Framework for the Upskilling for the 4th Industrial Revolution: Challenges, Curriculum and the Way Forward

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***Abstract*—The Fourth Industrial Revolution (4IR or Industry 4.0) presents a significant shift in the operation of industries and economies. It is a manufacturing paradigm that integrates cyber-physical systems, artificial intelligence (AI), robotics, and the Internet of Things (IoT) to create more intelligent, connected industrial systems. Unlike previous industrial revolutions, 4IR offers unprecedented advances, enabling machines to learn, adapt, and make decisions in manufacturing environments. However, operating, maintaining, and integrating these emerging technologies requires dedicated skill sets to thrive in this new landscape. The purpose of this work is to develop a pedagogical framework to promote key skills needed for the fourth industrial revolution and the implementation of its curriculum in tertiary education institutions in Zimbabwe. Quantitative and qualitative data were collected via stakeholder engagements, online surveys, and interviews with educators and captains of industry. This study developed a comprehensive framework for 4IR education within tertiary institutions from four skill sets: general, soft skills, hard skills, and critical skills. The framework will play a key role in the effective upskilling of communities in the 4IR, especially those in low-resource Sub-Saharan regions.**

Keywords—component, formatting, style, styling, insert (key words**)**

I. INTRODUCTION

The Fourth Industrial Revolution (4IR) or Industry 4.0 signifies a profound shift in the way we manufacture, operate, and regulate industrial systems. Unlike the first three industrial revolutions, as shown in Figure 1, which brought mechanization (1IR), mass production (2IR), and automation (3IR), the 4IR is marked by the integration of cyber-physical systems, artificial intelligence (AI), robotics, and the Internet of Things (IoT) to produce innovative, networked industrial environments [1][2]. This integration facilitates autonomous decision-making, end-to-end communication, and real-time data analysis in manufacturing setups [2]. The implementation of 4IR technologies is restructuring the workforce and workplace environments, leading to changes in job types, increased productivity, and new skill demands [3]. Knowledge management processes are also being drastically influenced by Industry 4.0 as organisations compete with each other through knowledge in this new age [4]. Despite the numerous advantages of 4IR, some manufacturers are still reluctant to fully adopt these technological changes due to the complexities involved in implementation and upgrading [1].

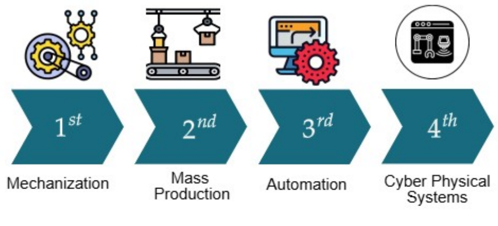

Figure 1: Industrial revolutions

The 4IR is powered by a constellation of enabling technologies that are revolutionising conventional industrial processes [5]. These fundamental technological pillars are AI, IoT, robotics, big data analytics, cloud computing, and additive manufacturing [6]. AI is the cognitive spine, processing enormous amounts of information and making smart decisions, while the IoT generates interconnected devices that interact and exchange data within manufacturing ecosystems [7]. Robotics embodies this intelligence through physical expressions, enabling it to perform intricate tasks independently. Advanced analytics converts raw information into actionable insights, facilitating predictive maintenance and real-time decision making [6]. These technologies complement each other, exhibiting features of generality, novelty, and typical lifespan of general-purpose technologies [5]. This technological fusion has the potential to reshape work, organisations, and society itself [7].

The 4IR is transforming the workforce, requiring rapid upskilling to remain competitive [8]. The 4IR presents both opportunities and challenges for businesses and labour markets, which require a digital mindset and lifelong learning [3]. Some of the essential skills required include soft skills, digital skills, and leadership skills [8], [3]. The failure to upskill risks a decline in productivity, loss of competitiveness, and even job displacement [9]. Solving these challenges calls for concerted efforts from businesses, learning institutions, and governments to invest in critical infrastructure and foster lifelong learning [3], [10]. Developing nations have extra challenges preparing their workforce for 4IR, calling for specific skill development initiatives [8].

This research aims to develop a comprehensive upskilling framework that addresses the unique challenges and opportunities of the Fourth Industrial Revolution. The primary objectives include identifying and analyzing the key technological competencies required for the readiness of the 4IR workforce, developing a structured curriculum framework that can be adapted in different educational and professional contexts, examining the specific challenges faced by low-resource communities, particularly in Sub-Saharan Africa, and proposing practical implementation strategies that can be scaled across different organizational and regional contexts.

