Productivity *Analysis*

Digital Transformation and Workforce Skills Strategy for Pakistan's Manufacturing Sector

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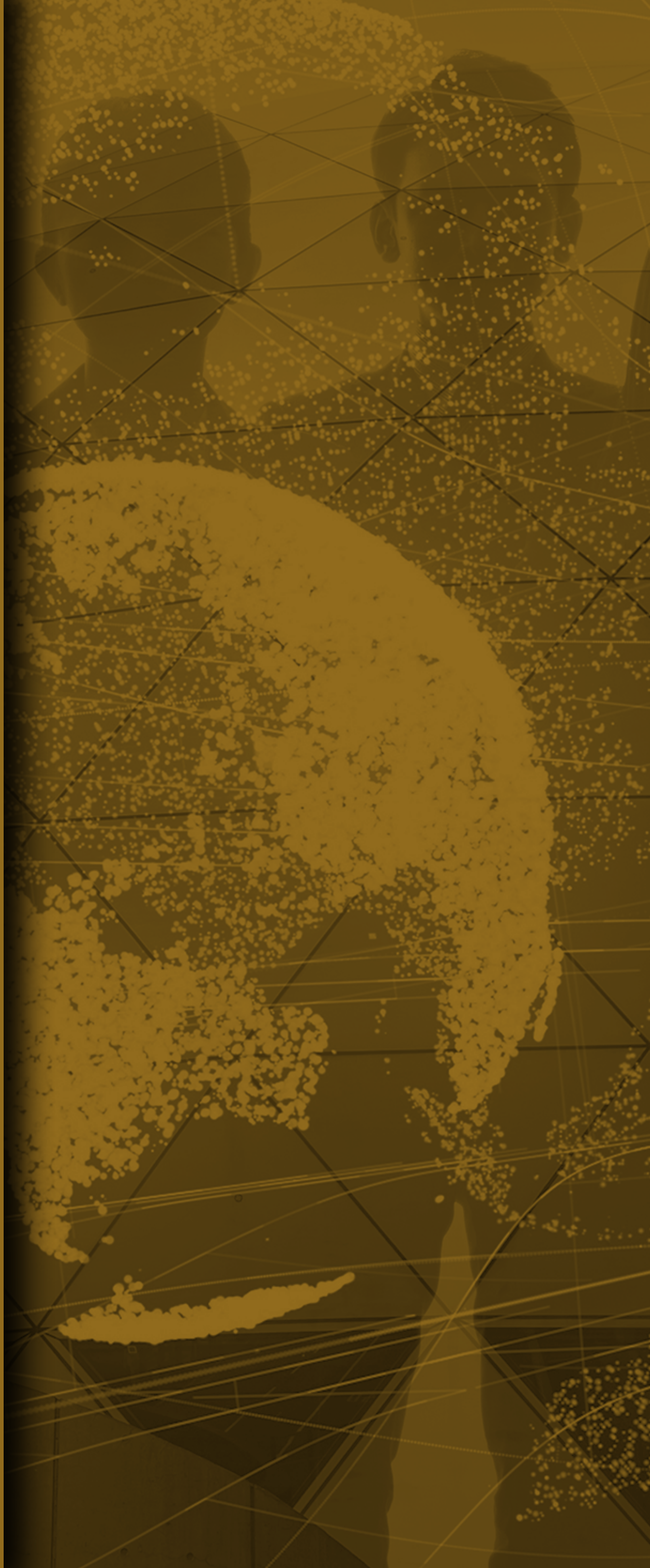

DIGITAL TRANSFORMATION AND WORKFORCE SKILLS STRATEGY FOR PAKISTAN'S MANUFACTURING SECTOR

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Dr. Amjad Hussain wrote this publication.

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CONTENTS

CONTENTS

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EXECUTIVE SUMMARY

Digital transformation in Pakistan's manufacturing sector is urgently needed to foster productivity, competitiveness, and economic resilience. This report presents the sector's current state, challenges, infrastructure, and skill development and provides a well-structured roadmap for achieving digital transformation through skill development.

Digital technology adoption, workforce skills, and curriculum alignment are some of the major areas that hinder progress in the manufacturing sector. Enterprise resource planning (ERP), automation, data analytics, and other technologies are being adopted by enterprises in Pakistan. However, a gap remains between the requirements of the sector and the expertise of graduates of technical or engineering institutions. Emerging technologies such as blockchain, digital twins, and cloud computing are less emphasized in the curricula, teaching-learning process, and industry practices than established technologies like CAD/CAM, ERP, and data analytics. To tackle these issues, this report suggests a digital transformation roadmap that focuses on assessing the existing state of digital skills, targeting specific training plans, and providing supporting infrastructure. Central to the roadmap is encouraging collaboration between industries, academia, and policymakers. This collaboration shall ensure that the skills imparted by technical and engineering education are aligned with sector needs.

The costs of digital transformation can be offset by offering tax rebates, subsidies, or low-interest loans, especially for small and medium-sized enterprises (SMEs). This study also calls for establishing innovation hubs and digital facilitation centers to provide companies with access to digital transformation resources. A supportive environment for digital adoption requires significant investments in digital infrastructure, such as high-speed internet access and cybersecurity.

It is also recommended that a national digital skills framework be developed. The framework should contextualize the education and training efforts concerning the manufacturing sector's needs. Reskilling the workforce with modern digital technologies should also be part of the framework.

Lastly, transforming the manufacturing sector from conventional to digital can increase productivity and competitiveness while driving economic resilience. Realizing this paradigm shift will take effort and collaboration from all involved: industries, academia, and government. Pakistan can achieve this transition to Industry 4.0 for its manufacturing sector by implementing the recommendations and roadmap presented in this study, contributing to sustainable economic growth, prosperity, and new avenues for employment and innovation.

INTRODUCTION

Background and Scope

Skilled human resources have always been a critical requirement for and indicator of a nation's journey to progress and prosperity. Mechanization of the manufacturing and service sectors has been a visible change since the industrial revolution in the sixteenth century, and digitalization has been a key prime mover in global economies since the advent of the computer in the middle of the twentieth century. The developed world achieved the goal of mechanization and digitalization through its well-trained human resources. The development and growth of skilled human resources, as well as the development and deployment of cutting-edge technologies, are pivotal to achieving sustainable national progress as they benefit all sectors of the economy and society. The developed world has taken this route, and many developing nations like China, India, Malaysia, Singapore, and Turkiye follow the same path.

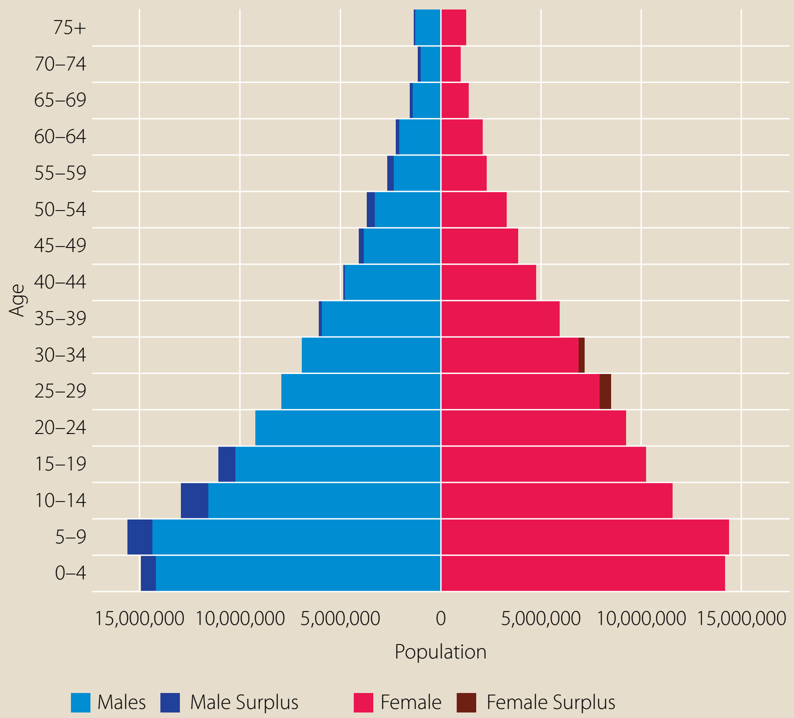
In addition to general literacy, the quality and quantity of technical human resources is a key requirement for industrial growth. More importantly, technological challenges are becoming more diverse with every passing year. The increase in population and ever-growing urban population has put the finite resources of energy, food, and water under extreme pressure. Process automation, robotics, computerized control, digitalization of the manufacturing and service sectors, development of intelligent materials, more efficient use of energy, and innovative organizational patterns of production are some of the strategies deployed to increase productivity and optimize the use of critical resources. Occupational profiles are continually changing, so these technological shifts require human resources to be developed and deployed accordingly. Appropriate training and development of human resources not only serve the demands of industries and society but also open vistas of opportunities for self-employment in terms of setting up new technology firms.

According to the Pakistan Bureau of Statistics (2024), the estimated population of Pakistan in 2023 was 241.49 million, with a population growth rate of 2.55% and population density of 303.4 per square kilometer. Pakistan has an extraordinary asset in the form of a "youth bulge," which means that young people make up the largest segment of its population. Fifty-nine percent of the population is between 15 and 59 years old while 27% is between 15 and 29 (Figure 1). This youth bulge can translate into economic gains only if the youth have skills consistent with the requirements of a modern economy.

Pakistan is experiencing a substantial "demographic dividend" inclined toward youth. Sixty-four percent of the population was under the age of 30 in 2018 (Ahmad, 2018). The youth population needs better technical education to contribute to the drive for national progress and prosperity.

FIGURE 1

POPULATION PYRAMID OF PAKISTAN, BASED ON THE 2017 CENSUS.



Source: Abbasi786786 (2021). CC BY-SA 4.0.

The lack of trained workers and the shortage of the requisite skills and training result in the manufacturing sector's rise in unfilled jobs. This gap between the required and the acquired skills becomes a barrier to shifting from an import-based conventional economy to a knowledge-based Indigenous economy.

Global Perspective on the Need for Skilled Human Resources

The world in 2050 will be primarily shaped by the following factors:

- Population and its growth and spread
- Resources and their utilization
- Globalization
- Climate change
- Technology

A vast majority of demographers agree that we are marching toward not only a more urban world but also a longer living one. This phenomenon is unprecedented in world history. For 99.9% of human history, average life expectancy at birth was less than 30 years (Hayflick, 2000). Over the past two centuries, average life expectancy has more than doubled (Roser, 2018). This aging phenomenon will hit some places harder than others.

As reflected in Table 1, the median age in Japan in 2010 was 44.2 years, making Japan the world's oldest country at the time. In contrast, Pakistan's median age in 2010 was 18.8 years, less than half that of Japan. By 2050, Pakistan's median age will rise to 26.3 years and Japan's will increase by almost a decade to 52.8 years. In 2050, the elderly dependency ratio (percentage of people aged sixty and older relative to those of "working age," between 15 and 60) will be higher all around the globe. Many countries in the present Western world have a dependency ratio exceeding 60%. The developing countries, e.g., Pakistan, with huge "youth bulges" have a window of opportunity: rich, aging countries will have to attract skilled foreign workers. For present-day developing countries, having a multitude of young people will not be enough unless they capitalize on exporting their young people to rich, elderly countries. For this, considerable improvements in education and governance will be required. Youth bulges must be converted into value-adding bulges through appropriate technical education so that they may fit into the future world.

TABLE 1

WORLD AGING PATTERNS BY 2050 (MEDIAN AGE IN YEARS).

Serial No.	Country	2010	2050	Change*
1	Argentina	28.9	41.9	+ 13
2	Brazil	28.2	43.9	+ 16
3	China	34.1	52.1	+ 18
4	Germany	43.3	47.9	+ 5
5	India	23.6	38.3	+ 15
6	Iraq	17.9	27.8	+ 10
7	Islamic Republic of Iran	26.1	43.5	+17
8	Japan	44.2	52.8	+9
9	Pakistan	18.8	26.3	+ 8
10	Republic of Korea	36.6	56.7	+ 20
11	Russian Federation	37.0	41.7	+ 5
12	Saudi Arabia	23.5	32.0	+ 9
13	United Kingdom	38.2	42.9	+ 5
14	USA	35.9	41.9	+ 6
15	Vietnam	27.2	40.2	+ 13

Note: In the source file, see the "Estimates" sheet for 2010 data and the "Medium variant" sheet for 2050 projections.
* Rounded to the nearest whole number.
Source: Adapted from United Nations Population Division (2024).

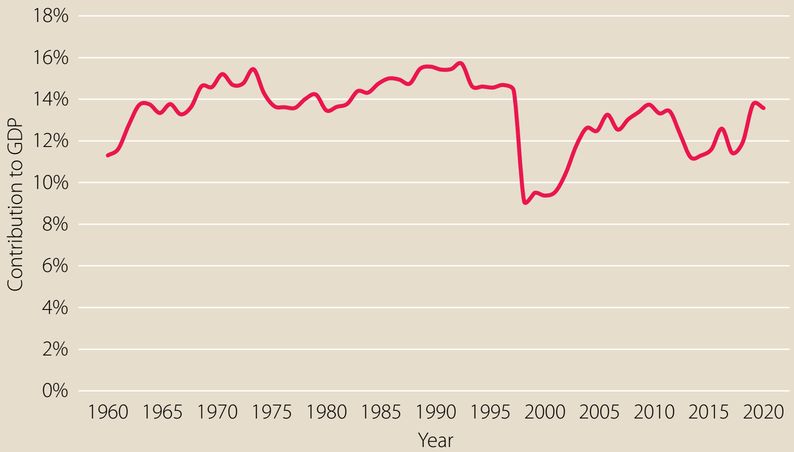
Similarly, it is impossible to exploit Pakistan's natural resources if the quantity and quality of the national technical human resources are not improved. The indigenization and localization of technology are only possible through the training and development of technical human resources. Ample and competent human resources are a prerequisite to meeting the challenges presented by globalization. Sustainable product manufacturing is the way forward, and the availability of the right human resources is as important as affordable raw materials and energy. Pakistan's current manufacturing landscape has little to no automation of enterprises, and it is not ready to meet the challenges brought about by Industry 4.0. Industrial equipment and processes must also comply with local and global environmental standards. The evolution toward Industry 4.0 and global environmental compliance requires technically competent and trained human resources who can assess the current state of technology and catalyze the transformation.

Contribution of the Manufacturing Sector to the GDP of Pakistan

The manufacturing sector in Pakistan has undergone periods of growth and decline; however, the sector's contribution to GDP has remained relatively stagnant over the past few decades (Figure 2). Factors contributing to stagnation include reliance on traditional industries, limited diversification, and inadequate adoption of advanced technologies.

FIGURE 2

HISTORICAL CONTRIBUTION OF THE MANUFACTURING SECTOR TO THE GDP OF PAKISTAN.



Source: Author's creation based on data from Trading Economics (2024).

Figure 2 illustrates the manufacturing sector's contribution to Pakistan's GDP from 1960 to 2020, reflecting growth, decline, and stagnation periods. The sector grew from 11.3% to approximately 15% between the 1960s and 1980s.

The growth during this period can be attributed to factors including but not limited to industrial policies, public sector investments, and export-oriented growth. However, a sharp decline from 15% to 9% occurred from the mid-1990s to 2000 due to economic liberalization challenges, energy shortages, political instability, and increasing global competition. The sector experienced some recovery in the 2000s, benefiting from export revival, foreign direct investment, and modernization efforts. Yet, post-2008, it has fluctuated between 11% and 14%, hindered by energy crises, policy inconsistencies, and security.

This stagnation highlights structural and policy issues, such as dependence on traditional sectors (e.g., textiles), a lack of diversification, and little involvement in global value chains. Chronic energy shortfalls and subpar infrastructure, compounded by elevated costs of doing business, have held back growth. In addition, the pace of technology adoption and limited investment in research and development (R&D) within Pakistan have made it difficult for local manufacturers to compete with more dynamic regional players: Bangladesh, India, and Vietnam. Pakistan has no other option but to cure the massive infrastructure backlog, embrace emerging technologies, diversify its industrial structure, and pursue stable, investor-friendly policies to revitalize the manufacturing sector as the engine of economic growth.

Problem Statement

Emerging technologies such as automation, data analytics, AI, and IoT have transformed the manufacturing sector globally. Unfortunately, Pakistan's growth trajectory is different. The digital transformation of the manufacturing sector in Pakistan is hampered by the shortage of appropriate skills in the workforce, infrastructure deficits, and weak links between industry and academia.

The lack of synergy between industry, government, and academia has further delayed the manufacturing sector's ability to adapt to digital transformation. The solution lies in assessing the current skills, determining the required skills, and collaborating with other stakeholders to generate a scalable roadmap for skill development. The roadmap should, therefore, be in accordance with the manufacturing sector's specific needs and technological development outlook (short- to long-term) and align with overall national economic goals, enabling sustainable growth and global competitiveness for Pakistan's manufacturing sector.

LITERATURE REVIEW AND OBJECTIVES

Pakistan's manufacturing sector suffers from low productivity and a lack of competitiveness in the international market (Hussain et al., 2015). The absence of digitalization and the related skill gaps are among the top productivity killers (Malik et al., 2024). Enabling the workforce with digital capabilities will help organizations in Pakistan exploit the transformative potential of Industry 4.0 technologies. These technologies offer many promises, but coverage on the ground is limited due to capability or capacity issues in the effective use of tools by the workforce. This literature review presents the impacts of digitalization on the productivity of the manufacturing sector, the role of digital technologies in productivity, and the challenge of workforce skill evolution.

The Impact of Limited Digitalization on Productivity

Evidence of the link between digitalization and productivity points to the fact that weak diffusion of digital technologies may impede productivity growth (Porokhovskiy, 2019). Organizations that invested extensively in developing digital technologies experienced significant productivity yields, while firms with little or no investment in digital technologies did not reap comparable benefits. Potential efficiency gains and competitive advantages cannot be materialized with insufficient digitalization.

The productivity gains from digitalization depend on associated organizational changes. IT investments combined with workplace restructuring and skill building generate productivity improvements. Organizations that do not complement digitalization with these reforms will never fully reap the productivity gains promised by digital technologies (Al Naim, 2023).

The nature of SMEs also presents unique challenges regarding limited digitalization. In SMEs, digital technology adoption can be limited due to the prevalence of a risk-averse culture, poor skill levels, and reliance on outdated technologies (Elhusseiny & Crispim, 2022). As a result, productivity may stagnate in these firms, and they need to digitalize wisely for better performance.

