The driving logic of digital transformation in TVET

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ABSTRACT

In this paper, three levels of external drivers that steer digital transformation processes in the technical and vocational education and training (TVET) sector are examined. They include primary drivers (Industry 4.0, Industry 5.0, and the associated facilitating digital technologies); secondary drivers (the digital economy, digital society [Society 5.0], environmental sustainability, and digital governance); and tertiary drivers (Employment 4.0 and Employment 5.0). The driving logic underpinning digital transformation in the TVET sector exhibits a hierarchical progression whereby primary drivers determine the trajectory of secondary drivers, subsequently catalyzing tertiary drivers to propel the overarching digital transformation of the TVET landscape. This paper makes a valuable contribution to the academic methodologies and frameworks employed by TVET stakeholders by effectively identifying the driving logic behind digital transformation in the TVET sector.

Key words: technical and vocational education and training, digital transformation, drivers, logic

INTRODUCTION

Industry 4.0 and Industry 5.0, which encompass emerging digital technologies such as artificial intelligence (AI), quantum technology, and 6G, are shifting from an explosion of "technology points" to groundbreaking "new technology clusters". Developments have included moves away from personal computer (PC) Internet, consumer Internet, and the Internet of Things to mobile Internet, industrial Internet, and the Internet of Intelligence, respectively, and from weak AI to strong AI and subsequently to super AI. Characterizing the Fourth and Fifth Industrial Revolutions, AI usage is permeating all major industrial sectors, including manufacturing, education, training, and finance. The McKinsey Global Institute highlighted that AI is contributing to a transformation of society that is "happening ten times faster and at 300 times the scale or at roughly 3000 times the impact".[1] This development is catalyzing the radical digital transformation of the economy, society, the environment, and governance. Digital technologies are transforming sectors and future jobs at an unprecedented rate, leading to digital and other skill gaps and increasingly wide digital divides in various regions and countries.

Technical and vocational education and training (TVET) institutions are pivotal in addressing these challenges through the skilling, upskilling, and reskilling of the workforce. The swift evolution of digital technologies under Industry 4.0 and Industry 5.0 has started to transform global TVET systems, but this reformation must be aligned with technological innovation, digital governance, the digital economy, digital society, and the green economy, which are intrinsically interlinked. New digital technologies contributing to digital transformation can ultimately enhance the quality of education systems and have become vital for most organizations in a contemporary world that is experiencing emerging and evolving changes.[2] TVET institutions play a critical role in closing digital skill gaps and overcoming digital divides by serving as hubs for digital skill training, research and development, and

fostering a digital mindset and institutional culture. Their efforts require a systematic digital transformation in TVET systems, tailored training programs, research, and strategies to address the multifaceted barriers limiting digital inclusion and integration.

Despite growing recognition of the importance of digital transformation in TVET, there is limited comprehensive understanding of the key drivers propelling this transformation. Existing research has primarily focused on the impact of digital technologies on TVET and the challenges associated with their adoption.[3–5] However, there is a need for a holistic examination of the external factors influencing the digital transformation of TVET systems. We aimed to address this need by providing an in-depth analysis of the external drivers underpinning the digital transformation of TVET systems. By elucidating the interplay between various drivers and the underlying logic driving digital transformation within the TVET sector, we hope to contribute to the development of a digital mindset and institutional culture among TVET leaders and practitioners. Understanding these drivers is crucial for informing TVET policymakers, managers, and practitioners about the methodologies that underpin TVET's digital transformation. This knowledge is essential for developing effective strategies and policies to facilitate the successful integration of digital technologies into TVET, systematically plan for digital transformation, and enhance the relevance of TVET programs in a rapidly evolving digital landscape. The insights derived from this research can underpin the development of targeted interventions and policies aimed at addressing pervasive digital skill disparities, digital talent deficits, and digital divides. Moreover, these insights can contribute significantly to advancing global sustainable development.

UNDERSTANDING DIGITAL TRANSFORMATION

Definition of digital transformation
Digital transformation has become a hot topic in seminars, policies, strategies, and actions in different sectors. However, there is no consensus on a definition of digital transformation. The recent buzz concerning digital transformation is starting to undermine its credibility, causing confusion in research and academic circles. Consistent definitions would allow researchers to communicate more effectively with practitioners and provide them with better guidelines for understanding and implementing digital transformation.[6]

Based on scientific reviews and an analysis of 134 published definitions of digital transformation, Cheng Gong and Vincent Ribiere developed a unified definition of digital transformation as "a fundamental change process, enabled by the innovative use of digital technologies accompanied by the strategic leverage of key resources and capabilities, aiming to radically improve an entity and redefine its value proposition for its stakeholders".[2] According to this definition, an entity may be an organization, a business network, an industry, or a society.

