
I22	shorter response time to customer requests and market demands	4	4	4	4	4	4	4	4	3	2	4	9	0.81
I23	Improve end-to-end visibility	4	4	4	4	4	4	4	4	3	4	4	10	0.9
I24	Enhance track and trace capabilities	4	4	4	4	4	4	4	4	2	3	4	9	0.81
I25	Improved deeper understanding of processes	3	3	2	2	2	1	1	2	4	3	4	2	0.18
I26	Provide real-time feedback	4	4	4	4	4	3	2	4	4	4	4	9	0.81
I27	Improve the monitoring of process performance	4	4	4	4	4	4	4	4	3	3	4	9	0.81
I28	Improve operational efficiency	4	4	4	4	4	4	4	4	4	4	4	11	1
I29	Provide agility in manufacturing processes	4	4	4	4	4	3	4	4	4	4	4	10	0.9
I30	Handle different products variant	4	4	4	4	3	2	4	4	4	4	4	9	0.81
I31	Enhance responsiveness to business needs	4	4	4	3	4	4	4	4	4	2	4	9	0.81
I32	Create innovation opportunities	3	4	4	4	4	4	4	4	4	4	4	10	0.9
I33	Development of more functional products	4	4	4	3	4	3	4	4	4	4	4	9	0.81
I34	Automate tasks and processes	3	4	4	4	4	4	4	4	4	4	4	10	0.9
I35	Provide faster batch control	3	3	3	3	4	4	4	4	3	3	3	4	0.36
I36	Reduce changeover times	4	4	4	4	4	4	3	3	4	4	4	9	0.81
I37	Minimize human error	3	3	3	4	4	3	3	2	2	3	2	2	0.18
I38	Improve quality control	4	4	4	4	4	4	4	4	3	2	4	9	0.81
I39	Increased labor productivity	2	2	2	4	3	4	3	4	2	3	3	3	0.27

I40	Improve overall equipment effectiveness	4	4	4	4	4	4	4	4	3	4	4	10	0.9
I41	Provide an automated reporting	4	4	4	4	4	4	4	4	2	3	4	9	0.81
I42	Improve asset availability and uptime	4	4	4	4	4	4	4	4	3	2	4	9	0.81
I43	Reduce lead time	4	4	4	4	4	4	4	4	3	3	4	9	0.81

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