Bridging the Digital Skills Gap

Enhanced digitalization translates to an increase in the demand for a workforce that can adopt Industry 4.0 and other digital technologies, with expertise in AI, IoT, and automation. But in Pakistan, a skills gap limits the benefits of digital transformation (Batool et al., 2024). For instance, the manufacturing sector workforce often lacks the programming and analytical skills required to operate and maintain smart devices, data sensors, and logic-based feedback loops. Consequently, technologies such as 3D printing, robotics, and data analytics are underutilized in the sector.

Resistance to change and to the adoption of digital technologies is further exacerbated by the workforce's lack of the required skills and the requirements of performing in a digitalized production system. Consequently, digital technologies face resistance from employees who fear losing their jobs, which is a barrier to the sector's digital transformation (Mahmood et al., 2021). However, these concerns can be addressed by upskilling programs, vocational training, and educational reforms.

Emerging Technologies and Workforce Challenges

The emerging technologies outlined in the subsequent subsections are essential for achieving digital transformation within the manufacturing sector. These technologies address significant challenges, including operational inefficiencies, resource optimization, and maintaining global competitiveness. They facilitate advanced data-driven decision-making, automation, and seamless connectivity across production systems, all of which are critical for the transition to Industry 4.0.

Despite their transformative potential, the adoption of these technologies within Pakistan's manufacturing sector remains constrained. The primary barriers to adoption include skill shortages, resistance to change, and inadequate infrastructure. Highlighting these technologies provides a framework for identifying the specific areas where interventions are needed to bridge the gap between current capabilities and global best practices.

Data Analytics and Visualization

Data analytics and visualization help manufacturers make decisions based on insights derived from complex and big data. Most of the workforce in Pakistan is not properly trained in data collection, analysis, and visualization (Sajjad & Ahmad, 2024). This gap between the skills required for digital transformation and the skills acquired by the current workforce has resulted in poor adoption of data-driven decision-making practices, thus introducing inefficiencies. This skill gap can be minimized through strategic investment in training on data visualization and analytical tools that will allow production processes to be optimized while effectively managing costs.

Artificial Intelligence and Machine Learning

AI and machine learning (ML) can transform predictive maintenance, quality control, and process automation. AI and ML allow the development of intelligent systems capable of analyzing large datasets and making decisions. The lack of skilled human resources in AI and ML prevents Pakistani manufacturers from taking advantage of predictive models for equipment maintenance or AI-powered inspection systems (Sheikh et al., 2019).

Internet of Things

The devices and systems used for monitoring and improving operations can be connected in real time using IoT. Due to the lack of skilled human resources for IoT implementation, data security, and sensor integration, organizations in Pakistan are still at risk and smart factory adoption rates remain low, but there is great potential for revolutionizing supply chain processes and improving production efficiency with IoT (Sheikh et al., 2019). Training workers to interpret data, secure systems, and deploy new IoT technologies is essential for properly implementing IoT to enhance the productivity and competitiveness of the manufacturing sector.

Automation and Sensor Technology

Automation systems and sensors enhance accuracy, reduce human error, and increase productivity. Skills in programming, system integration, and maintenance are necessary for various technologies, including robotics and supervisory control and data acquisition (SCADA). Failure to employ workers with such skills results in underutilized automated systems and production processes that are not fully automated. To resolve this, the workforce should be trained in programming and system maintenance skills (Ali & Rehman, 2020).

Cloud Computing

Cloud computing offers scalable, diverse, and cost-effective options to enable the processing and analysis of big data. With cloud computing, in-house or contracted professionals and industry experts can remotely analyze, recover, and store data from anywhere.

To implement cloud computing in manufacturing effectively, the following skills are required:

- Understanding cloud platforms, such as Amazon Web Services, Microsoft Azure, and Google Cloud.

- Proficiency in cloud architecture, for example, designing and deploying scalable applications in the cloud.

- Using cloud-based data management and research for productivity enhancement and predictive maintenance insights.

- Knowledge of cybersecurity policies specific to the cloud to prevent attacks leveraging sensitive manufacturing information.

- Connecting cloud services with existing production systems, like manufacturing execution systems and ERP.

Cloud computing is significant in digital transformation because it enables manufacturers to transform quicker with on-demand resources and lower overall computing infrastructure costs; it also provides ease of collaboration and creativity.

Cybersecurity

IoT comes with significant risks of cyberattacks, especially in digitalized production and business environments. Examples of these risks include different types of data breaches and the utilization of one's own network for unauthorized access to other places. To protect against these risks, cybersecurity expertise is crucial, and a well-constructed cybersecurity system is essential to protect confidential business details, customer details, etc. Cybersecurity includes network safety features, employee training, and practices such as regularly updating software to fix vulnerabilities. It is difficult to find skilled and qualified personnel in Pakistan to defend the digital environment (Mirza & Shahid, 2018).

Blockchain

Blockchain is a form of digital ledger technology that records every transaction or event in an irrefutable, time-stamped manner. Blockchain is widely used in multiple manufacturing industries; it helps to ensure the tracing and tracking of the product throughout the supply chain, from raw materials through production to end consumers. This ensures the transparency, traceability, and authentication of components and the prevention of counterfeiting. Self-executing contracts can automate many different processes, such as logistics and payments. The manufacturing sector can make use of blockchain technology because its features, such as transparency, trust, and efficiency, are beneficial, but Pakistan does not have enough experts in blockchain technology (Tahir et al., 2024).

Digital Marketing

While digital marketing may lack direct affiliations with production functions, it most certainly affects the success of modern manufacturing. In this digital world, the most straightforward and effective way to connect manufacturers with customers is through online channels such as Facebook, LinkedIn, and WhatsApp. This strategy requires professionals who are proficient in search engine optimization (SEO), social media marketing, content creation, and e-commerce. Using digital channels, manufacturers can enhance their brand image, improve customer relationships, and gain a competitive edge. However, there is a shortage of skilled workers in many organizations (Saeed & Rashidi, 2017), which are unable to keep abreast of all the rapid changes in the business environment. There is an essential need to bridge the gap between the skills required for the modern marketplace and the current skills of marketing teams.

Digital Twin Technology

The research and development on the use of digital twin technologies has transformed the manufacturing sector's digital revolution. Digital twins are digital models that behave exactly like a physical system, thus allowing the designers to predict and optimize system functions and responses before they are physically implemented. They accelerate and improve the quality of manufacturing processes and reduce lead time. Real-world applications of digital twins have shown many benefits. Digital twins are a game changer for manufacturing operations; they help improve worker productivity and bring remarkable changes in production and maintenance.

Additive Manufacturing

Additive manufacturing, commonly known as 3D printing, involves building components layer by layer by depositing materials according to a 3D computer-aided design (CAD) model. Additive manufacturing enables the manufacture of geometries that would be impossible to produce with traditional manufacturing techniques. It facilitates the production of prototypes and tailored designs. Over the past thirty years, a great deal of research has been carried out to transition additive manufacturing methods to commercial pathways across various industries. These studies have resulted in the application of additive manufacturing technologies to industries such as automotive, aerospace, biomedical science, and energy.

In traditional subtractive manufacturing methods, a significant amount of raw material must be cut and discarded. Additive manufacturing, on the other hand, uses only the raw materials that are required for manufacturing the product; thus, the remaining raw materials can be used elsewhere. While prototyping using traditional methods often takes days or even weeks, additive manufacturing technology can be used to build workable prototypes in only hours. When creating a product, parts must go through several manufacturing processes and assembly workshops, which affects the product's overall quality. Additive manufacturing minimizes the operator's intervention in product quality by producing the part in a single stage. Because components are designed in advance, custom-designed products can be produced cheaply (by modifying a CAD design) and complex parts can be created with little setup cost.

Condition Monitoring

Condition monitoring is the identification and diagnosis of potential equipment failures. By using these systems, one can minimize downtime and maintenance costs by planning predictive maintenance activities. Condition monitoring helps decrease equipment breakdown, upgrade safety, streamline maintenance, and enhance overall equipment effectiveness. It is commonly used for turbines, pumps, fans, compressors, gearboxes, industrial-grade motors, and automobiles. Implementation of condition monitoring requires skills related to maintenance, sensor technologies, and predictive analytics. These skills are hard to find in Pakistan's current manufacturing landscape.

Enterprise Resource Planning

ERP systems can monitor every single process within manufacturing, logistics, and finance, offering visibility and traceability of the entire business process. These end-to-end integrated systems serve as the company's central source for data and workflow and can be used across multiple departments. ERP systems are based on a single, well-defined data structure called a schema, shared across the entire database. This ensures that the data used throughout the enterprise is consistent and is based on common definitions and user experiences. These basic concepts then connect systems and users through business processes powered by workflows across multiple functional departments (finance, human resources, engineering, marketing, and operations). ERP systems enhance decision-making processes by offering readily available data, but they also require professionals who are not only proficient with the technicalities of the system but also able to integrate the system into current workflows and resources.

Radio Frequency Identification

Radio-frequency identification (RFID) technology allows the use of electromagnetic fields to identify and track tags without physical contact. RFID is beneficial in inventory management, asset tracking, and supply chain visibility, among many more applications. RFID can be implemented in the manufacturing sector to automate inventory counts, eliminate human errors, and allow for real-time merchandise tracking. However, the utilization of RFID is limited in Pakistan's manufacturing sector due to limited knowledge regarding RFID system architecture, design, integration, and data analysis. Expertise in configuring tools (including RFID hardware such as tags and readers), developing middleware, and exploring results from RFID-generated data is essential. Developing this expertise requires workforce training programs and industry-academia collaborations on RFID applications in manufacturing processes. If worked on, these skills will help the workforce to provide firms with better inventory accuracy, less wastage, and more efficient operation.

Objectives

The fast-paced development of technologies from the Fourth Industrial Revolution has transformed the global manufacturing environment, which focuses on digital transformation as an important, value-generating process of productivity and competitiveness. Pakistan, on the other hand, has unique challenges in manufacturing that have made it lag behind such changes, including inadequate skills in the workforce that prevent businesses from adapting to a digitalized environment. This study was conducted with the following objectives:

1. Analyze the current state of Pakistan's manufacturing sector in terms of current skills and emerging skills needed for digital transformation.

2. Identify the specific digital skills required to drive the manufacturing sector's transformation, taking emerging technologies into consideration.

3. Analyze the gap between the skills acquired by the workforce and the skills required for the digitalized manufacturing landscape.

4. Collaborate with key industry stakeholders, policymakers, and educational institutions to gather insights and recommendations for the design and implementation of the proposed roadmap.

5. Develop a comprehensive and strategic roadmap for integrating digitalization efforts with workforce skill development, considering manufacturing-specific needs and future technological needs.

METHODOLOGY

This research aims to formulate a comprehensive roadmap strategy to digitalize Pakistan's manufacturing sector. To achieve the research objectives, a multistep approach was taken. Firstly, a literature review examined the need for digitalizing the manufacturing landscape. It also identified the digital technologies required to transform the manufacturing sector and their effects on industrial performance in terms of productivity and competitiveness. Subsequently, focus group discussions and interviews with local industry representatives were carried out to determine the current skill requirements for the digitalization of Pakistan's manufacturing sector. In this step, the list of digital technologies and skills required to drive the manufacturing sector's transformation was compiled.

The second step was to find the gaps between the required and acquired skills: comprehensive, structured surveys were designed and used to record responses from multiple relevant stakeholders: industry professionals, academic professionals, and students. To capture the list of required skills, the responses were collected from various manufacturing industries, including textiles, automotive, beverages, electronics, packaging, and chemicals.

In parallel, the skills of the technical and vocational workforce were appraised via structured surveys of graduating students from different disciplines with direct relevance to the manufacturing sector. These mainly included mechanical, chemical, textile, electrical, industrial, manufacturing, and mechatronic degree programs. This also provided the opportunity to investigate the effectiveness of the teaching-learning process in engineering and technology education.

Moreover, the curricula of the selected programs were analyzed to check the level of focus and emphasis of the selected digital technologies. The curriculum guidelines published by the relevant regulatory bodies like the Pakistan Engineering Council, the National Technology Council, and the Technical Education and Vocational Training Authority were analyzed. This analysis helped us understand the representation of these skills in the curriculum and the effectiveness of the teaching-learning process in equipping graduates with the knowledge and skills necessary to meet industrial requirements.

Additionally, another survey was conducted to collect the faculty's viewpoints and record their claims about imparting necessary digital skills during the selected degree programs. The responses to this survey were considered alongside the curriculum analysis to draw conclusions regarding the effectiveness of the teaching-learning process in engineering and technology education at the national level.

By comparing the outcomes of the acquired competencies (from the student and alumni survey), required digital skills (from the industry survey), and the availability of the relevant subject domains in the curriculum (from the curriculum analysis), we concluded the following:

- Significant gaps exist between the acquired and required digital skills as evidenced by the mismatch between the industry expectation and current skill levels of the graduates.

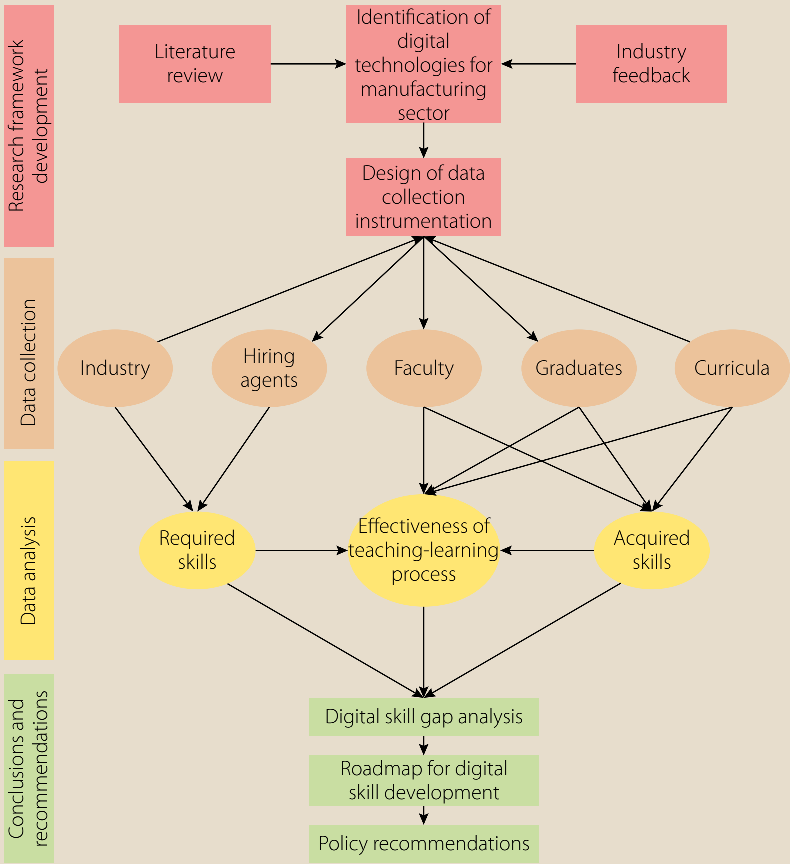
- The teaching and learning process for imparting necessary digital skills is effective for the topics it covers but insufficient in scope. This insufficiency leaves graduates unprepared for the sector's needs despite the process being well-executed for the existing curriculum.

- The necessary content related to the digitalization of the manufacturing sector is partially available in the existing curricula, but its coverage is inconsistent and often lacks depth, especially for emerging technologies such as blockchain, IoT, and digital twin technologies.

Considering the above findings, the research developed a comprehensive roadmap for enhancing the productivity of Pakistan's manufacturing sector through digitalization-supported technical and vocational skill development. Multiple relevant stakeholders from industry, academia, regulatory bodies, and public and private sector institutions were involved and their feedback was incorporated. This roadmap provides a step-by-step approach to promoting digital skills in the manufacturing sector. Figure 3 shows a detailed schematic of the research methodology.

FIGURE 3

RESEARCH METHODOLOGY.



Source: Author.

Data Sources

The following data sources were used in this research:

- Published research literature on skill requirements for digitalization in the context of manufacturing industries

- Interviews and surveys of the workforce, industry representatives, faculty, experts, policymakers, etc.

- Curriculum guidelines of the relevant disciplines from the Technical Education and Vocational Training Authority, the Pakistan Engineering Council, and the National Technology Council of the relevant disciplines

- Published reports by the APO, the National Productivity Organization of Pakistan, and other relevant institutions

DATA COLLECTION AND ANALYSIS

The current state of digitalization in the manufacturing sector and the workforce's readiness was assessed by surveying different stakeholders. The stakeholders' map for this project includes the following:

- Industry professionals/employers
- Graduates (BSc Engineering, BSc Engineering Technology, and Diploma of Associate Engineer)
- Faculty members of engineering, engineering technology, and technical and vocational education and training institutes
- Hiring agents

Structured questionnaire-based surveys were used to collect the data. To ensure maximum and diversified participation, the questionnaires were circulated online. The collected information was analyzed to assess the status of digitalization in the sector and the need for graduates to develop their skills. In addition to the primary data collected through the surveys, national curricula of BSc Engineering, BSc Engineering Technology, and Diploma of Associate Engineer (DAE) course were analyzed to assess the level of integration of digital skills.

The total number of responses collected from each category is shown in Table 2. The detailed breakdown of different categories of survey respondents is given in Figure 4.

TABLE 2

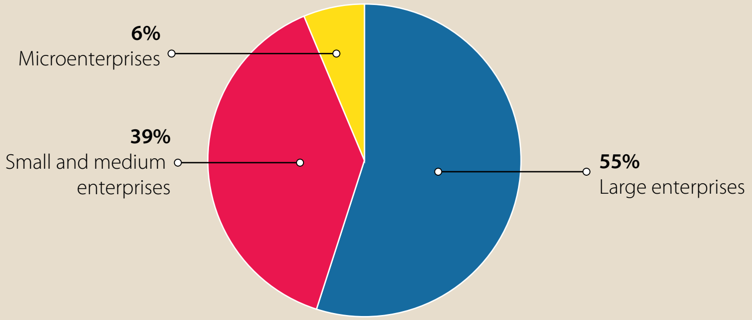
NUMBER OF SURVEY RESPONDENTS.