Understanding digital transformation in TVET
The *UNESCO Strategy for TVET (2022-2029)* and the UNEVOC thematic area of digital transformation stress the importance of digital transformation and its role in the creation of resilient societies. UNESCO defines digital transformation in TVET as "the planned and structured introduction of technology into institutions and national TVET systems, with the goal of enhancing scope, scale, efficiency, and effectiveness, ultimately driving more sustainable development".[7]

The digital transformation of TVET involves both digital educational technologies and systematic institutional transformation. Based on *Digital Transformation in Global TVET: Methodology and Practices*, which was published in March 2024 by the UNESCO Chair on Digitalization in TVET, Shenzhen Polytechnic University, China, the digital transformation of TVET covers 10 dimensions.

1. Cultivating students' digital literacy and skills through TVET institutions to build a robust foundation of digital literacy among students, equipping them with the necessary digital skills to navigate and contribute effectively to the labor market and digital economy.

2. Deepening integration of education with industry through collaboration between TVET institutions and industries to ensure that education aligns with current and emerging industry needs, preparing students for real-world challenges.

3. Enhancing teachers' professional development regarding digital transformation and upskilling them in digital methods, skills, and technologies to critically facilitate transformative digital learning experiences for students.

4. Digitally transforming existing programs and curricula to reflect advances in digital technology, e-curricula, and their applications across industries.

5. Developing digital resources in TVET institutions to foster the development and utilization of digital resources and platforms for learning, such as e-books, digital labs, and online learning platforms, to enhance the learning process.

6. Increasing community engagement by incorporating digital technologies in community engagement activities—at domestic, regional, and global levels—to

extend learning beyond the classroom and foster a lifelong learning culture.

7. Conducting digital technology research and innovation in TVET institutions to foster a culture of curiosity and continual learning.

8. Conducting research on TVET digital transformation theories and practices to vitally understand their impact and how they can be improved.

9. Enhancing digital governance and streamlining governance processes using digital platforms to increase the efficiency and transparency of TVET institutions.

10. Consolidating digital infrastructures by ensuring that TVET institutions invest in up-to-date digital infrastructures to support the successful and widespread implementation of digital transformation strategies.[8]

The 10 dimensions of digital transformation in TVET cover governance, technical and vocational education, applied digital research, local and international community engagement, and digital infrastructures, which together form a holistic framework for TVET digital transformation. The 10 dimensions can also be understood as 10 approaches to facilitating digital transformation in TVET institutions.

THE PRIMARY DRIVERS OF DIGITAL TRANSFORMATION IN TVET

Industrial revolutions are significant sequential socioeconomic and technological changes that occur during distinct historical periods, leading to substantial advances across various industrial sectors.[9] Industrial revolutions are claimed to be the most profound revolutions in human history because of their sweeping impact on people's daily work and lives. The term "industrial revolution" was a succinct catchphrase used to describe a historical period in 18th-century Great Britain, when the pace of change dramatically increased.[10] This acceleration of technical processes and innovation led to the development of new tools and machines and subtle practical improvements in various sectors that affected labor, production, and resource use.

The evolution of Industrial Revolutions

The First Industrial Revolution, from approximately 1760 to 1840, marked the advent of steam power and mechanization. This period catalyzed the transition of agrarian societies into industrialized ones, mechanizing production and leading to urbanization and the emergence of factory-based economies.[11] The Second Industrial Revolution, spanning the late 19th century to the mid-20th century, was characterized by the widespread use of electricity to facilitate mass production, significantly driving the growth of modern industrial economies.[12] The Third Industrial Revolution, emerging in the late twentieth century, ushered in the era of digitalization and automation, profoundly altering communication and data-processing paradigms.[9] The Fourth Industrial Revolution, known as Industry 4.0, involved the integration of advanced technologies across various domains, leading to the profound and unprecedented reshaping of industries and societies. Characterized by the convergence of digital, physical, and biological systems, Industry 4.0 has introduced a new era of automation, AI, and smart technologies, shaping industries and economies in innovative ways.[13] Industry 4.0 is well known for introducing innovative technologies, including big data, AI, augmented reality/virtual reality (AR/VR), cloud computing, adaptive robotics, additive manufacturing, and the Internet of Things (IoT).[11–13] Industry 4.0 has shifted from a massive automation approach to a customer-driven paradigm. This transformation process has been related to virtual and extended reality integration, AI-based supply chains, twin-design collaborative robots, and digital machinery prototyping.[14,15]