Respondent Category	Number of Responses
Industry	237
Hiring agents	27
Faculty members	359
Graduates	1,101
Total	1,724

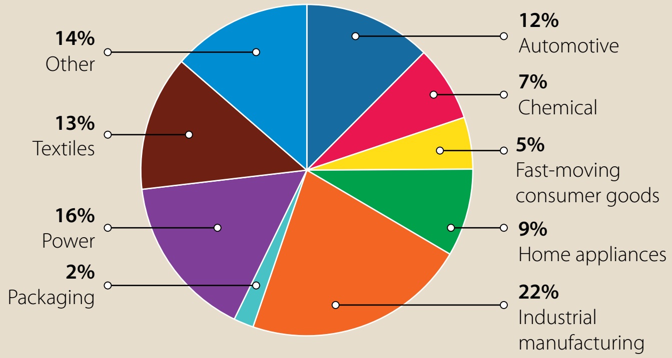
FIGURE 4

DEMOGRAPHIC DETAILS OF THE RESPONDENTS.

a. Distribution of industry respondents by business size



b. Distribution of industry respondents by industry



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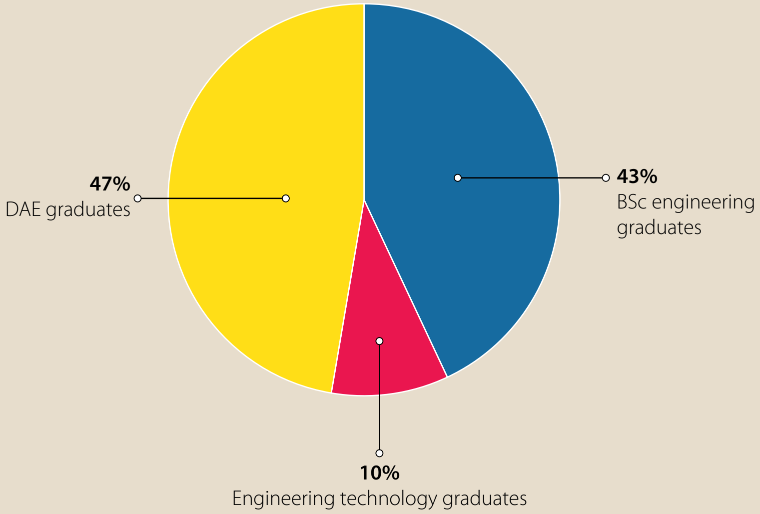
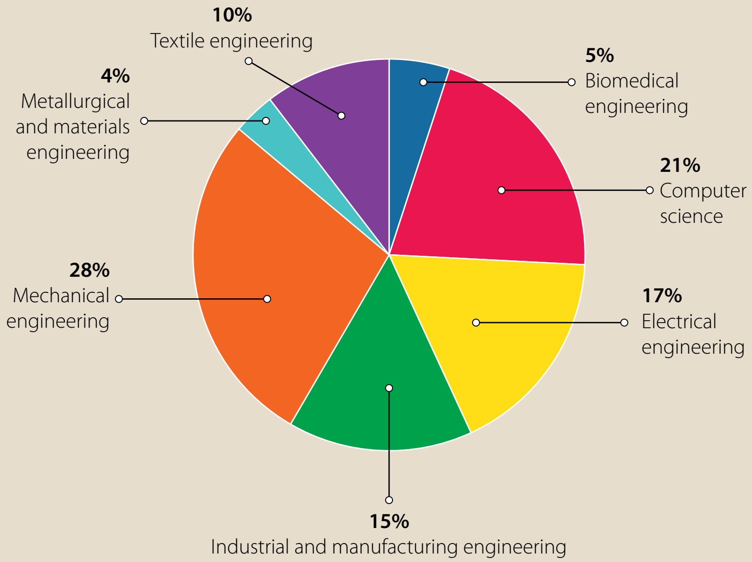
c. Distribution of responding graduates by degree program



d. Distribution of responding graduates by discipline



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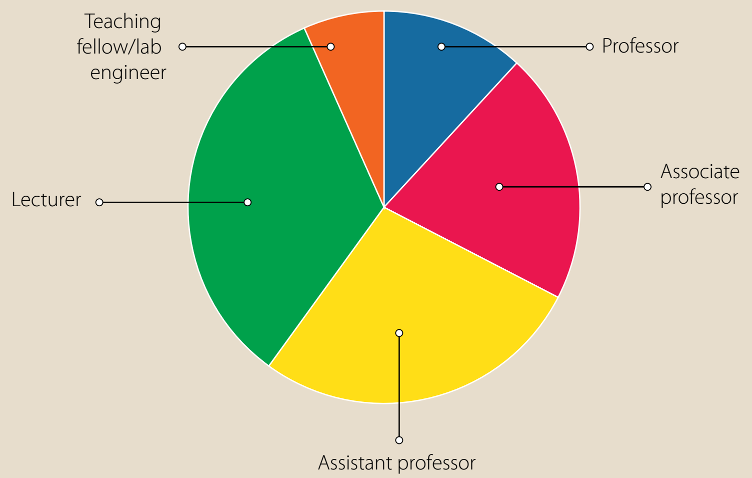
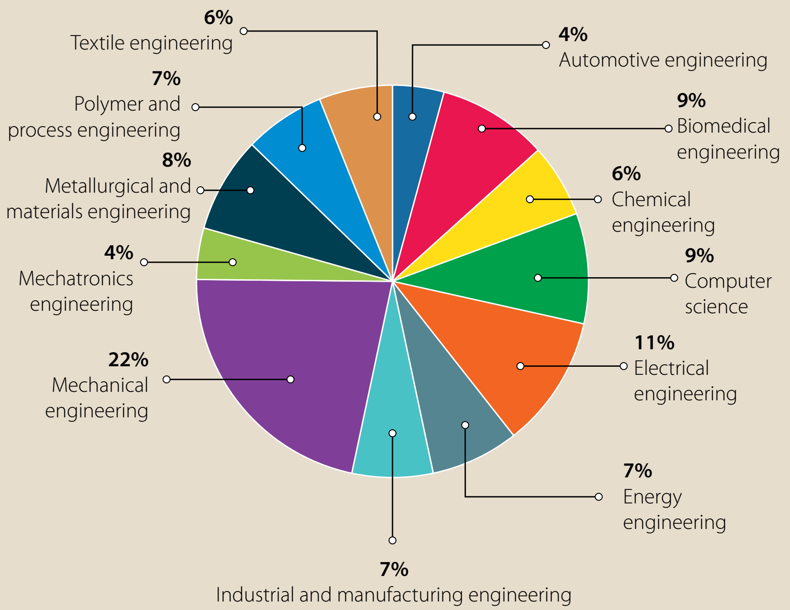
e. Distribution of the responding faculty members by position



f. Distribution of the responding faculty members by discipline



Data Collected from the Manufacturing Sector

Level of Digitalization in the Manufacturing Sector

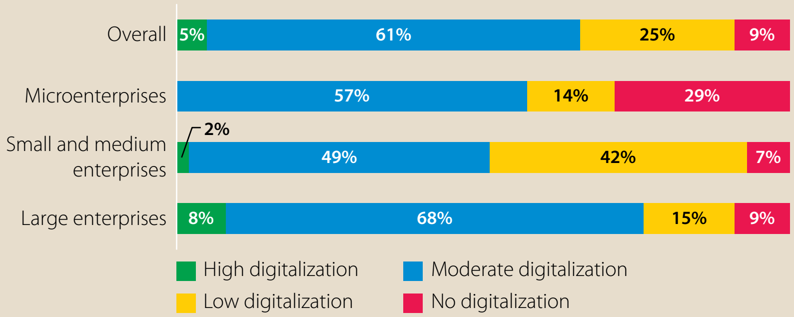
Analysis of digitalization levels indicates high variations of maturity and adoption of digital transformation in all firm sizes (Figure 5). Overall, 61% of enterprises have moderate digitalization levels. Highly digitalized enterprises account for just 5% of the total, while 25% of the enterprises reported low levels of digitalization, and a significant 9% are entirely undigitalized. Large organizations showed a significant preference for digitalization, with 8% of the companies having high digitalization and the majority of large firms, 68%, having moderate digitalization, which shows that progress is being made in the use of digital tools. In comparison, 15% still report low usage of digital tools, and 9% have no digitalization.

Compared with large enterprises, the pace of digitalization in SMEs appears relatively slow. Only 2% have high levels of digitalization and 49% are moderately digitalized. A large proportion, 42%, have a low level of digitalization, that is, they are not adopting new technologies, which still is a challenge for most SMEs. However, only 7% of SMEs reported no digitalization: the lowest percentage of all firm sizes. The lack of digitalization for this 7% likely emanates from the limited availability of resources or lack thereof. Microenterprises lag behind the most in digitalization, with no reported cases of high digitalization. Though 57% have achieved moderate digitalization and 14% have low digitalization, 29% reported having no digitalization at all. The significant obstacles microenterprises face in leveraging digital tools likely explain the lack of high digitalization and the high percentage of undigitalized companies. These figures highlight the need for appropriate support to be directed primarily to SMEs and microenterprises to improve their digital capacity and close the gap between them and larger enterprises.

The level of digitalization also differs across industries: some industries are moving forward, while others seem to lag behind. Other than the textile, power, packaging, and fast-moving consumer goods (FMCG) industries, which have 21%, 23%, 40%, and 8% highly digitalized firms respectively, no firm in any other industry is highly digitalized (Figure 6). Most firms surveyed across all industries are moderately digital, leaving room for adopting state-of-the-art digital technologies. Other than the power and packaging industries, there are a significant number of firms with no to low digitalization. The textile, automotive, manufacturing, and FMCG industries have 22%, 50%, 27%, and

FIGURE 5

LEVEL OF DIGITALIZATION IN MICRO, SMALL AND MEDIUM, AND LARGE ENTERPRISES.

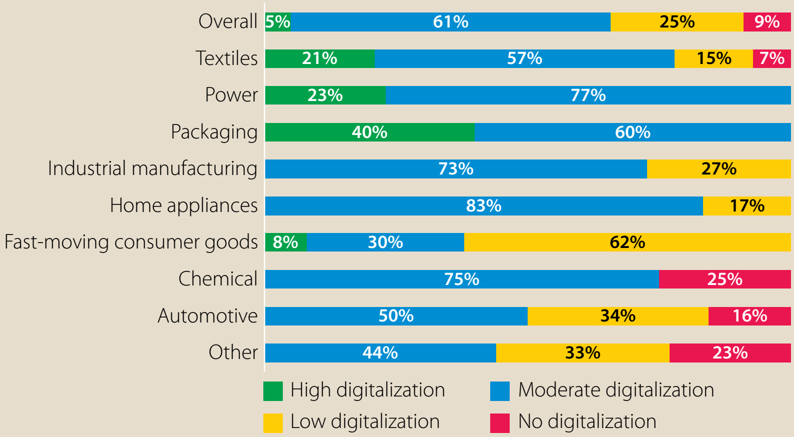


Source: Primary data collected during this study.

62% no to low digitalization, respectively. Fifty-six percent of the firms categorized as "other" have no to low digitalization. With the digitalization drive picking up momentum, there is room for the full integration of digital technologies to enhance operational efficiency, innovation, and competitiveness.

FIGURE 6

LEVELS OF DIGITALIZATION BY INDUSTRY.



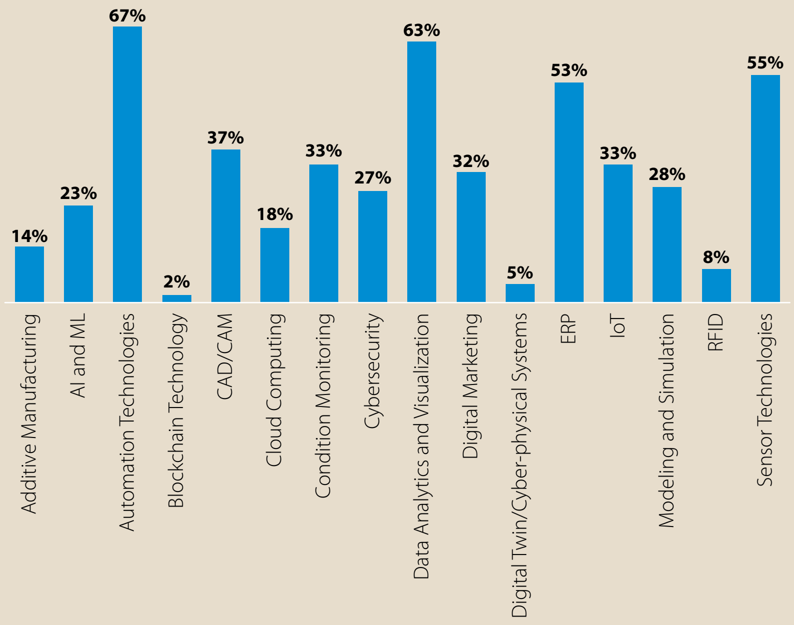
Source: Primary data collected during this study.

Adoption of Different Digital Technologies

The data collected during this study indicates that different technologies have different levels of adoption. Automation technologies, data analytics and visualization, sensor technologies, and ERP have relatively high levels of adoption: 67%, 63%, 55%, and 53%, respectively (Figure 7). Blockchain technology, digital twins, RFID, additive manufacturing, and cloud computing have very low levels of adoption: 2%, 5%, 8%, 14%, and 18%, respectively. The low to moderate level of digital technology adoption, less than 40%, provides an opportunity to integrate these technologies into industrial systems for better productivity.

FIGURE 7

PERCENTAGE OF FIRMS THAT HAVE ADOPTED DIGITAL TECHNOLOGIES.

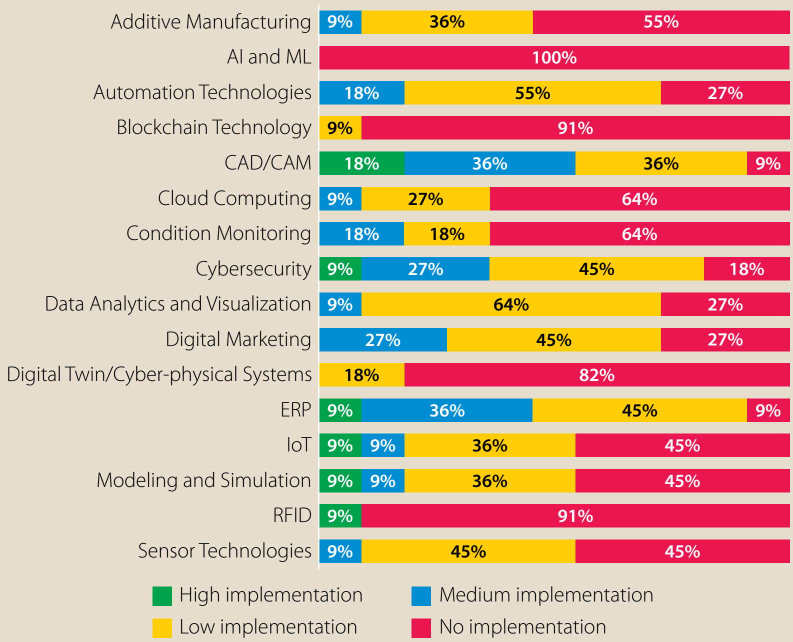


Note: ML, machine learning; CAD, computer-aided design; CAM, computer-aided manufacturing; ERP, enterprise resource planning; RFID, radio-frequency identification.
Source: Primary data collected during this study.

Eighty percent of the firms in the industrial manufacturing industry surveyed during this study have low or no implementation of digital technologies (Figure 8). For instance, AI, blockchain, and digital twin technologies are implemented at low to no levels in all firms. Less than 10% of the firms have a high implementation of IoT, cybersecurity, modeling and simulation, ERP, and RFID. Only CAD/computer-aided manufacturing (CAM) technology is implemented at medium or high levels in more than 50% of the firms.

FIGURE 8

LEVEL OF ADOPTION OF DIGITAL TECHNOLOGIES IN THE INDUSTRIAL MANUFACTURING INDUSTRY.

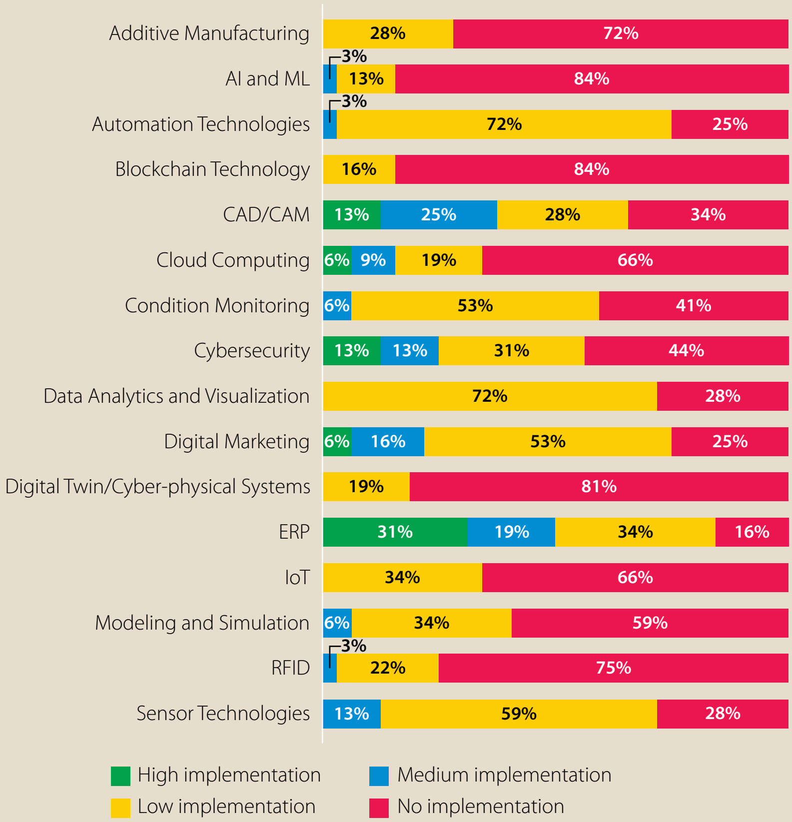


Note: CAD, computer-aided design; CAM, computer-aided manufacturing; ERP, enterprise resource planning; ML, machine learning; RFID, radio-frequency identification.
Source: Primary data collected during this study.

More than 85% of the firms in the automotive industry surveyed during this study have low or no implementation of digital technologies (Figure 9). For instance, additive manufacturing, blockchain, data analytics and visualization, and digital twin technologies are implemented at low to no levels in all firms. Cloud computing, digital marketing, cybersecurity, CAD/CAM, and ERP are highly implemented in 6%, 6%, 13%, 13%, and 31% of the firms, respectively. Only ERP is implemented at medium or high levels in 50% of the firms.

FIGURE 9

LEVEL OF ADOPTION OF DIGITAL TECHNOLOGIES IN THE AUTOMOTIVE INDUSTRY.

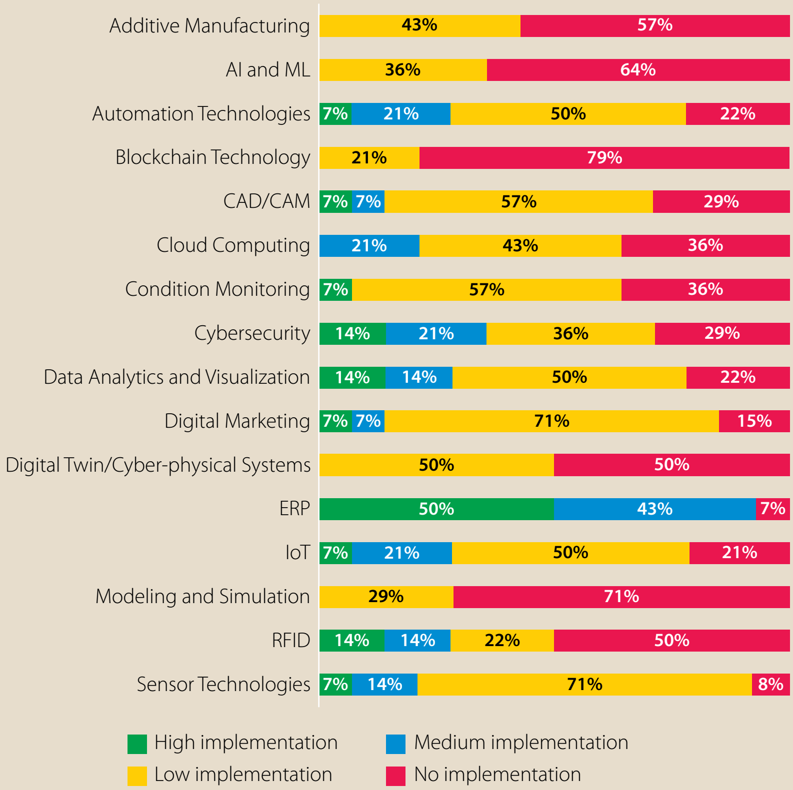


Note: CAD, computer-aided design; CAM, computer-aided manufacturing; ERP, enterprise resource planning; ML, machine learning; RFID, radio-frequency identification.
Source: Primary data collected during this study.

More than 80% of the firms in the textile industry surveyed during this study have low or no implementation of digital technologies (Figure 10). For instance, additive manufacturing, AI and ML, blockchain, and digital twin technologies are implemented at low to no levels in all firms. Compared to the industrial manufacturing and automotive industries, the textile industry implements digital technologies more effectively. Eighty-three percent of the responding firms have implemented medium- or high-level ERP.

FIGURE 10

LEVEL OF ADOPTION OF DIGITAL TECHNOLOGIES IN THE TEXTILE INDUSTRY.

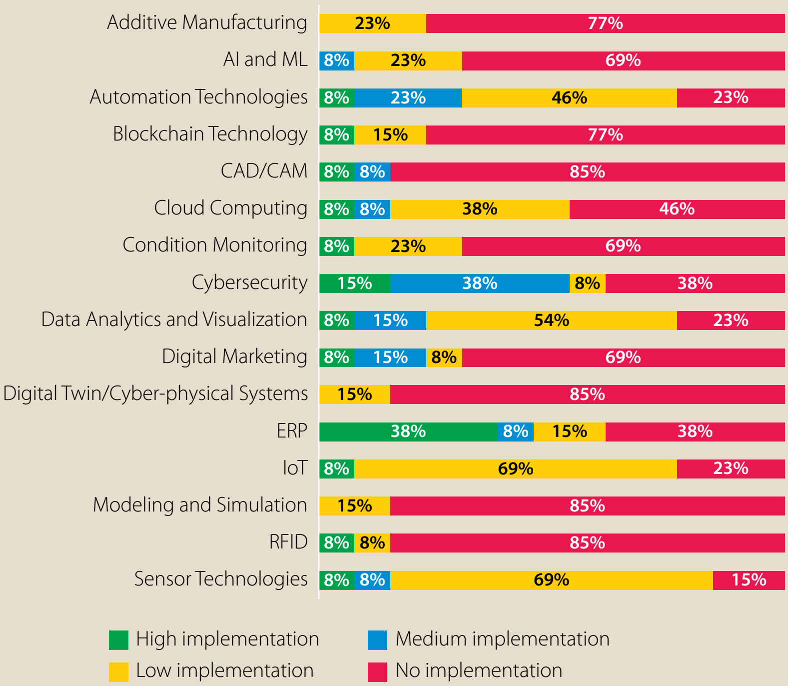


Note: CAD, computer-aided design; CAM, computer-aided manufacturing; ERP, enterprise resource planning; ML, machine learning; RFID, radio-frequency identification.
Source: Primary data collected during this study.

More than 80% of the firms in the FMCG industry surveyed during this study have low or no implementation of digital technologies (Figure 11). For instance, all firms report low to no implementation levels of additive manufacturing, digital twins, and modeling and simulation technology. Compared to other industries, the FMCG industry has better implementation of digital technologies. Fifty-three percent of the responding firms have implemented medium- or high-level cybersecurity. FMCG organizations are usually larger and have the resources to implement digital technologies such as AI, IoT, cybersecurity, and condition monitoring.

FIGURE 11

LEVEL OF ADOPTION OF DIGITAL TECHNOLOGIES IN THE FAST-MOVING CONSUMER GOODS INDUSTRY.



Note: CAD, computer-aided design; CAM, computer-aided manufacturing; ERP, enterprise resource planning; ML, machine learning; RFID, radio-frequency identification.
Source: Primary data collected during this study.

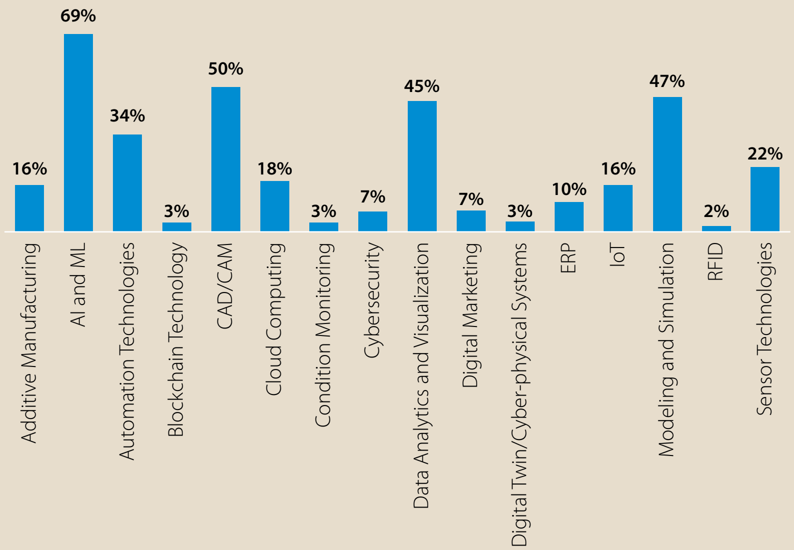
Proficiency of Graduates in Digital Technologies

This section presents the data collected from recent graduates on their perceived proficiency in digital technologies. The data analysis reveals significant variation in the understanding of different technologies among the graduates (Figure 12). The graduates were reasonably familiar with AI (69%), CAD/CAM (50%), modeling and simulation (47%), and data analytics and visualization (45%). Very few graduates were familiar with all other digital technologies. For instance, less than 10% of the respondents were familiar with RFID, condition monitoring, digital twins, blockchain technology, cybersecurity, and digital marketing. Between 10% and 30% of the respondents were familiar with ERP, additive manufacturing, cloud computing, IoT, and sensor technologies.

The analysis shows that graduates are limited in their exposure to digital technologies and that there are critical gaps in the curricula regarding emerging technologies. The variations recorded in the familiarity of different technologies among the graduates can be attributed to factors including but not limited to curriculum priorities, access to resources, and specialized laboratories. The graduates are familiar with commonly known tools such as CAD/CAM, modeling, and simulation. However, familiarity with digital technologies is lacking, which might be due to their novelty and the perception that they are not directly relevant to current industry needs. The lack of knowledge of blockchain may be due to its recent emergence and disconnection from conventional engineering practices, while digital twin technology may not yet be fully integrated into the standard curricula because of its interdisciplinary nature and resource limitations. These technologies need to be integrated through interdisciplinary approaches and mutual collaborations to address these gaps. This shall align the students with the present and future needs of modern manufacturing.

FIGURE 12

GRADUATES' FAMILIARITY WITH DIGITAL TECHNOLOGIES.

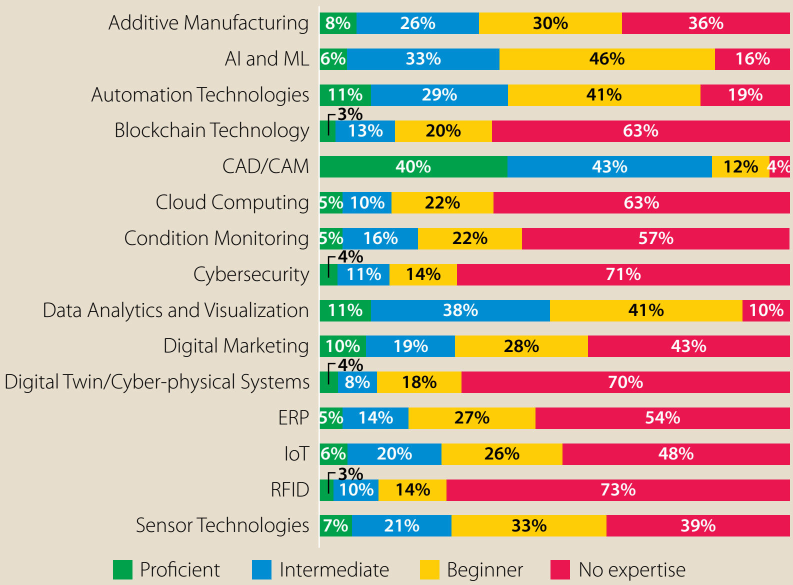


Note: CAD, computer-aided design; CAM, computer-aided manufacturing; ERP, enterprise resource planning; ML, machine learning; RFID, radio-frequency identification.
Source: Primary data collected during this study.

Based on their own self-evaluation, most mechanical engineering graduates are not proficient in using digital technologies, with very few exceptions (Figure 13). CAD/CAM is the only digital technology in which more than 50% of the graduates are intermediate or proficient. The graduates are most deficient in digital technologies such as RFID (73%), cybersecurity (71%), digital twins (70%), cloud computing (63%), blockchain (63%), condition monitoring (57%), and ERP (54%). Although technologies like RFID, cybersecurity, digital twins, cloud computing, and blockchain are not core skills for mechanical engineers, graduates should possess a beginner to intermediate level of understanding of these technologies to aid in digital transformation and Industry 4.0. On the other hand, condition monitoring and ERP are core skills for mechanical engineers, so most graduates should be proficient in these technologies; action should be taken to improve the integration of these technologies in the teaching-learning process.

FIGURE 13

PROFICIENCY OF MECHANICAL ENGINEERING GRADUATES IN DIGITAL TECHNOLOGIES.

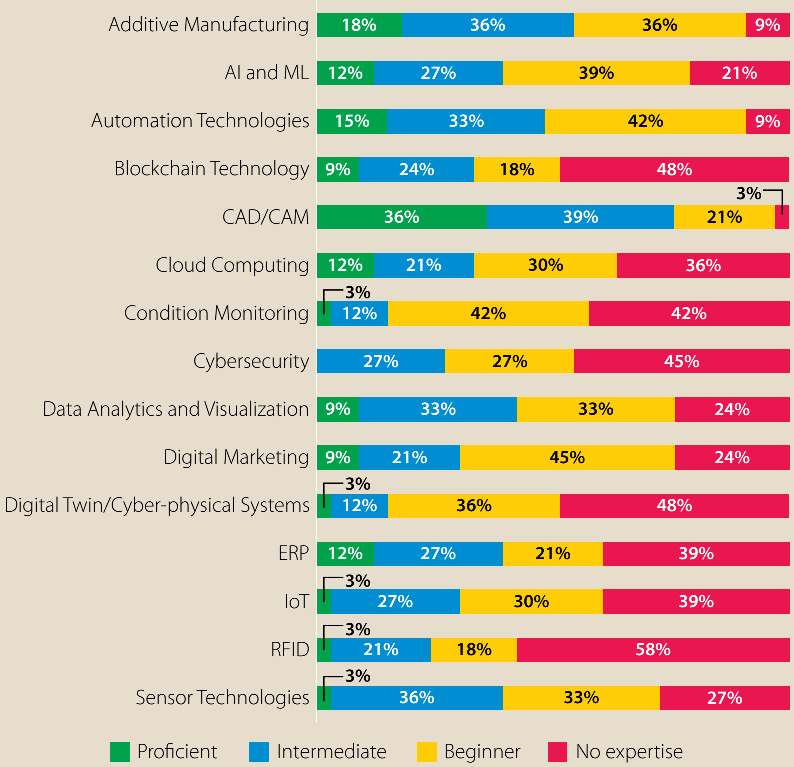


Note: CAD, computer-aided design; CAM, computer-aided manufacturing; ERP, enterprise resource planning; ML, machine learning; RFID, radio-frequency identification.
Source: Primary data collected during this study.

Based on their self-evaluation, most industrial and manufacturing engineering graduates are not proficient in using digital technologies, with very few exceptions (Figure 14). CAD/CAM and additive manufacturing are the only digital technologies in which more than 50% of the graduates are intermediate or proficient. The graduates are most deficient in digital technologies such as RFID (58%), condition monitoring (57%), digital twins (48%), blockchain (48%), and cybersecurity (45%). In the context of digital transformation and Industry 4.0, these technologies are critical to enabling industrial engineers to lead the paradigm shift.

FIGURE 14

PROFICIENCY OF INDUSTRIAL AND MANUFACTURING ENGINEERING GRADUATES IN DIGITAL TECHNOLOGIES.

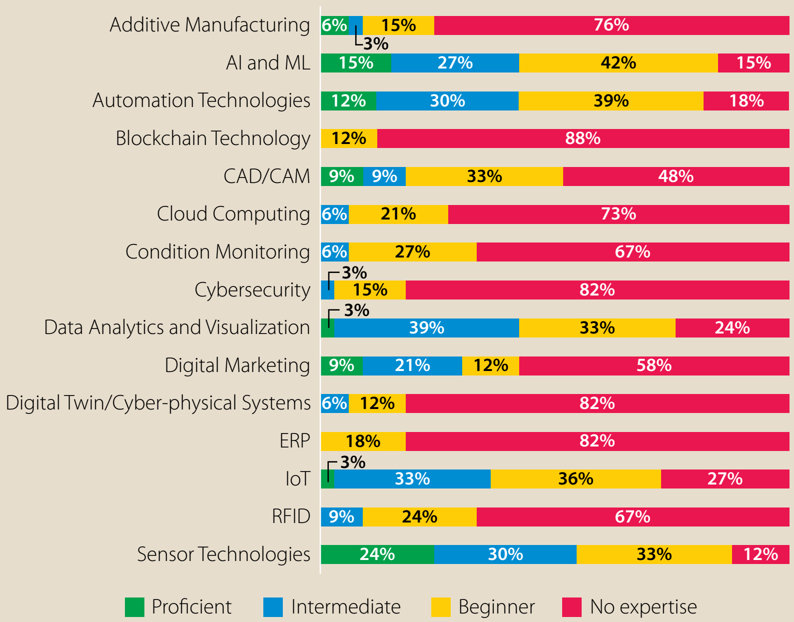


Note: CAD, computer-aided design; CAM, computer-aided manufacturing; ERP, enterprise resource planning; ML, machine learning; RFID, radio-frequency identification.
Source: Primary data collected during this study.

Based on their self-evaluation, most electrical engineering graduates are not proficient in using digital technologies, with very few exceptions (Figure 15). Sensor technology is the only digital technology in which more than 50% of the graduates are intermediate or proficient. However, around 40% of the graduates are intermediate or proficient in data analytics and visualization, AI, IoT, and automation technologies. RFID, digital twins, blockchain, cybersecurity, and cloud computing are key related technologies, and the graduates' lack of proficiency is a cause of great concern.

FIGURE 15

PROFICIENCY OF ELECTRICAL ENGINEERING GRADUATES IN DIGITAL TECHNOLOGIES.



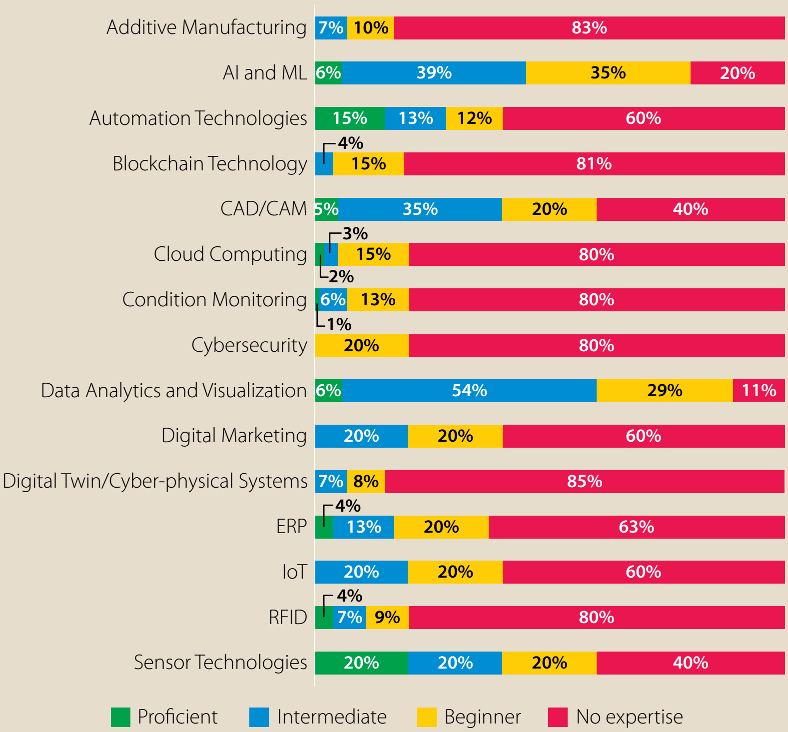
Note: CAD, computer-aided design; CAM, computer-aided manufacturing; ERP, enterprise resource planning; ML, machine learning; RFID, radio-frequency identification.
Source: Primary data collected during this study.

Based on their self-evaluation, most textile engineering graduates are not proficient in using digital technologies, with very few exceptions (Figure 16). Data analytics and visualization are the only digital technologies in which more than 50% of the graduates are intermediate or proficient. More than 80%

of graduates have no expertise at all in RFID, condition monitoring, additive manufacturing, digital twins, blockchain, cybersecurity, and cloud computing. RFID and condition monitoring are key technologies related to textile engineering, and graduates should be proficient in or at least possess intermediate skills in these technologies. Technologies such as digital twins, blockchain, cybersecurity, and cloud computing do not form the core of textile engineering but are nonetheless important given the globally competitive textile industry. The graduates should have at least a beginner-level understanding of these technologies to be able to identify opportunities for continuous improvements.