Although the Industry 4.0 paradigm has yet to be disseminated worldwide, technological pioneers and many business and technology investors are endeavoring to reach Industry 5.0.[16] Industry 5.0 has its roots in Industry 4.0[17] and is a response to, rather than a mere extension of, Industry 4.0. Industry 5.0 can be defined as a rediscovered, widened purposefulness that goes beyond producing goods and services for profit and encompasses three core elements: human-centricity, sustainability, and resilience. The European Commission (EC) defined Industry 5.0 as follows: Industry 5.0 recognizes the power of industry to achieve societal goals beyond jobs and growth to become a resilient provider of prosperity, by making production respect the boundaries of our planet and placing the wellbeing of the industry worker at the center of the production process.[18]

Industry 5.0 combines various enabling technologies, including human-machine interaction, intelligent materials, big data analytics, cloud computing, hyper personalization, collaborative robots, digital twins AI, and blockchain technology. These innovative technologies and intelligent systems facilitate transactions, the management of networks and privacy, and mass customization Industry 5.0,[19] based on the development of Industry 4.0, represents a socially pulled and technologically pushed digital transformation.

Recent Industrial Revolutions driving the digital economy, smart society, environmental sustainability, and digital governance

The evolution of Industrial Revolutions, from Industry 1.0 to Industry 5.0, has had a profound impact on various economic sectors, including agriculture and

industry. Each Industrial Revolution has introduced new technologies and paradigms that have reshaped production processes, workforce dynamics, and economic growth. Industry 4.0 and 5.0 have paved the way for prosperity and development in numerous industrial sectors[20] by driving the digital economy, increasing productivity, creating new business models, and enhancing decision-making.[21] Both Industrial Revolutions have played crucial roles in the move toward a data-driven, automated economy in which technology serves as a key enabler of economic activities.

Industry 5.0 has led to revolutionary structural changes in traditional societies, causing them to transition from societies focused on production and profit to postindustrial societies based on knowledge. The new smart society, called Society 5.0 by the Japanese government, is based on the values of Industry 5.0, including diversity, value creation, problem-solving, resilience, decentralization, environmental harmony, and sustainability.[22]

The aim of the sustainable development goals (SDGs) adopted by the United Nations (UN) in 2015 is to develop ecological support to guarantee high environmental performance with a more positive impact than previously.[23] This began with Industry 4.0, but Industry 5.0, which has sustainability as one of its key values, represents the future of industrial transformation, offering potential solutions to environmental issues that were inadequately addressed or exacerbated by Industry 4.0.[24] Both Industry 4.0 and Industry 5.0 have considered environmental issues and a green economy and aimed to support sustainability.

By introducing new digital technologies and concepts, Industry 4.0 and Industry 5.0 have been key drivers of the continual evolution of digital governance.[25] They have prompted policymakers to think critically about how to frame policy alignment, manage digital resources and technologies, provide digital learning to close digital gaps, protect data, maintain cybersecurity, and promote sustainable and inclusive economic growth to ensure a balanced, responsible, and human-centric approach to the digital future.

SECONDARY DRIVERS OF DIGITAL TRANSFORMATION IN TVET

The UN adopted the concept of SDGs in 2015 as a multifaceted framework for addressing global challenges through a balanced approach to global sustainable development. The SDGs traditionally rest on three pillars of sustainability: environmental, economic, and social.[26] Governance and law have been integrated as additional pillars, emphasizing the importance of

effective institutional and legal frameworks for achieving sustainable development.[27] Industry 4.0 and 5.0 have been driving global sustainable development from digital economy, smart society, environmental sustainability, and digital governance perspectives.

Digital economy
The digital economy rests on the application of modern information technology to various economic activities, mainly reflected in the extensive application of the Internet, big data, AI, cloud computing, and other digital technologies in various industrial sectors.[28] The increased fluidity of information and technology has made the digital economy more agile and efficient.

Data are fundamental to the development of the digital economy,[28] which involves collecting, analyzing, and using data to create economic value and transforming data into useful information, insights, or products to enhance efficiency, develop new revenue streams, or strengthen existing business models. Digital industrialization and industrial digitalization are the two central pillars of the digital economy.[29] Digital industrialization focuses on the development of industries around digital technologies, such as big data, cloud computing, AI, and the IoT, which have become independent sectors driving new economic growth. Conversely, industrial digitalization involves the integration of digital technologies and the Internet into traditional manufacturing and service industries to transform and upgrade them by enhancing efficiency, reducing costs, and bolstering competitiveness.