FIGURE 16

PROFICIENCY OF TEXTILE ENGINEERING GRADUATES IN DIGITAL TECHNOLOGIES.

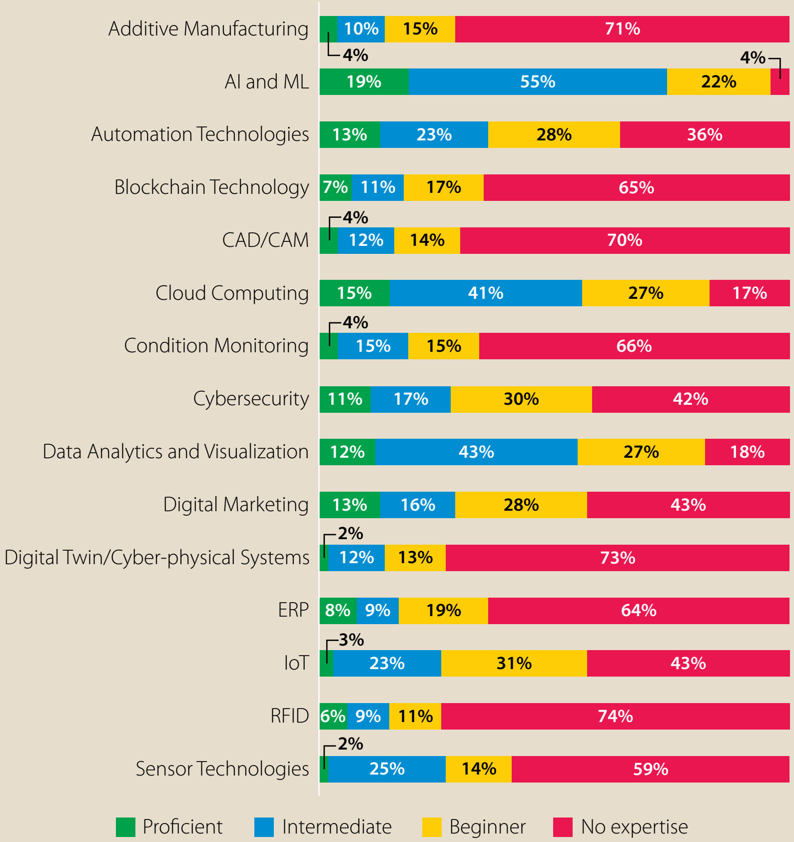


Note: CAD, computer-aided design; CAM, computer-aided manufacturing; ERP, enterprise resource planning; ML, machine learning; RFID, radio-frequency identification.
Source: Primary data collected during this study.

Based on their self-evaluation, most computer science and engineering graduates are not proficient in using digital technologies, with very few exceptions (Figure 17). AI, cloud computing, data analytics, and visualization are the only digital technologies in which more than 50% of the graduates are intermediate or proficient. More than 60% of the graduates have no expertise in RFID, ERP, digital twins, and blockchain technologies, which are core technologies related to computer science and engineering.

FIGURE 17

PROFICIENCY OF COMPUTER SCIENCE AND ENGINEERING GRADUATES IN DIGITAL TECHNOLOGIES.



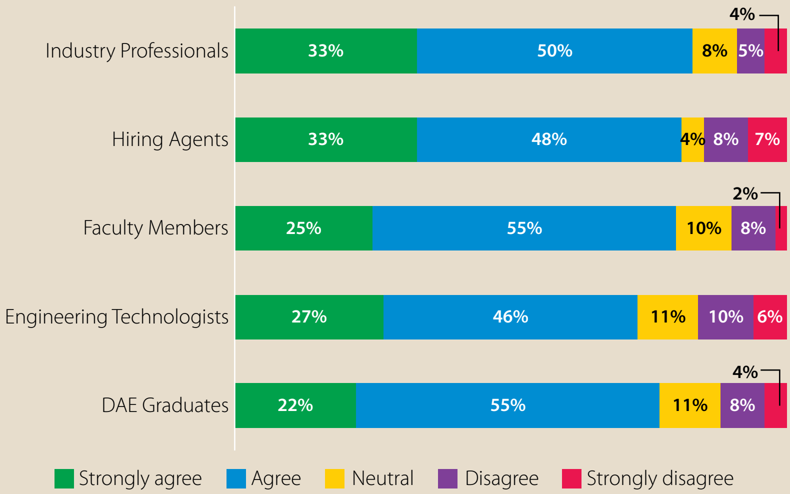
Note: CAD, computer-aided design; CAM, computer-aided manufacturing; ERP, enterprise resource planning; ML, machine learning; RFID, radio-frequency identification.
Source: Primary data collected during this study.

Regarding the skill gap between the required and acquired digital skills in DAE and BSc Engineering Technology, the majority of respondents from all categories in the primary data collection agreed that a skills gap exists. As reflected in Figure 18, 83%, 81%, 80%, 73%, and 77% of industry professionals, hiring agents, faculty members, engineering technologists, and DAE graduates agreed or strongly agreed that a skill gap existed, respectively. This clearly shows that existing technical education is not fulfilling the needs of industries.

Regarding the satisfaction level of the industry professionals or employers with the existing skill set of DAE and BSc Engineering Technology graduates, only 39% of the industry respondents were satisfied with the graduates' existing skills, while 36% were dissatisfied or highly dissatisfied (Figure 19). This trend indicates that the sector's existing technicians and engineering technologists need to update their skill sets, justifying the need to update the curriculum and teaching-learning process for DAE and BSc Engineering Technology.

FIGURE 18

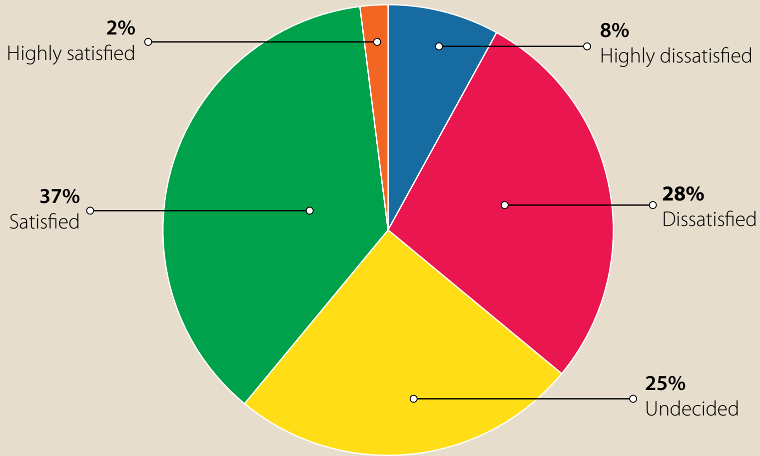
FEEDBACK FROM STAKEHOLDERS REGARDING THE EXISTENCE OF A SKILL GAP IN DIPLOMA OF ASSOCIATE ENGINEER AND BSC ENGINEERING TECHNOLOGY GRADUATES.



Note: DAE, Diploma of Associate Engineer.
Source: Data collected during this study.

FIGURE 19

SATISFACTION LEVEL OF INDUSTRY PROFESSIONALS WITH THE EXISTING SKILL SETS OF DIPLOMA OF ASSOCIATE ENGINEER GRADUATES.



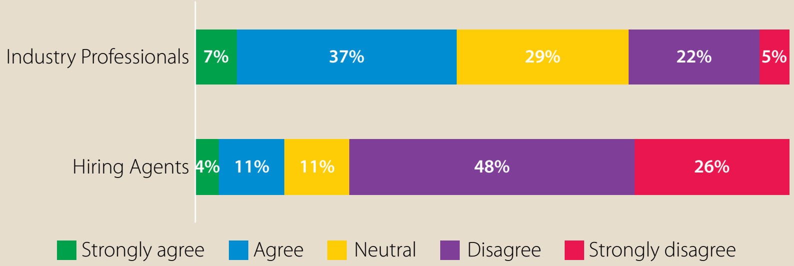
Source: Data collected during this study.

Regarding the availability of technical human resources, only 15% of the hiring agents agreed or strongly agreed that technical human resources are available for export to the international market (Figure 20). On the other hand, 44% of the industry professionals or employers agreed or strongly agreed that technical human resources are available for hiring. The difference between the perception of these two stakeholders can be explained based on the level of adoption of digital technologies in the local and international markets. As technological transformation in the local industry is in the nonexistent to nascent phase, most technical work does not currently involve the use of digital technologies. If technology-driven transformation is to be realized at the national level, contemporary and future technical human resources need to be equipped with the core digital skills.

More than half of the industry professionals (52%) and hiring agents (59%) surveyed considered current DAE and engineering technology graduates' proficiency in digital technologies to be insufficient, compared to only 14% of faculty members (Figure 21). Interestingly, 60% of the faculty members

FIGURE 20

PERCEPTION OF STAKEHOLDERS REGARDING THE AVAILABILITY OF TECHNICAL HUMAN RESOURCES.

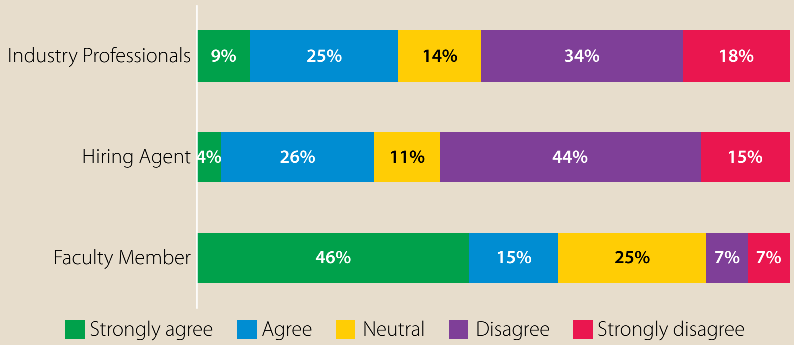


Note: DAE, Diploma of Associate Engineer.
Source: Data collected during this study.

surveyed considered graduates' digital skills to be sufficient. This indicates the ineffectiveness of the teaching-learning process at DAE and engineering technology levels, which has failed to integrate modern digital skills. Imparting contemporary digital skills will boost the probability of graduates' employment.

FIGURE 21

PERCEPTION OF STAKEHOLDERS REGARDING THE SUFFICIENCY OF DIPLOMA OF ASSOCIATE ENGINEER AND ENGINEERING TECHNOLOGY GRADUATES' PROFICIENCY IN DIGITAL TECHNOLOGIES.



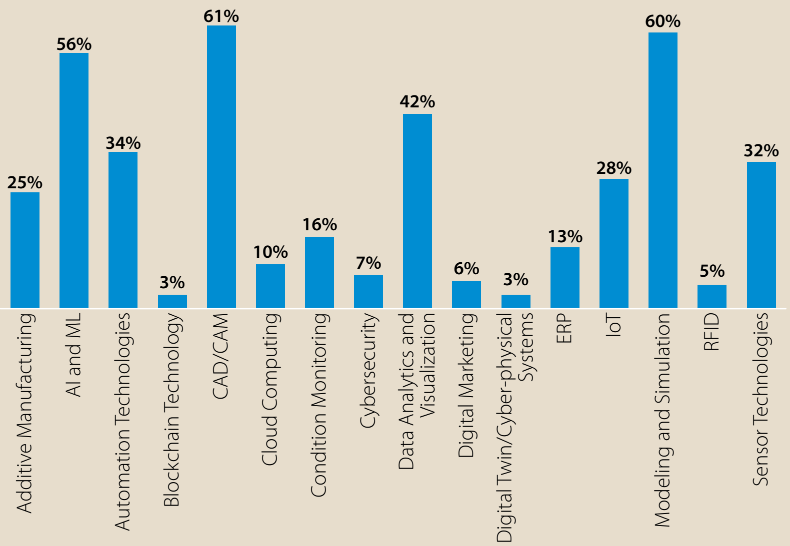
Source: Data collected during this study.

Integration of Digital Technologies in the Teaching and Learning Process

This section provides details of data collected from faculty members regarding the integration of digital technologies in the teaching-learning process. The data analysis reveals significant variations in the integration of different technologies in the teaching-learning process (Figure 22). Technologies such as CAD/CAM (61%), modeling and simulation (60%), AI (56%), and data analytics and visualization (42%) are moderately integrated into the teaching-learning process. Integration of all other digital technologies is very low. For instance, less than 20% of faculty members consider digital twins, blockchain technology, digital marketing, cybersecurity, cloud computing, ERP, RFID, and condition monitoring to be integrated. Integration of automation technologies, sensor technologies, IoT, and additive manufacturing is slightly better: between 20% and 40% of the faculty members believe that these technologies are integrated into the teaching-learning process.

FIGURE 22

INTEGRATION OF DIGITAL TECHNOLOGIES IN THE TEACHING-LEARNING PROCESS AS PERCEIVED BY FACULTY MEMBERS.



Note: CAD, computer-aided design; CAM, computer-aided manufacturing; ERP, enterprise resource planning; ML, machine learning; RFID, radio-frequency identification.
Source: Primary data collected during this study.

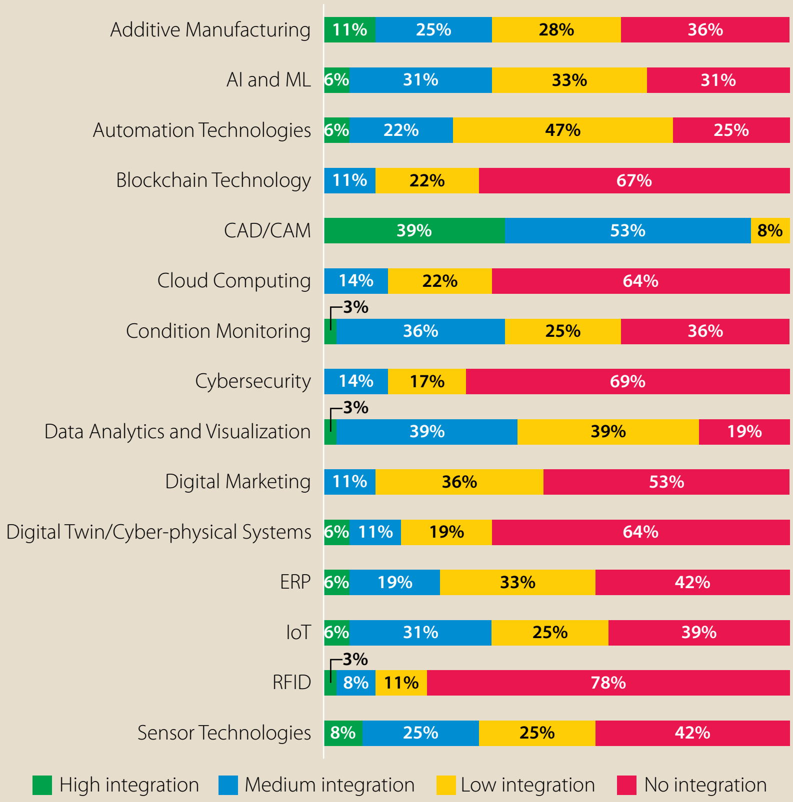
The analysis shows that digital technologies are very poorly integrated and that there are critical gaps in graduates' knowledge of emerging technologies. Recent graduates' self-evaluations of their proficiency levels in digital technologies were similar to faculty's assessments of how well the technologies are integrated into the curriculum. For instance, 42% of the faculty members reported that data analytics and visualization are integrated into the teaching-learning process and 45% of students are familiar with the technology; a similar pattern was observed for most of the technologies (the comparative analysis is presented in Figure 31). This indicates that programs covering a particular technology produce graduates familiar with that technology, which in turn indicates that the teaching-learning process is not the problem.

Most mechanical engineering faculty members do not perceive digital technologies to be well integrated in the teaching-learning process, with a few exceptions (Figure 23). CAD/CAM is the only digital technology considered to be well-integrated into the teaching-learning process, as more than 90% of the faculty members reported medium or high integration. Integration of data analytics and visualization is also perceived to be better than that of most other technologies, with over 40% of faculty rating its integration as medium or high. The integration of RFID, cybersecurity, cloud computing, digital twins, and digital marketing is very low: 78%, 69%, 64%, 64%, and 53% of the faculty members perceived no integration of these technologies in the teaching-learning process. Although these technologies are not core skills for mechanical engineers, graduates should possess a beginner to intermediate level of understanding of these technologies to aid in digital transformation and Industry 4.0.

Most industrial and manufacturing engineering faculty members do not perceive digital technologies to be well integrated in the teaching-learning process, with a few exceptions (Figure 24). CAD/CAM, automation technologies, and additive manufacturing are the only digital technologies considered to be well-integrated into the teaching-learning process: more than 70% of the faculty members reported medium or high integration. The integration of data analytics, visualization, and ERP is also perceived to be better than that of most other technologies, with more than 30% of faculty ranking their integration as medium or high. The integration of digital twins, cybersecurity, IoT, digital marketing, and blockchain technology is very low: more than 70% of the faculty members think these technologies are not

FIGURE 23

INTEGRATION OF DIGITAL TECHNOLOGIES IN THE TEACHING-LEARNING PROCESS AS PERCEIVED BY FACULTY OF MECHANICAL ENGINEERING.



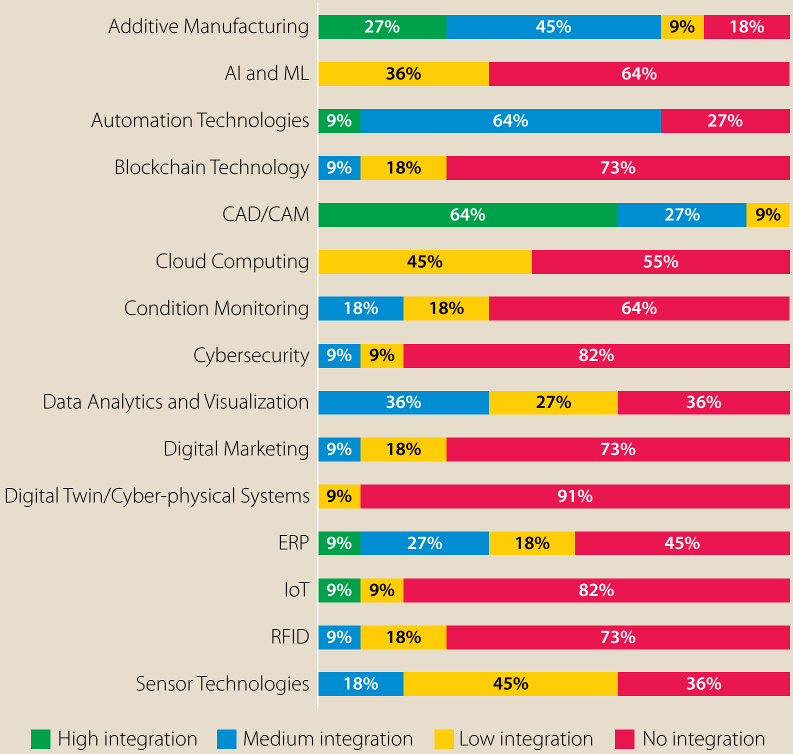
Note: CAD, computer-aided design; CAM, computer-aided manufacturing; ERP, enterprise resource planning; ML, machine learning; RFID, radio-frequency identification.
Source: Primary data collected during this study.

integrated into the teaching-learning process. These technologies form the core of modern industrial systems and should be integrated into the teaching-learning process for industrial engineers.

Most electrical engineering faculty members do not perceive digital technologies to be well integrated in the teaching-learning process, with a few exceptions (Figure 25). AI is the only digital technology considered to be integrated into the teaching-learning process by more than 50% of the faculty

FIGURE 24

INTEGRATION OF DIGITAL TECHNOLOGIES IN THE TEACHING-LEARNING PROCESS AS PERCEIVED BY FACULTY OF INDUSTRIAL AND MANUFACTURING ENGINEERING.



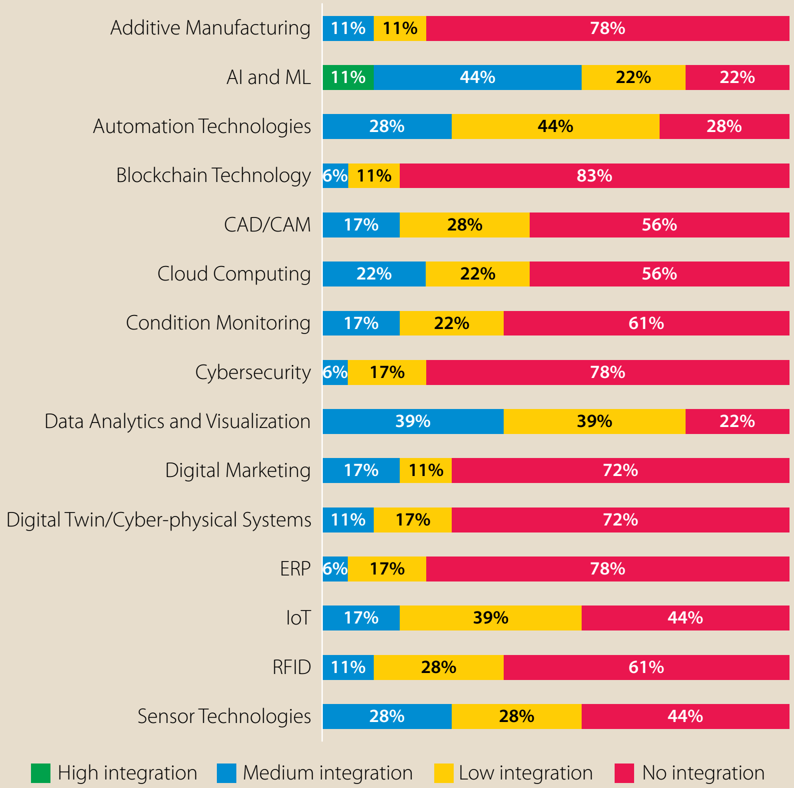
Note: CAD, computer-aided design; CAM, computer-aided manufacturing; ERP, enterprise resource planning; ML, machine learning; RFID, radio-frequency identification.
Source: Primary data collected during this study.

members and is the only technology some (11%) ranked as being highly integrated. None of the faculty members reported high integration in the teaching-learning process for any other technologies.

The integration of blockchain, ERP, additive manufacturing, digital twins, and digital marketing is very low: more than 70% of faculty members think these technologies are not integrated into the teaching-learning process. This shows that even the core technologies related to electrical engineering are not integrated into the teaching-learning process, and steps should be taken to modernize the teaching-learning process and include these technologies in the curricula of electrical engineering departments across the country.

FIGURE 25

INTEGRATION OF DIGITAL TECHNOLOGIES IN THE TEACHING-LEARNING PROCESS AS PERCEIVED BY FACULTY OF ELECTRICAL ENGINEERING.

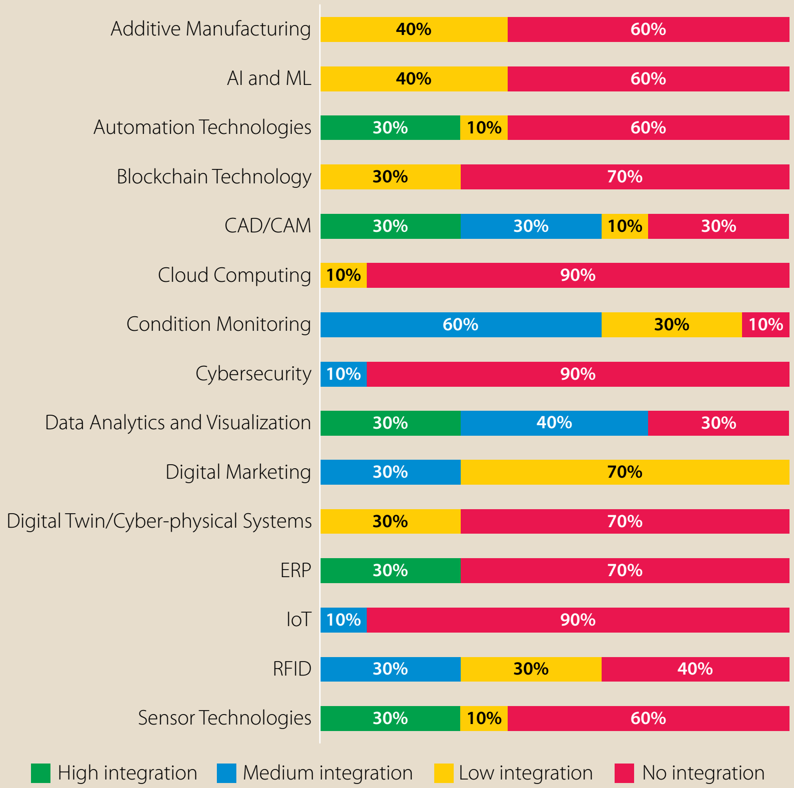


Note: CAD, computer-aided design; CAM, computer-aided manufacturing; ERP, enterprise resource planning; ML, machine learning; RFID, radio-frequency identification.
Source: Primary data collected during this study.

Most textile engineering faculty members do not perceive digital technologies to be well integrated in the teaching-learning process, with a few exceptions (Figure 26). Integration of data analytics and visualization, CAD/CAM, and condition monitoring are the only technologies considered to be well integrated into the teaching-learning process: more than 60% of the faculty members reported at least medium integration of these technologies in the curriculum. On the other hand, 90% of the faculty members reported no integration of IoT, cloud computing, and cybersecurity in the teaching-learning process. These technologies are important for textile engineers as most modern textile equipment relies heavily on these technologies. ERP is another important technology for textile engineers, and 70% of the faculty members perceive that it is not integrated into the teaching-learning process.

FIGURE 26

INTEGRATION OF DIGITAL TECHNOLOGIES IN THE TEACHING-LEARNING PROCESS AS PERCEIVED BY FACULTY OF TEXTILE ENGINEERING.

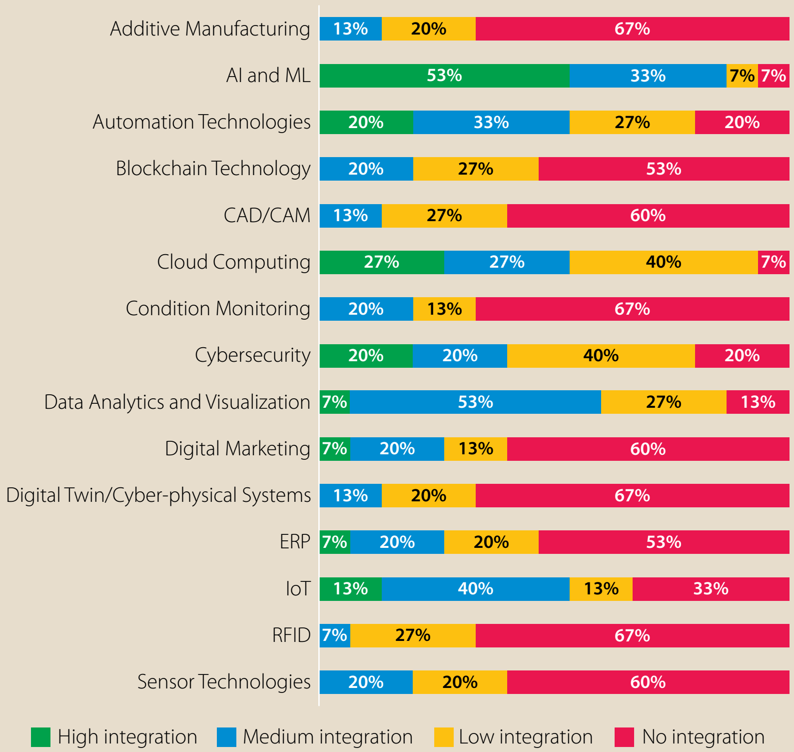


Note: CAD, computer-aided design; CAM, computer-aided manufacturing; ERP, enterprise resource planning; ML, machine learning; RFID, radio-frequency identification.
Source: Primary data collected during this study.

Most computer science faculty members do not perceive digital technologies to be well integrated in the teaching-learning process, with a few exceptions (Figure 27). More than 80% of faculty members ranked AI as being integrated into the teaching-learning process at a medium or high level. More than 50% of the faculty members reported at least medium integration of data analytics and visualization, IoT, automation, and cloud computing. Digital twins, digital marketing, blockchain technology, and ERP are core relevant skills, but at least 50% of respondents believe these technologies are not integrated into the teaching-learning process.

FIGURE 27

INTEGRATION OF DIGITAL TECHNOLOGIES IN THE TEACHING-LEARNING PROCESS AS PERCEIVED BY COMPUTER SCIENCE FACULTY.



Note: CAD, computer-aided design; CAM, computer-aided manufacturing; ERP, enterprise resource planning; ML, machine learning; RFID, radio-frequency identification.
Source: Primary data collected during this study.

Curriculum Analysis

This section describes the current extent of digital technology integration in academic curricula across three major education streams: BSc Engineering, BSc Engineering Technology, and DAE programs. Strengths, gaps, and opportunities for curriculum interventions that can strengthen synergies in digital transformation are identified. The degree of integration of digital technologies in these curricula also has implications for the changes required to develop the skills of the workforce.

BSc Engineering

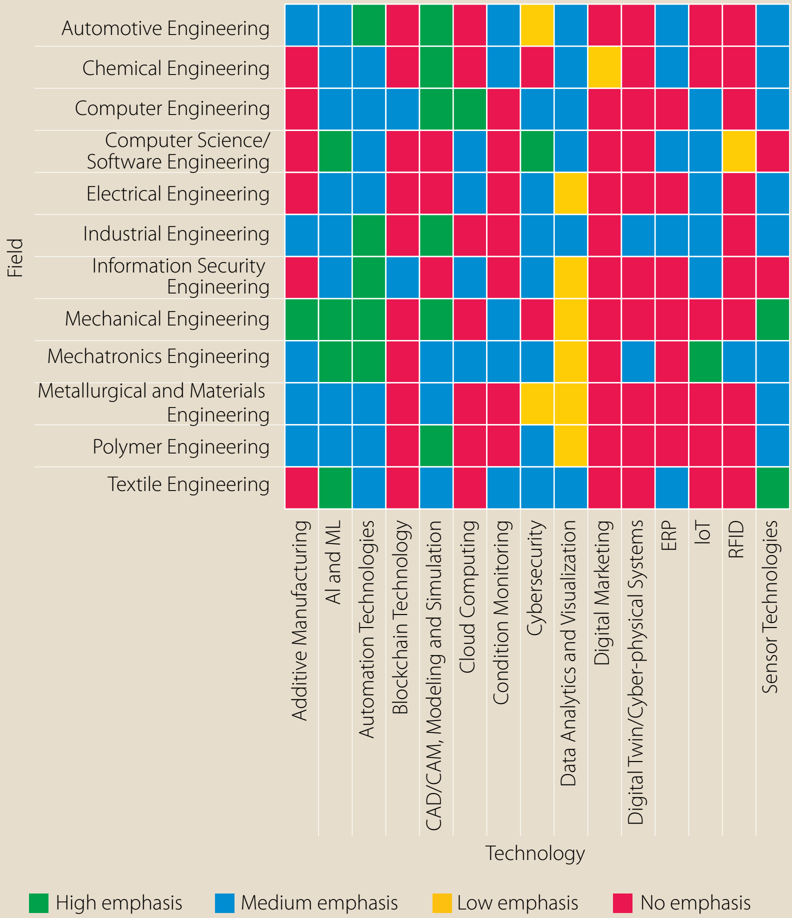
The analysis of benchmark curricula of different BSc Engineering programs indicates significant variation in their technological content (Figure 28). Many fields do not emphasize critical emerging technologies such as blockchain, digital marketing, RFID, and additive manufacturing. The lack of emphasis on these technologies demonstrates a stark misalignment between the curriculum content and technologies required for digital transformation.

Certain specialty domains, such as computer science and related fields, emphasize new technologies, especially cybersecurity and data analytics and visualization. These programs can better cater to the requirements of digital transformation. Likewise, core engineering disciplines such as mechanical engineering and mechatronics engineering show a moderate-to-high level of focus on technologies like modeling and simulation, automation, sensor technology, and CAD/CAM to keep pace with manufacturing and automation needs. A number of digital technologies are still underrepresented. Some courses have integrated technologies like AI, IoT, and digital twins, but not on a large scale. The lack of integration points to an urgent need for fundamental curriculum reform in these disciplines to align them with current industrial practices and trends.

The results indicate that the curricula of BSc Engineering programs should be improved. In some disciplines, modern technologies have been reasonably well integrated in a few programs, while many others have not kept pace. Automation, AI, and data analytics and visualization are the most integrated in all BSc Engineering programs, while digital marketing is the least integrated skill: it is only integrated at a low level in chemical engineering and is not integrated in any other engineering program. Similarly, blockchain, digital twins, and RFID are only integrated in two disciplines. Industrial engineering, mechanical engineering, automotive engineering, and mechatronics engineering have a somewhat balanced focus on most technologies, but most of the other programs have a very limited focus on digital technologies. In conclusion, most of the engineering program curricula are outdated and need significant revisions to include the cutting-edge, modern technologies that are being implemented in modern production systems.

FIGURE 28

CURRICULUM ANALYSIS OF BSC ENGINEERING PROGRAMS.



Note: CAD, computer-aided design; CAM, computer-aided manufacturing; ERP, enterprise resource planning; ML, machine learning; RFID, radio-frequency identification.
Source: Authors own creation based on analysis of the curricula.

BSc Engineering Technology

The analysis of the benchmark curricula for BSc Engineering Technology programs identified weak integration of emerging and advanced technologies in all domains (Figure 29). No-to-low emphasis on critical technologies, such as AI, digital marketing, additive manufacturing, and blockchain, is recorded in many fields. These shortcomings indicate misalignment of the curriculum with digital technologies, preventing graduates from learning future-ready skills that will enable them to fulfill the ever-changing needs of industries. Digital technology–based programs, such as information security engineering technology, are the only programs that place a high emphasis on digital technologies. Mechanical engineering technology and mechatronics engineering technology focus on modeling and simulation, CAD/CAM, automation, and sensor technology, reflecting their ties to manufacturing and automation. These domains are most suited to help graduates gain industry-specific skills.

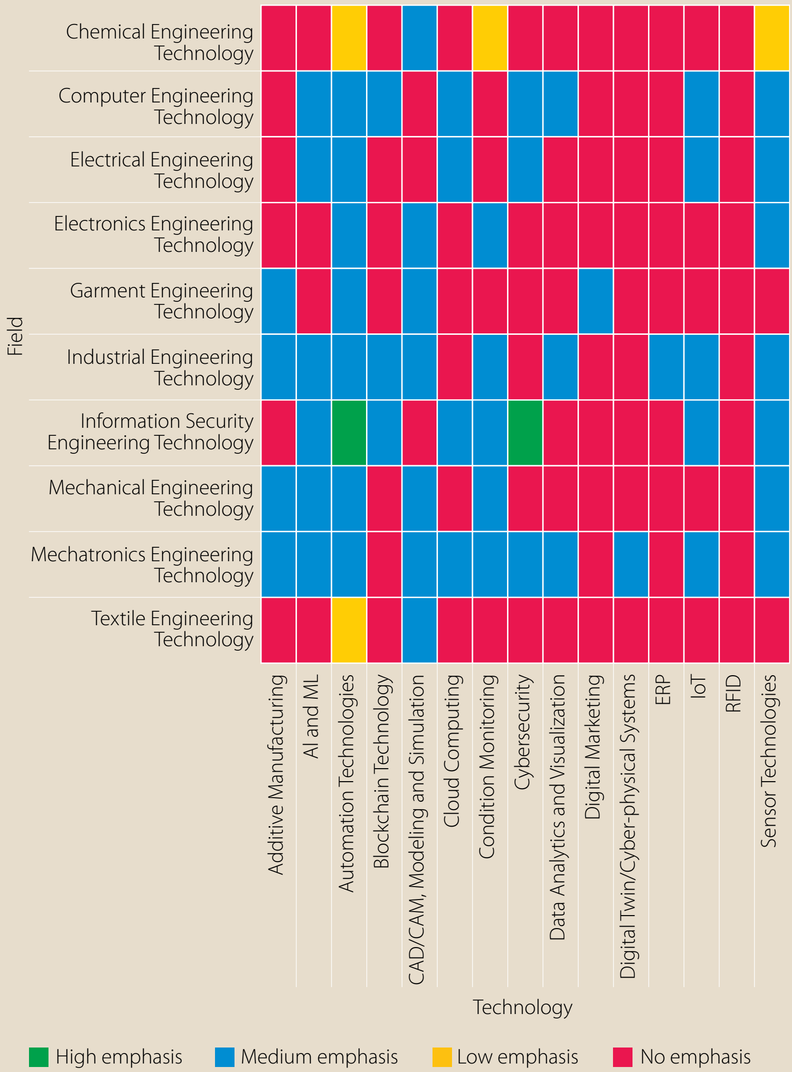
There is still a large underrepresentation of digital technologies such as digital twin technologies, ERP, and RFID in most areas. Although there are some isolated examples of emphasis and integration, such as a moderate emphasis on digital twins in mechatronics engineering technology, broader acceptance and usage of cutting-edge tools is significantly lacking.