The momentum behind digital industrialization and industrial digitalization has catalyzed significant shifts in the skills required by the labor market. Consequently, it is essential that TVET programs and curricula, as well as strategic goals for talent development within TVET institutions, are flexible, creative, and represent proactive adaptation to the changing demands arising from industrial digitalization and digital industrialization. This synchronization is crucial for maintaining the significance and effectiveness of TVET in an increasingly digitalized industrial environment.

Smart society (Society 5.0)
Society 5.0 is a Japanese concept that aims to solve problems such as aging, low birth rates, and a lack of competitiveness through the adoption of technological advances. Thus, it aims to contribute to a better world, with SDGs guiding sustainable technology use.[30] Society 5.0 envisions a future in which technology and society are seamlessly integrated to enhance human life and solve pressing social issues. It is a concept deeply rooted in the idea of a symbiotic relationship between technological progress and human-centric values, aiming to

create a sustainable and inclusive society.[31] This vision includes a reimagined innovation ecosystem, a new approach to corporate social responsibility, and a reevaluation of legal norms to support a society that is both technologically advanced and focused on human security and well-being.

Society 5.0 represents a human-centered, technology-driven evolution of society, to which digital literacy and the integration of AI and the IoT are pivotal. This evolution will shape the future of work by demanding new skills and transforming job descriptions. Society 5.0 emphasizes the importance of digital literacy, including the use of computers, the Internet, and digital devices, as well as the ability to understand network performance and digital communication.[32] Advances in information and Internet technologies have led to the creation of "smart" factories and the emergence of new job roles. Society 5.0 will require graduates to possess new skills to adapt to these changes, and TVET institutions must align their curricula accordingly.[33] The advent of Society 5.0 is significantly influencing the digital skills required for the future world of work. It necessitates enhanced digital literacy and communication skills, innovative leadership strategies that prioritize human capital, and transformations in the job market. TVET institutions therefore play a crucial role in developing students' skills and preparing them for evolving work demands.

Environmental sustainability

Environmental sustainability is a multifaceted concept that encompasses the preservation of natural resources and ecosystems while also integrating social and economic considerations to maintain and improve human well-being both now and in the future.[33,34] It is a decision-making framework for balancing environmental protection with social justice and economic development.[35] Sustainable development encompasses environmental management, agricultural productivity, and forest conservation with the aim of minimizing environmental harm.[8] Environmental sustainability is a complex and critical concept intended to ensure the longevity and health of our planet and its inhabitants. It involves a delicate balance between environmental conservation, social equity, and economic viability. Despite challenges in defining and assessing sustainability, it remains a key framework for guiding decisions toward a more sustainable future and maintaining alignment with the green economy.

An increase in industrial production normally requires more energy and increases carbon emissions. Innovation can reverse this trend through smarter production planning and the use of more energy-efficient technologies.[18] Digital transformation, including AI, big data analytics, the IoT, and cloud computing, can facilitate pollution control, waste management, sustainable production, renewable energy, and urban sustainability.[36] Digital technologies, spearheaded by AI, are central to promoting environmental sustainability. They are vital tools for pursuing SDGs and innovatively addressing the most pressing environmental issues of our time. Environmental sustainability depends on the development of digital and green skills[37] and by integrating such skills into their programs and curricula, TVET institutions play a pivotal role in preparing the workforce for the demands of new environmental industries. This alignment between TVET, industry, and the green economy is essential for fostering a sustainable future.

Digital governance

Industry 4.0 and Society 5.0, which include digital governance, are mutually supportive, and both contribute to the digital transformation of industrial and societal systems.[25] Industry 4.0, 5.0, and digital governance are closely linked. Industry 5.0 enhances governance through stakeholder integration, AI-driven human-centricity, and sustainable and resilient production. It also promotes safety, innovation, and responsible technology policies to prevent authoritarian governance, and it contributes to the digital transformation of various sectors, including smart cities.

International, regional, and national organizations develop digital strategies to address the challenges of digital transformation posed by Industry 4.0 and 5.0, contributing to closing digital skill gaps and digital divides worldwide to foster inclusive global sustainable development so that no one is left behind. On June 11, 2020, the UN Secretary-General issued a *Roadmap for Digital Cooperation* to show how the international community can better harness the opportunities presented by digital technologies while addressing their challenges.[38] In September 2021, the UN Secretary-General released the report *Our Common Agenda*, which proposes a Global Digital Compact to be agreed upon at the Summit of the Future in September 2024. The Global Digital Compact is expected to "outline shared principles for an open, free, and secure digital future for all".[39] In 2022, the UN launched a global initiative, Gateways to Public Digital Learning, which is jointly coordinated by UNESCO and United Nations International Children's Emergency Fund (UNICEF) to help countries establish and improve public digital learning platforms as part of the UN TES (Transforming Education Summit) follow-up.[40] It facilitates cross-border cooperation to ensure that all students, teachers, and families have access to high-quality, well-organized, and curriculum-aligned digital education content. UNESCO has published a series of critical documents and standards that have been instrumental in guiding

global education systems toward the adoption of digital technologies. These reports, documents, guidelines, and standards illustrate UNESCO's multifaceted role as a think tank, standard-setter, capacity builder, information disseminator, and advocate for international cooperation.[41] The *UNESCO Guidelines for ICT in Education Policies* are designed to enhance educational development, access, and lifelong learning; improve trainees' and teachers' information and communication technology (ICT) skills; support sustainable mobile learning through policy development; and emphasize results-oriented technologies and personalized learning environments.[42] The *UNESCO Strategy for TVET (2022-2029)* promotes digital transformation by developing flexible digital learning pathways, micro-credential frameworks, and skills for digital and green economies.[8] *UNESCO AI and Education: Guidance for Policy-Makers (2021)* is crucial for ensuring that AI tools are used safely, inclusively, and in ways that benefit educational processes.[43] In June 2020, the International Telecommunication Union (ITU) launched the *Digital Skills Assessment Guidebook*, which offers a comprehensive tool for national digital skill assessments.[44] It aids policymakers and stakeholders in determining the supply of digital skills, assessing industry demands, pinpointing skill gaps, and formulating policies for future needs. The significance of digital transformation within the global educational sphere is strongly emphasized by prominent international bodies, such as the UN, UNESCO, and the ITU, among others. These organizations direct their strategic and policy initiatives toward tackling overarching educational concerns on a global scale. These bodies widely acknowledge that the integration of digital technologies can improve the quality, accessibility, and adaptability of education systems worldwide.

To adapt to economic changes, enhance employment opportunities, bridge skill gaps, promote innovation and entrepreneurship, and achieve social inclusivity and SDGs, regional organizations have also published several strategic documents to ensure that digital transformation is prioritized in educational reforms and skill development programs. For example, the European Union (EU) has initiated a number of policy initiatives *via* the EU Skills Agenda. The updated *Digital Education Action Plan (2021-2027)* outlines the EC's vision for high-quality, inclusive, and accessible education and training systems fit for the digital age. Its two priorities are to foster the development of a high-performing digital education ecosystem and to boost digital skills and competencies for digital transformation.[18] The Association of Southeast Asian Nations (ASEAN) published the *ASEAN Education Work Plan 2021-2025*, highlighting the need to enhance education quality, foster student mobility, and implement digital transformation in education.[45] The work plan

recognizes digital transformation as a fundamental strategy for addressing current education and skill challenges. The African Union (AU) introduced the *Digital Transformation Strategy for Africa (2020-2030)* and the *African Union Digital Education Strategy and Implementation Plan (2023-2028)* in 2020 and 2022, respectively.[46,47] The outlined strategies provide policy directives aimed at augmenting digital education, propelling the use of digital technologies, and increasing public awareness of digital proficiencies. Encompassing digital education across various TVET tiers, they underscore the significance of digital competencies in professional milieux.

To ensure alignment between education systems and continuously evolving digital transformation trends and to effectively provide students with the requisite skills and knowledge, many countries have instituted national-level digital strategies in recent years. In 2022, Huawei[48] claimed that 170 countries and regions across the globe had implemented comprehensive digital transformation strategies. For example, China has implemented several strategies to expedite its digital transformation. *The Plan for the Overall Layout of Building a Digital China* envisions China as a global leader in digitalization by 2035, emphasizing the application of digital technology across various sectors.[49] The *National Digital Learning Strategy* for China has taken three years to implement and emphasizes application-focused initiatives, the sharing of high-quality resource dissemination, the stimulation of educational innovation, and the transformation of China's digital learning landscape into a robust platform for advancing global sustainable development objectives.[50] The German Federal Government's *High-Tech Strategy 2025* presents Germany's digital transformation strategy,[51] the aim of which is to position Germany as an innovation leader by leveraging research and high-tech advances to address societal challenges and ensure sustainable economic growth.