Chemical engineering technology, garment engineering technology, and textile engineering technology place little emphasis on both traditional technologies (i.e., established digital technologies such as automation, CAD/CAM, and modeling and simulation) and advanced technologies. This indicates a possible disconnect between their curricula and contemporary manufacturing and industrial trends. Conversely, traditional disciplines such as mechanical engineering technology and industrial engineering technology uphold a modest focus on established core technologies like modeling and simulation, automation, and CAD/CAM, allowing students to develop industry-relevant skills at low to moderate levels.

Figure 29 strengthens the case for an overhaul of BSc Engineering Technology curricula. While information security engineering technology has evolved, staying relatively attuned to changing industry expectations and requirements, many other fields have fallen behind and are still lacking contemporary digital skills. To address the gap between required and acquired skills, it is essential to integrate emerging technologies such as AI, digital twins, IoT, and blockchain technology into these programs.

FIGURE 29

CURRICULUM ANALYSIS OF BSc ENGINEERING TECHNOLOGY PROGRAMS.



Note: CAD, computer-aided design; CAM, computer-aided manufacturing; ERP, enterprise resource planning; ML, machine learning; RFID, radio-frequency identification.
Source: Authors own creation based on analysis of curricula.

Diploma of Associate Engineer

A comprehensive analysis of the curricula of relevant DAE programs indicates a near absence or low emphasis on most digital technologies across domains (Figure 30), including critical and emerging technologies like blockchain, digital marketing, RFID, and additive manufacturing. This highlights the need to integrate digital technologies that are glaringly absent in most DAE curricula.

There are some future-oriented fields, such as IoT application technology (IoT-AT), instrument technology, and software technology, that are focused on essential areas like automation or cybersecurity and trend more toward industry needs and the future technological landscape. Modeling and simulation and CAD/CAM and automation receive balanced attention across multiple fields (e.g., mechanical technology and electrical technology). Given their fundamental role in manufacturing and maintenance, these topics seem reasonably well integrated into the curriculum.

Traditional fields such as mechanical, electrical, and chemical technology still emphasize conventional technologies, with very little focus on emerging tools like AI, IoT, and sensor technology. This might result in graduates in these areas being less adaptable to the needs of digital transformation.

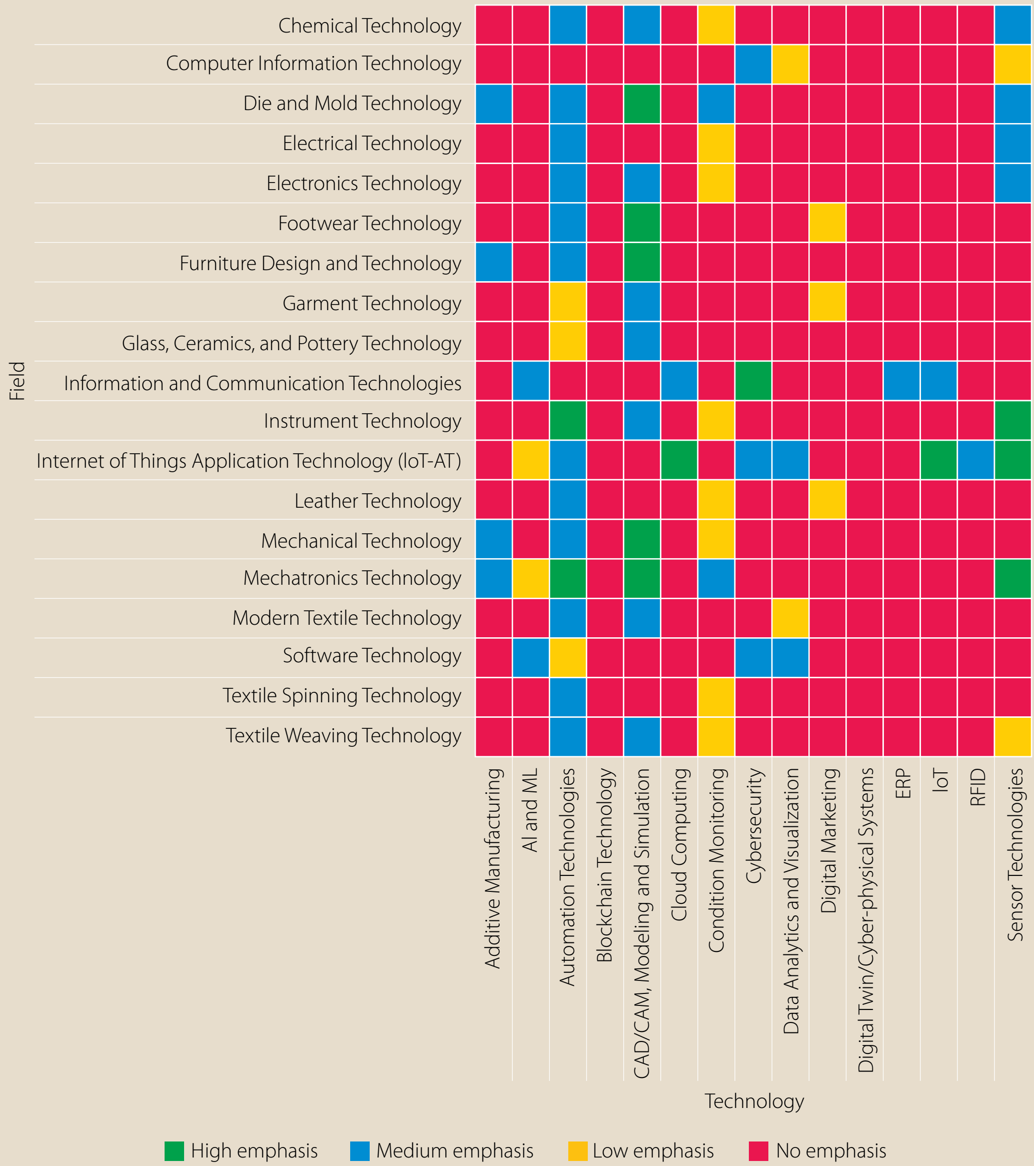
Specialized fields like IoT-AT and information and communication technology exhibit the highest level of adoption of modern technologies with relevance to connectivity, automation, and digital transformation. In most other disciplines, there is little focus on contemporary technologies such as AI and IoT, which are vital to enabling digital transformation.

None of these DAE programs emphasize blockchain or digital twin technologies. Only a few have any emphasis on digital marketing, all at a low level. RFID and ERP are a moderate priority only in IoT-AT and information and communication technology, respectively.

In conclusion, this evaluation reveals a clear mismatch between prioritized skills and skills required for digitalization, indicating an urgent need for curriculum revision in all DAE programs. Digital technologies need to be introduced into the curricula so that students can acquire the industry-ready skills needed in the contemporary digitalized production environment.

FIGURE 30

CURRICULUM ANALYSIS OF DIPLOMA OF ASSOCIATE ENGINEER PROGRAMS.



Note: CAD, computer-aided design; CAM, computer-aided manufacturing; ERP, enterprise resource planning; ML, machine learning; RFID, radio-frequency identification.
Source: Authors own creation based on analysis of the curricula.

Conclusions

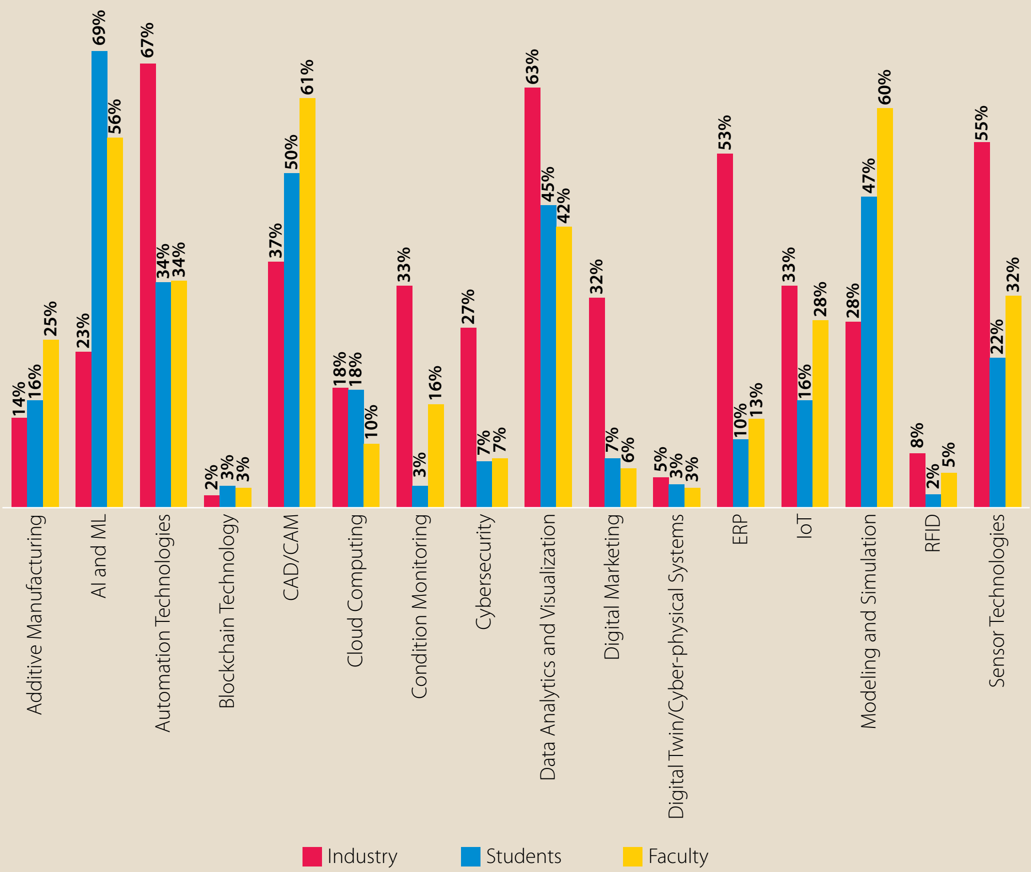
The data shows a misalignment between the sector-wide adoption of digital technologies and the readiness of students and faculty in technical education (Figure 31). For example, data analytics and visualization are implemented in 63% of the firms, but only 45% of the graduates have some level of familiarity. Similarly, only 42% of the faculty members reported that data analytics and visualization are integrated into the teaching-learning process. Of the programs analyzed, data analytics and visualization are part of the curriculum of all BSc Engineering programs (low-to-medium emphasis), primarily in the final year design projects; three of the 10 BSc Engineering Technology programs (medium emphasis); and four of the 19 DAE programs (low-to-medium emphasis). All other BSc Engineering Technology programs and DAE programs completely lack any inclusion of data analytics and visualization in the curriculum. There is a need to integrate data analytics and visualization or enhance its emphasis at all technical and engineering education levels.

AI and ML, CAD/CAM, modeling and simulation, additive manufacturing, and, to a very small degree, blockchain are the only technologies where graduates' learning surpasses sector adoption. Sixty-nine percent of the graduates are familiar with AI, but only 23% of the sector has implemented it. There is reasonable emphasis on AI in engineering and engineering technology curricula, but it needs to be better incorporated into the DAE curriculum. Additionally, awareness of using AI and ML in business and production systems needs to be raised in the sector to enhance decision-making and productivity. In the case of additive manufacturing, only 14% of the sector has implemented it at some level, but it is reasonably integrated into relevant curricula at all technical and engineering education levels.

IoT technology is moderately adopted in the sector: 33% of industry respondents claim that they have implemented IoT at some level, but only 16% of the graduates are familiar with it, indicating that graduates are not sufficiently prepared to enter the job market. Twenty-eight percent of faculty members reported that IoT is integrated into teaching-learning. This indicates that the pedagogical approach taken to inculcate IoT-related skills is ineffective and should be revised to include more hands-on training and projects related to IoT. IoT is reasonably represented in the BSc Engineering (50%, medium-to-high level) and BSc Engineering Technology (50%, medium level) curricula; however, it must also be included at an introductory level in the DAE curricula.

FIGURE 31

COMPARISON OF DIGITAL TECHNOLOGY ADOPTION IN THE MANUFACTURING SECTOR AND ITS INTEGRATION IN THE TEACHING-LEARNING PROCESS.



Note: CAD, computer-aided design; CAM, computer-aided manufacturing; ERP, enterprise resource planning; ML, machine learning; RFID, radio-frequency identification.
Source: Primary data collected during this study.

Automation and sensor technologies are widely adopted in the sector. However, the vast majority of graduates are unfamiliar with them. Both automation and sensor technologies are well represented in the curricula at all levels of technical and engineering education. This indicates that more practical content and resources related to these technologies are needed to enhance the effectiveness of the teaching-learning process.

The modern technologies cloud computing, blockchain, and digital twins are sparsely represented across all data samples. Industry awareness of the use of modern technologies and their inclusion in the curricula of all engineering and technology education levels needs to be enhanced. Analysis of the stakeholders' responses and curricula of all technical and engineering education levels reveals that, contrary to modern technologies, there is satisfactory awareness of CAD/CAM (used by 37% of firms; considered to be well-integrated into the teaching-learning process by 50% and 61% of the students and faculty members respectively). The inclusion of RFID in all technical and engineering education curricula and its implementation in the sector is also recommended.

Graduates' level of familiarity with ERP, cybersecurity, condition monitoring, and digital marketing is a key concern. These technologies are being implemented in the sector, but inculcation of these skills is not part of the teaching-learning process at any level. The low emphasis on the skills related to these technologies can be attributed to their absence in the benchmark curricula. These technologies must be included in BSc Engineering, BSc Engineering Technology, and DAE curricula at an introductory level in all fields and a higher level in the relevant fields.

Revamping technical and engineering education curricula is necessary to bridge the gaps between sector requirements and graduates' skill sets. The curricula should include technologies aligned with sector demands, such as data analytics, IoT, automation, sensor technologies, ERP, and digital marketing, or newer technologies such as blockchain and digital twins. This alignment must involve introducing these technologies at foundational levels in the DAE curricula and integrating them at a deeper level throughout engineering and engineering technology programs.

Furthermore, pedagogical approaches need to change from traditional to modern learning methods. Student-centered pedagogy should be encouraged. The learning environment in the technical and engineering education institutes needs a paradigm that includes problem-based learning, kinesthetic learning, complex problem-solving, and project-oriented problem-based learning. Cooperative and collaborative learning should also become part of the teaching-learning environment. These transformations shall ensure lifelong learning among graduates.

In conclusion, fostering an ecosystem where technical education dynamically responds to sector needs will require collaboration between academia, industries, and policymakers. This proactive approach will ensure a skilled workforce capable of driving innovation, enhancing productivity, and meeting the evolving technological demands of modern industries.

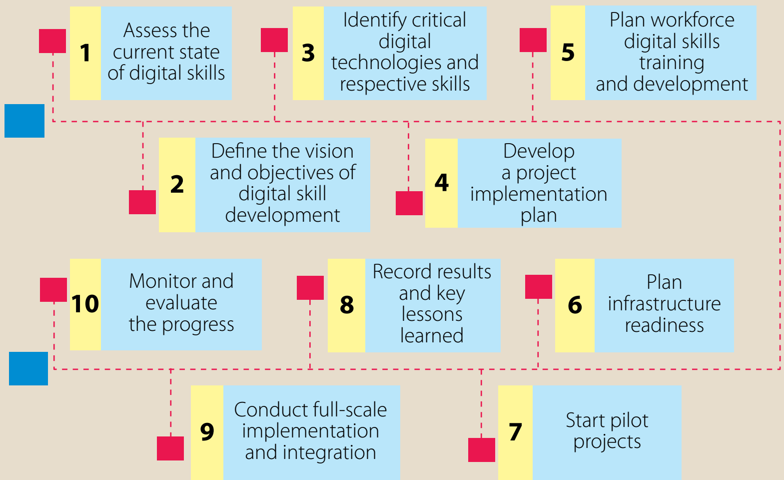
DIGITAL TRANSFORMATION ROADMAP FOR PAKISTAN'S MANUFACTURING SECTOR

Digital technologies will be the most influencing driver of competitiveness over the next several years. Technologies such as IoT, AI, data analytics, cloud computing, and cybersecurity are becoming more popular in manufacturing. However, as discussed previously, the implementation of most digital technologies is low to moderate in Pakistan's manufacturing sector. A similar trend is seen in the skill sets of graduates and the integration of these technologies in technical and engineering curricula and the teaching-learning process. In conclusion, digital transformation in Pakistan's manufacturing sector is inadequate. Establishing a roadmap for the sector's digital skill development is crucial for the smooth adoption, integration, and implementation of digital technology. A digital transformation skill development roadmap is a proactive and strategic step-by-step guide that outlines the critical milestones of skill development required to transform the digital landscape of Pakistan's manufacturing sector. Developing a digital skill development roadmap for the country's manufacturing businesses comes with significant benefits: strategic alignment, incremental progress, training and upskilling of the workforce, resource optimization, and monitoring and control for improvement.

The following ten-step approach (Figure 32) can be used for digital skill development in Pakistan's manufacturing sector. This roadmap provides a generic journey for digital skill development; however, a customized journey may be developed that varies from organization to organization.

FIGURE 32

DIGITAL TECHNOLOGY SKILL DEVELOPMENT ROADMAP.



Source: Author.

Assessment of the Current State of Digital Skills

This first step is to assess the digital skills relevant to Pakistan's manufacturing sector and map its current state, starting by auditing the existing manufacturing processes, systems, and technologies to determine the relevant technologies, level of implementation, digital maturity, and readiness level. The same may be done at the industry level. The manufacturing sector includes the most contributing industries to the GDP of Pakistan, such as textiles, automotives, beverages, electronics, packaging, chemicals, and processing. This list of required digital technologies provides the directory of skills necessary for transforming the manufacturing landscape:

- Additive manufacturing
- AI
- Automation
- Blockchain
- CAD/CAM
- Cloud computing
- Condition monitoring
- Cybersecurity

- Data analytics and visualization
- Digital marketing
- Digital twin technologies
- ERP systems
- IoT
- RFID technologies
- Sensor technologies

Defining the Vision and Objectives of Digital Skill Development

Understanding the required digital skills helps create a clear vision and objectives. The objectives must be SMART: specific, measurable, achievable, relevant, and time-bound. Engaging stakeholders for their input is vital so that their concerns can be addressed proactively. This ensures that the digital skill transformation strategy is aligned with the manufacturing sector's overall business strategy and goals. It also provides the opportunity to understand the drivers and barriers for this transformation and, thereby, set realistic expectations regarding milestones. Precise definitions of goals and objectives help develop good project implementation plans.