TERTIARY DRIVERS OF DIGITAL TRANSFORMATION IN TVET

Employment 4.0 and 5.0 were derived from industrial, economic, and societal transformations due to technological advances, prompting changes in work, skills, and organizational structures and leading to the digital economy, smart society, environmental sustainability, and digital governance.

Changing job profiles
The online white-collar workforce already recognizes the future of work in 2020. Eighty-four percent of employers intend to rapidly digitalize working processes, significantly expand remote work, and potentially move 44% of their workforce to remote working.[52] Industry

4.0 and 5.0 have led to the creation of new job profiles that require a mix of existing and new skills to manage digitalization trends, with a focus on cyber-physical systems and smart production for adapted general knowledge areas, such as supply chain management.[53] The World Economic Forum stated that the largest job creation and destruction effects come from environmental, technological, and economic trends.[54] Digital technologies, including AI, are poised to have a profound impact on work. While there is a significant risk of job displacement, particularly for low-skilled workers, there is also the potential to create new, highly skilled jobs and to promote technological innovation. Based on the *Future of Jobs Report 2023*, 83 million jobs are projected to be lost and 69 million created in the next five years, constituting a structural labor market churn of 152 million jobs, or 23% of the 673 million employees in the studied dataset.[54] The fastest-expanding roles today are technology-related roles driven by technology, digitalization, and sustainability. AI and machine learning specialists top the list, followed by sustainability specialists, business intelligence analysts, and information security analysts. The fastest-declining roles are also driven by technology and digitalization because they are mostly manual work roles that are easily replaced by automation.[54] According to Zhou and Chu,[55] AI is expected to replace 278 million laborers in China by 2049, representing 35.8% of current employees and particularly affecting female, older, less educated, and lower-income workers. Frey and Osbourne[56] calculated that 47% of jobs in the United States (US) will be at high risk of automation in the next two decades.

Meanwhile, digital technologies are also creating vast new realms of work, such as robotics, AI-enabled analytics, machine learning, and virtual personal assistance. PricewaterhouseCoopers (PwC) estimated that AI would create 297 million future jobs in China between 2017 and 2037.[57]

Restructuring human resources

The advent of Industry 4.0 and 5.0, the digital economy, smart society, and environmental sustainability have caused significant changes in employment and human resources (HR). Industry 4.0 and 5.0 are transforming human resources management (HRM) frameworks and tools, with recruitment and training being the most affected areas due to changes in competencies and development processes.[58] Industry 4.0 and 5.0 have also transformed job profiles, application forms, and the emergence of a platform economy, necessitating new education and training directions for human capital development.[59] Industry 4.0 and 5.0 require a holistic approach to HRM to manage knowledge and competence challenges, with a focus on developing employees to handle complex processes and retain their

jobs in changing environments.[60] The evolution toward Employment 4.0 and 5.0 is leading to HR restructuring due to the need for new skill sets, changes in job profiles, and the development of HR practices that can accommodate the integration of advanced technologies. Organizations must adapt their HR frameworks to ensure that employees are engaged, well trained, and capable of working with increasingly sophisticated systems. The Industry 5.0 focus on sustainable HRM and the personalization of technology further emphasizes the importance of human-centric approaches in the workplace.

Increasing skilling, upskilling, and reskilling

As the digital economy, digital society, and environmental, social, and governance (ESG) issues become mainstream, and the world of work changes rapidly, there is an increasing need for skilling, upskilling, and reskilling in digital technologies. The International Labour Organization (ILO) predicted a general increase in the need for technical skills,[60] claiming that the number of hours worked involving technical skills will increase from 31 billion in 2016 to 60 billion in 2030 in the US, and from 41 billion to 60 billion in Western Europe.[61] Thus, new entrants to the workforce will need skills in related technologies for initial employment. In terms of upskilling, the *McKinsey Global Survey* reported that up to 87% of 1216 surveyed employers worldwide identified skill gaps either currently or within the next five years, with data analytics and ICT being the top two skill gap areas.[62] The European Training Foundation predicted that employed people would require more advanced digital skills to work in increasingly digitalized work environments.[63] Lastly, concerning reskilling, the World Economic Forum estimates that half of employees worldwide may need to change jobs and reskill by 2025 due to their old jobs being made obsolete by the application of new technologies.[52] Li Ling found that "technology use, monitoring, and control" and "technology design and programming" are likely to be among the top 10 skills for reskilling and upskilling the future-ready workforce in 2025, which was not the case in 2015 and 2020.[64] This highlights the importance of digital reskilling.

Increasing demand for TVET-job market alignment

The rapid changes in job profiles, HR structures, and skill needs brought about by digital transformation are placing considerable pressure on TVET systems to align with the evolving job market. This increasing demand for TVET-job market alignment is emerging as a powerful driver of digital transformation within TVET itself.

Employment 4.0 and 5.0 represent a shift in thinking

toward more human-centric, technologically advanced work environments. This shift is characterized by the need for new job profiles, skills, and a flexible workforce that can adapt to changes induced by automation and digital transformation. According to the *Future of Jobs Report 2023* by World Economic Forum, employers estimate that 44% of workers' skills will be disrupted in the next five years, with 6 in 10 workers requiring training before 2027.[54] However, only half of workers generally have access to adequate training opportunities today. Notably, training workers to work with AI and big data ranks third among company skill and training priorities over the next five years, with 42% of surveyed companies prioritizing these areas.[54] Progress toward Society 5.0 further requires educational institutions to adapt their curricula to prepare students and train and equip teachers for the new jobs and skills demanded by the evolving labor market.[33] Surveyed companies reported that investing in learning, on-the-job training, and process automation were the most common workforce strategies they were likely to adopt to achieve their business goals.[54]

The rapid evolution of emerging technologies, the digital economy, digital society, and the labor market has required the alignment of TVET with the demands of the future job market. This alignment is critical for producing a skilled workforce equipped with the necessary knowledge and competencies to thrive in an increasingly digitalized smart economy and society. It involves the integration of modern technologies, the development of digital and transversal skills, active industry engagement, and the anticipation of future labor market trends. Addressing these areas will ensure that TVET graduates are well prepared for the evolving demands of the global economy.

However, the adoption of Industry 4.0 technologies varies by region, and education systems are challenged to align with these new requirements. As organizations transition to these new work models, it is important to consider the well-being and job satisfaction of employees to ensure smooth and successful transitions. Despite these challenges, the overarching trend is toward a digital transformation that supports both industrial and societal development, making the alignment of TVET with the evolving job market an increasingly critical imperative.

SYNTHESIS OF ANALYSIS

By extensively analyzing the drivers of digital transformation in TVET, we established a comprehensive understanding of the phenomenon and its catalysts. At the forefront of digital transformation in TVET are Industry 4.0 and its successor, Industry 5.0,

bolstered by the underlying enabling technologies. These digital tools boost progress toward Industry 4.0 and Industry 5.0 by prompting digitally infused societal evolution. They furnish digital and technical apparatuses that are crucial for advancing the digital transformation of TVET. Furthermore, they propel a transition toward a digital economy, the realization of a smart society (Society 5.0), environmental sustainability, and the promotion of digital governance aligned with global SDGs.

Positioned on the next tier of influence, the secondary drivers encompass economic, social, and environmental sustainability considerations, as well as governance within the framework of the UN SDGs. The digital economy requires the use of digital technologies to enhance operational efficiency and drive value creation. Society 5.0 envisions a human-centric communal structure seamlessly interwoven with technology, necessitating digital literacy and the acquisition of novel skills. Environmental sustainability requires that economic progress be harmonized with ecosystem preservation *via* the use of digital technologies. Digital governance offers strategic frameworks and directives for the implementation of digital transformation across various industry sectors. These changes collectively propel transformation in workforce dynamics, underscoring the imperative for TVET institutions to produce graduates with excellent digital and transversal skills.

Furthermore, tertiary drivers encompass a comprehensive understanding of the workforce transformation prompted by Employment 4.0 and 5.0. This shift in employment practices is guided by the principles of Industry 4.0 and Industry 5.0, as well as the four integral dimensions of the global framework for sustainable development. The emergence of new job roles due to technological advances is fostering demand for emerging digital skills and significant skilling, upskilling, and reskilling, calling for labor market alignment facilitated by the digital transformation of TVET.

The inherent interconnectedness among these three levels of drivers involves progression, with primary drivers steering secondary drivers, which in turn catalyze tertiary drivers, ultimately propelling the digital transformation of TVET. Thus, the primary, secondary, and tertiary drivers not only drive TVET digital transformation individually but also collectively form a cohort fostering systematic digital transformation (Figure 1).