Prioritizing Critical Digital Technologies and Respective Skills

This critical step involves evaluating the feasibility and potential impact of digital technologies on productivity, efficiency, utilization, and cost savings in the manufacturing sector to determine which are the most relevant and beneficial. Subsequently, aligning prioritized digital technologies with the defined objectives and business strategy is crucial. These technologies may include IoT, AI, ML, cloud computing, big data analytics, robotics and automation, and prototyping.

Developing a Project Implementation Plan

The development of the project implementation plan includes identifying primary stakeholders, assessing the availability of resources, assessing potential project risks, developing mitigation strategies, and determining key milestones, performance indicators, deliverables, and timelines. It also includes assigning responsibilities and developing performance assessment and accountability mechanisms. Collecting feedback from and involving stakeholders (such as employees, management, customers, suppliers, vendors, regulatory bodies, government, and NGOs) through an integrated approach is critical for a successful project implementation plan.

Planning of Workforce Digital Skills Training and Development

Creating a digital skills training and development plan is essential for smooth technology adoption, implementation, and integration. Firstly, skill gaps in the current workforce should be investigated and identified. These gaps can then be addressed by designing a comprehensive training and development program, which may be run in collaboration with third parties. To train the workforce, it might be necessary to purchase the latest machinery related to digital technologies, which will require some capital.

Planning of Infrastructure Readiness

This step requires preparing the infrastructure for the training, development, and implementation activities. This includes planning for scalable IT solutions, implementing data capturing and security measures, and installing relevant digital technologies and physical infrastructure for a smooth transition. These IT solutions may include data collection, analysis, security management, internet connectivity, sensor technology, and CAD software.

Starting Pilot Projects

After preparing the digital infrastructure for implementation, the next step is to implement pilot projects for selected digital technologies in controlled environments. This helps determine the effectiveness of the training and development program, collect feedback from the workforce, and further refine the solutions. The learning outcomes can be mapped, and the efficacy of the teaching-learning process can be recorded for further improvement.

Recording Results and Key Lessons Learned

As a result of digital skills implementation, the manufacturing systems' productivity and performance improvement outcomes can be recorded and scaling-up strategies can be finalized. Key lessons learned from the pilot projects must be recorded, considering their efficacy and expected improvements. There might be some success stories and objectives achieved, but failures can also impart valuable lessons. In either case, findings will provide beneficial insights for future improvements. These records will help generate better plans for future enhancements while attempting to digitalize manufacturing sector infrastructure.

Full-scale Implementation and Integration

Once pilot projects are concluded, successful projects can be rolled out across the manufacturing sector. These projects should be introduced incrementally so that the workforce can easily adapt.

Monitoring and Evaluating the Progress

Digital skill development is an ongoing process requiring the monitoring and assessment of progress against the set objectives. The performance of the digital skill development program should be monitored against well-defined key performance indicators (KPIs) to measure its impact and success. Regular reviews at the sectoral level and obtaining feedback regarding the workforce's ability to implement the digital technologies will enable the refinement of the roadmap and the digital skill development strategy. Managing rapid changes in digital technologies is challenging, but continuous review and monitoring mechanisms will help organizations keep up with trends, manage changes, and adapt to emerging requirements.

DISCUSSION AND POLICY RECOMMENDATIONS

Pakistan's manufacturing sector requires digital transformation for productivity gains, national competitiveness, and economic resilience. This chapter presents the results of the analysis and practical policy recommendations that can address innovation-led digitalization and workforce skill improvements. Industry-academic collaboration, technology adoption, and coherent policies promoting manufacturing transformation are vital for digitalizing the sector and upskilling the workforce.

Adoption of Digital Technology and Skill Development for the New Workforce

The data collected across manufacturing industries suggested heterogeneity in the adoption of digital technologies within the sector. Large organizations are more digitalized than SMEs and microenterprises. Automation, data analytics, and ERP technologies are at a medium level of adoption, with nearly 60% of large enterprises incorporating these tools in some way. However, cutting-edge digital technologies such as blockchain, digital twins, and IoT have limited adoption in large enterprises: only about 15% utilize IoT, while less than 10% have used blockchain.

Limited resources (both quantity and expertise), infrastructure bottlenecks, and shortages of skilled workers can explain lower adoption rates for advanced technologies. Cultural resistance to change and fear of job displacement can also induce reluctance to adopt new technologies, especially in manufacturing industries, where manual labor has the most influence. Access to funds, capacity building, and creating a culture of innovation will help implement these technologies.

Specific incentives and support will be needed for SMEs to increase the adoption of digital technologies. Government-led initiatives that provide subsidies, grants, and low-interest loans can make purchasing digital infrastructure easier. Technical guidance centers can also guide SMEs in the digital transformation process. Below are the policy recommendations for the adoption of digital technologies in the manufacturing sector:

- **SME-friendly incentives:** Financial incentives in the form of grants, subsidies, or low-interest loans must be provided to SMEs to help them invest in digital infrastructure. Digitalization support centers run by the government can also facilitate SMEs with a technical assessment of digitalization and support their first steps toward digital transformation.

- **Digital transformation roadmap:** A comprehensive digital transformation roadmap must be created for the manufacturing sector. It needs to be developed step-by-step through pilots before full-scale implementation. The roadmap should establish timelines, targets, and benchmarks for digitalizing specific industries.

- **Developing digital leadership:** Education programs should be initiated for executives or managers to recognize and promote the strategic importance of these transformative digital technologies in their organizations. By building competent, digitally literate leaders, the manufacturing sector can create a concrete culture of innovation and continuous improvement.

Lack of Skills and the Readiness of the Workforce

The data obtained from multiple stakeholders clearly outlines the workforce's skill deficit and the amount of digital capability required for good technology adoption. Survey results show that 50% of the workforce is versed in traditional engineering tools, but only 15% are skilled in digital technologies such as AI, blockchain, digital twins, and IoT. These competency gaps restrict the sector from harnessing the full potential of digital transformation, productivity, and competitiveness.

According to a survey of faculty members from technical institutions, the integration of digital technologies such as CAD/CAM and data analytics into the teaching-learning process is moderate, with approximately 40% of courses utilizing these digital tools. Despite the importance of advanced technologies like AI and IoT, less than 10% of the degree programs cover them. Faculty also mentioned that hands-on learning and application of digital technologies are rarely emphasized, thus making students unprepared to enter the modern, digitally complex workplace.

Curriculum analysis revealed that CAD/CAM and automation have reasonable coverage, being incorporated into about 40% of degree programs. However, the latest technologies are less emphasized. Less than 10% of the curricula focus on blockchain, AI, and IoT. The gap between industry demand and what most academic programs provide has made graduates less prepared for digitalized manufacturing.

Bridging these skill gaps requires making more effort to integrate digital technologies into educational curricula and providing students with ample practical exposure. The gaps can be mitigated through internship programs, apprenticeships, or co-op placements that offer students a chance to put their theoretical knowledge into practice, making them more industry-ready when they graduate. Here are the key policy recommendations for effective skill development of the workforce:

- **National digital skill development framework:** A national digital skill development framework needs to be developed to strengthen technical education curricula and incorporate disruptive technologies like AI, IoT, blockchain, and digital twins. Hands-on experience must be ensured by drafting a blueprint for engineering, engineering technology, and technical and vocational education and training programs together with industry partners.

- **Industry-academic collaboration:** Academic institutions should have advisory boards from the industries that work closely with them to update the curriculum periodically as per market requirements. Educational institutes should promote internship programs, apprenticeships, and joint R&D projects that expose students to practical applications of digital technologies.

- **Tailored training programs:** Partnerships between industries and academia can be utilized to create tailor-made training programs based on the requirements of different manufacturing industries. This allows the workforce to be explicitly equipped to meet the needs of each industry while supporting the digital transformation of the broader manufacturing sector.

- **Inclusion of digital skills into the curricula:** The national education frameworks and accreditation bodies of the degree programs should place more emphasis on digital technologies like AI, IoT, and blockchain in the benchmark curricula. One way to do this is to identify key skills by working with industry stakeholders and embed them in existing programs. Hands-on, project-based learning modules will also provide students with practical experience and build problem-solving skills.

Policy and Regulatory Challenges

Pakistan's manufacturing sector is suffering due to the absence of clear policies and regulatory frameworks conducive to digital transformation, which affects the ease of doing business. Policies today fall short of creating proper incentives for technology adoption or human capital development, which is reflected in reduced innovation rates and low R&D expenditure.

Complex regulations and the permits and approvals required to implement these technologies have become a challenge for manufacturers, especially SMEs. By making these processes less complex and providing guidance, the barriers to digital transformation can be lowered, and more manufacturers can be encouraged to embrace advanced technologies. Additionally, partial reimbursement for digitalization efforts (through government grants, subsidies, and tax incentives) can help mitigate technology adoption costs.

Nearly 70% of SMEs indicated that they struggled with the regulatory aspects of technology adoption. This is exacerbated by minimal policies guiding digital transformation, meaning support varies greatly across manufacturing industries. To tackle these problems, current regulations need to be overhauled and new frameworks that encourage digitalization objectives need to be introduced within the sector; some policy recommendations are given below:

- **Improving policy coordination:** An overarching policymaking body should be created to manage digital transformation efforts across sectors. This body should align policies, regulations, and incentives with the overall digital transformation goals.

- **Financial incentives to adopt new technologies:** Policies should be developed to offer tax savings for any investment in digital technologies and technology R&D activities. Through public-private partnerships, funding and technology can be made accessible so manufacturers have the financial resources needed to drive digital transformation.

Physical Infrastructure to Become Digital Ready

Pakistan's digital infrastructure faces some challenges that are barriers to transformative change in the manufacturing sector. Data analytics conclude that the availability of high-speed internet and concerns about data security are also major barriers to the adoption of digital technologies.

Digital technologies will not work properly without investment in high-speed internet, data security, and IT infrastructure. Collaboration between the public and private sectors needs to be encouraged to develop and modernize the digital infrastructure needed for industries to transition toward a higher level of digital maturity. Furthermore, innovation hubs and technology parks can help manufacturers by providing access to modern facilities and resources for experimenting with new technologies or solutions.

The data collected shows that data security is yet to be fully adopted by manufacturers, as only 20% indicated robust cybersecurity protocols. This creates a threat to digitalization, considering manufacturers' reliance on digital technology. A broad framework for developing the overall infrastructure strategy should include the need for data security measures and safeguarding against cybersecurity threats.

Policy recommendations for infrastructure development include:

- **Investment in digital infrastructure:** Developing public-private partnerships for developing high-speed internet, data security, and IT infrastructure facilitates the implementation and digital capabilities of the manufacturer.

- **Establishment of innovation hubs:** Innovative hubs and technology parks are critical for manufacturers, providing them with access to fully-fledged facilities and resources supporting experimentation and testing. It is important to develop and improve manufacturing operations through various technological capabilities and innovations.

- **Development of data-driven decision-making capabilities:** This can be achieved through investment in systems-supported data collection, storage, and analysis. Investments made in technological systems support the gathering and analysis of big data to aid manufacturing decisions. This creates and sustains competitive capabilities for production processes and operations.

- **Strengthening cybersecurity measures:** A national cybersecurity strategy should be developed to ensure data security compliance. Upgrading digital connectivity through improved internet connections is critical for IoT applications, cloud computing, data analytics, and other real-time data transmission applications in manufacturing.

Promoting an Innovative and Lifelong Learning Culture

With enormous technological changes ahead, creating an environment of lifelong learning is crucial to keeping the workforce competitive. The workforce needs ongoing learning opportunities to build the capabilities needed to support digital transformation.

Initiatives for lifelong learning aimed at digital skills must be developed to ensure that the workforce can receive training to effectively meet the requirements of digital business and manufacturing environments. Short courses, modular training programs, and online learning platforms can enable workers to upskill without having to take time off or give up their existing jobs. Finally, mentorship programs can also help workers cope with the challenges of digital transformation, as they will receive support from more experienced professionals.

Here are policy recommendations for lifelong learning:

- **Online learning platforms:** Online platforms should be created with low-cost digital skills training courses on in-demand and emerging digital technologies. Such platforms must offer various courses, from digital literacy to advanced capabilities like data analytics and AI.

- **Employee training incentives:** Manufacturers seeking to train and develop their employees should receive incentives. Companies that show a commitment to upskilling should be given tax rebates or subsidies and be encouraged to invest in it as part of their business growth.

Conclusion

Closing the skill gaps, incentivizing collaboration and technology adoption, and developing policies and infrastructure are vital for the successful digital transformation of the manufacturing sector. The recommendations in this chapter offer a cohesive framework for establishing a digital-ready workforce and an adaptive manufacturing ecosystem. If Pakistan adopts these policy measures, its manufacturing sector will be able to compete globally and become an engine of economic growth and productivity.

Digital transformation requires sustained commitment from all stakeholders: the government, industries, academia, and the workforce. This transformation will also require a mindset shift: an open-minded approach to accepting newer technologies, ways of working, and constant learning and adaptability. Through the development of an innovative and collaborative culture, along with a focus on continuous learning, the manufacturing sector in Pakistan will be able to unleash its full potential, which can greatly aid economic growth and competitiveness.

CONCLUSIONS

Pakistan's manufacturing sector stands at a crossroads: digital transformation is needed to improve the economy's productivity, competitiveness, and resilience as a whole. This analysis has identified critical gaps in digital technology adoption, skills, and curricula that must be addressed to realize this transformation and ensure that Pakistani manufacturing keeps up with the global march toward Industry 4.0, where advanced technology and human resources drive efficiency, innovation, and growth.

The results indicate that although large enterprises have taken the first steps toward technology adoption through ERP, automation, and data analytics, there is still a considerable lack of advanced technologies (e.g., IoT, digital twins, blockchain) that could also transform supply chain transparency and predictive maintenance. Insufficient awareness, skilled human resources, and infrastructure are the major barriers to their mass adoption. SMEs, especially, are crippled by a multitude of obstacles, ranging from lack of resources, infrastructure bottlenecks, and low technical know-how, stymieing their digital transformation process. SMEs hold an extremely important position in Pakistan's economy, so their slower adoption rate of digital technologies compared to that of large firms is a cause of concern.

One of the key findings of this study is that there is a mismatch between industry requirements and the capabilities of graduates of technical and engineering institutes. The graduates lacked familiarity with key digital areas such as cloud computing, digital twins, automation, and cybersecurity. The absence of these skills limits graduates' ability to contribute meaningfully to technology-driven environments, thereby hindering the sector's growth. Similarly, the integration of these technologies into academic curricula is limited, highlighting the urgent need for curriculum reform to bridge the skill gap. Current curricula often fail to provide practical exposure to digital tools and technologies that are becoming increasingly important for modern manufacturing. To effectively support the manufacturing sector's digital transformation, curricula need to be updated to include contemporary technologies and emphasize hands-on, project-based learning that encourages innovation and problem-solving.

The proposed ten-step digital transformation roadmap offers a structured approach to addressing these challenges. It focuses on measuring the current digital capabilities, designing specific training intervention programs, and preparing infrastructural support for integrating technology. It starts by evaluating the current digital maturity of manufacturing companies, analyzing the technologies that can boost productivity, and highlighting the necessary skills to harness the full potential of those technologies. It then focuses on developing comprehensive training and skill development programs, particularly targeting SMEs and recent graduates. Ensuring the infrastructure can support these technologies is also critical, as reliable internet, data security, and digital tools are fundamental to successful digital transformation.

Central to this roadmap is creating an ecosystem of collaboration between industries, academia, and policymakers. This ecosystem of collaboration shall ensure the acquired skills of graduates are aligned with those required by the sector. This collaboration is necessary to establish relevant curricula, provide hands-on exposure, and prepare market-ready graduates. It can also help create centers of excellence focusing on emerging technologies like AI, IoT, and blockchain, providing a platform for research, innovation, and skill development. Additionally, establishing platforms for continuous engagement between these stakeholders will help keep the workforce responsive to future technological and industrial developments.

Policy suggestions focus on SME-appropriate incentives, digital infrastructure improvement, and a national digital skills strategy. These initiatives aim to boost the adoption of emerging technologies, promote innovation, and facilitate workforce reskilling. Selective financial incentives like grants, subsidies, and low-interest loans should be provided for SMEs, which are usually unable to bear the financial burden of implementing new technologies. These incentives can lower the entry barriers for SMEs to invest in the technologies needed to undergo digital transformation and training. Another potential approach is to create innovation hubs and digital support centers that offer digital enablers for

SMEs and large enterprises to progress in their digital transformation. These hubs may catalyze knowledge transfer, provide access to digital technologies, and enable collaboration across industries.

Another important aspect needing attention is the enhanced development of digital infrastructure: high-speed internet, effective cybersecurity measures, and efficient hardware systems. These all lay the foundation for any successful digital transformation. Without these cornerstones, the best efforts to adopt any technology will fail. Hence, investments in digital infrastructure need to be prioritized, particularly among industrial clusters where manufacturing enterprises are concentrated. Public-private partnerships are critical to developing the underlying infrastructure to ensure reliable digital connectivity. Moreover, digitalization and increasing online dependency comes with many risks, so cybersecurity is essential to protect sensitive data and digital systems.

The final critical point raised by the research is that of a national framework to progress digital skills development. This framework would provide high-level guidance on aligning education, training, and workforce development initiatives with the manufacturing sector's current and future needs. This framework needs to be developed in consultation with stakeholders to be relevant. It must integrate digital literacy from elementary education to higher education and technical and vocational training, ensuring the future workforce is ready for advanced manufacturing technologies. Secondly, the focus should be on launching specific training programs to upskill the existing workforce in domains like AI, ML, IoT, automation, and data analytics. Such programs could be offered in collaboration with educational institutions, industry associations, and private training providers so that a larger cohort of participants can access the program.

The potential for Pakistan's manufacturing sector to improve its productivity and competitiveness through digital transformation is immense. That said, it will only be possible if all players in the ecosystem, companies, academia, and governments, work together to close the existing skill gaps, adjust curricula, and build a conducive policy framework. The proposed digital transformation roadmap focuses on enhancing skill development, having ready infrastructure, and engaging in collaborative policymaking for an actionable solution going forward. By implementing the policy recommendations and subsequent roadmap, Pakistan can harness digital technologies for sustainable growth and economic prosperity. Achieving digital transformation is a multiyear effort requiring technological, cultural, and organizational changes. Taking a holistic approach emphasizing capacity building, collaboration, and innovation, Pakistan can benefit from the full potential of Industry 4.0. This transition will enhance productivity and economic resilience and bring new employment, innovation opportunities, and sustainable long-term growth.

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LIST OF TABLES

LIST OF FIGURES

LIST OF CONTRIBUTORS

Dr. Amjad Hussain
Professor
Mechanical Engineering
University of Engineering and Technology, Pakistan
Corresponding author: chamjad@uet.edu.pk

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Santi Setiawati
Program Officer, Multicountry Division 2


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