Digital transformation within TVET is shaped not only by external influences but also by intrinsic factors. We
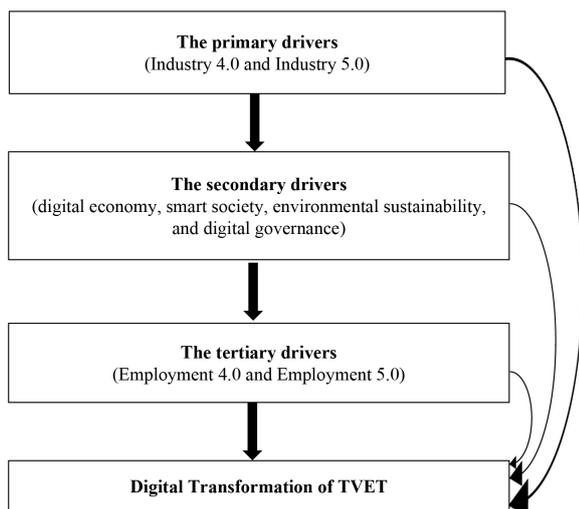
Figure 1. The driving logic of digital transformation in TVET. TVET, technical and vocational education and training.

predominantly considered the external drivers of this transformation. However, concurrently within the TVET sector, conspicuous internal drivers further steer this transformation. These include the absence of institutional strategic planning for digital transformation, the pressing need to augment the digital competence of TVET leaders and educators, inadequacies in digital learning and training infrastructures, learning setbacks among TVET students primarily affected by digital divides, deficiencies in essential ICT and pedagogical competencies among teachers/trainers, and a scaling up of risks and vulnerabilities associated with online safety, privacy, and mental well-being. In forthcoming research endeavors, a meticulous examination of these internal drivers is warranted to delineate a comprehensive overview of all the driving forces underpinning digital transformation in TVET.

CONCLUSION

We undertook a comprehensive exploration of the notion of "digital transformation" in relation to TVET to show that the digital transformation of TVET not only concerns digital educational technologies but also a systematic institutional transformation, covering 10 dimensions: TVET digital governance, TVET digital transformation methodologies, the digital transformation of programs and curricula, digital resource development, teacher development to support digital transformation, student digital skill development, digital transformation of community engagement, digital technology research and innovation, and digital infrastructure.[8] This study

underscores the multifaceted nature of digital transformation within the TVET domain.

We identified three paramount types of external drivers steering digital transformation in TVET: primary drivers (Industry 4.0, Industry 5.0, and facilitating digital technologies); secondary drivers (digital economy, digital society [Society 5.0], environmental sustainability, and digital governance); and tertiary drivers (Employment 4.0 and Employment 5.0). The driving logic underpinning the digital transformation of TVET involves a hierarchical progression, with primary drivers determining the trajectory of the secondary drivers and subsequently catalyzing tertiary drivers, thereby propelling overarching digital transformation within TVET.

Drawing inferences from this driving logic, it is imperative for TVET institutions to harmonize with shifting employment landscapes and the escalating need for digital skills. Embracing a holistic digital transformation approach is indispensable for addressing the emergent challenges of global sustainable development. Moving forward, a synthesis of these insights can guide the strategic alignment of TVET with evolving skill demands, ensuring a proactive stance toward navigating the complexities of the contemporary digital era and fostering sustainable development at the global, regional, and country levels.

Future research directions

Building on the study presented in this paper, three prospective research avenues support further exploration of the dynamics underpinning digital transformation within the TVET sector. Primarily, we concentrated on the external drivers of digital transformation, but future researchers could explore intrinsic drivers within the TVET sector, encompassing leadership dynamics, the strategic deployment of resources, and teachers' digital skills development. Such inquiries would contribute significantly to a more holistic understanding of the drivers of digital transformation within the TVET sector. Second, it would be intriguing to empirically investigate the dynamic associations between each of the three external drivers and digital transformation within the TVET sector. Such studies would illuminate the complexities of how each external driver individually influences the digital transformation of TVET. Lastly, with the rapid evolution of the digital landscape, research directed toward monitoring the impacts of improved transversal skills (*e.g.*, creative and analytical thinking skills) on digital transformation trajectories within TVET will become increasingly vital. Such research should evaluate the TVET sector's relevance and sustainability in the face of future skill challenges.

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Author contributions

Parua R: Writing—Reviewing and Editing. Yang W: Conceptualization, Writing—Original draft preparation. Both authors have read and approved the final version.

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The authors have no conflicts of interest to declare.

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No additional data.

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