This study addresses several critical questions that guide the development of the proposed framework:

1. What are the core technological competencies required for effective participation in the 4IR workforce?
2. How can educational institutions and organisations design curricula that address the key requirements of the 4IR, especially in Zimbabwean contexts?
3. How can upskilling frameworks be made sustainable and scalable across different resource contexts?

This paper is structured to provide a comprehensive analysis of 4IR upskilling requirements and solutions. Following this introduction, Chapter II examines the multifaceted challenges associated with implementing 4IR upskilling programs, with a particular focus on the disparities between developed and developing economies. Chapter III presents the core framework for upskilling, detailing the principles and components necessary for effective 4IR workforce development. Chapter IV focuses on curriculum design, providing practical guidelines for educational institutions and training organisations. Chapter V offers policy recommendations and identifies future research directions, while Chapter VI concludes with key insights and implementation strategies. This organisation ensures a logical progression from problem identification through solution development to practical implementation guidance.

II. Framework for Upskilling: Principles and Components

4IR can be considered an emerging and disruptive technology [11],(Kasza, 2016.). Several studies in the literature propose multiple frameworks to support upskilling in the 4IR era [13]. This is necessary for students, professionals, technicians, and managers, among others, to be relevant in a 4IR economy. Most of the technologies driving 4IR are interrelated; for example, the IoT interacts with big data, edge computing, and cloud computing. Some are even complementary. The cloud infrastructure is now considered the backbone of data science to the extent that data-related industries today rely on cloud computing infrastructure for their existence. Some technologies, although fundamentally different, share similar characteristics and concepts.
For example, autonomous vehicles share concepts with autonomous robots, although their architectures and application domains are completely different. These relationships help simplify upskilling requirements. Skills gained in one field are often viewed as transferable to another field, thereby reducing the need for retraining or upskilling. Figure 2 shows the key technologies that support 4IR, and Table 1 discusses these technologies in detail, as well as providing areas of current research.

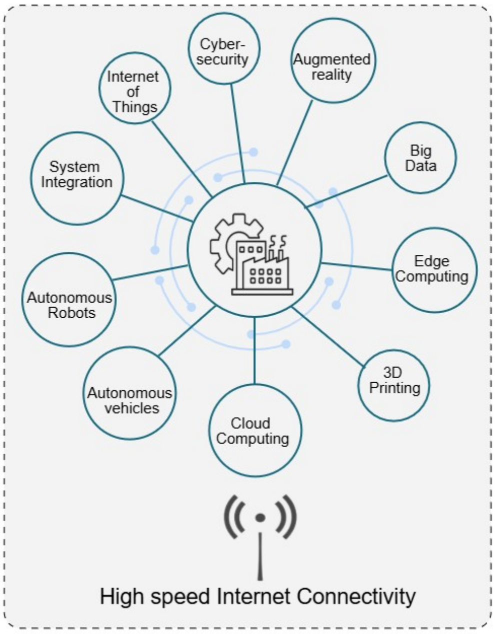

Figure 2: Key elements of 4IR

III. Methodology

This research adopts qualitative and quantitative approaches via stakeholder engagements, online surveys, and

Table 1: List of technologies required in the 4IR era.

Ref	Area	Description
[14]	The Internet of Things (IoT)	The Internet of Things is driving the fourth industrial revolution through enhanced device connectivity and ubiquitous data transmission. Connected devices gather data from remote locations and transmit it over the internet, creating smart ecosystems across industries such as agriculture, mining, transportation, e-commerce, and finance. The result is faster data access in industries, and also, IoT devices can be installed in remote locations that are challenging for people to access. Key considerations include addressing challenges such as power consumption, security, communication protocols, scalability, and integration with other emerging and disruptive technologies.
[15]	Cyber-Security (CS)	The increasing demand for connected devices and digitisation introduces security risks to networks. Cybersecurity plays a crucial role in detecting, classifying, and neutralising unauthorised access and digital attacks before they inflict damage on systems and networks. With 4IR systems becoming increasingly connected and ubiquitous, key advancements include integrating cybersecurity with other key technologies, such as machine learning, deep learning, and natural language processing, to provide intelligent cybersecurity services that detect and even predict complex threat landscapes.
[16]	Augmented Reality (AR)	Augmented Reality (AR) has emerged as a key technology over the past few years. It has been derived from Virtual Reality (VR), where the focus was on placing users in 3-dimensional synthetic environments. AR has been developed to supplement physical environments by allowing users to see 3D synthetic objects superimposed on real environments. This provides additional information that enhances a user's perception by enabling users to interact with virtual elements in real-time, providing unprecedented support in building systems, transportation, healthcare, education and manufacturing, among others. Current research trends emphasise the need for AR development and deployment in business and industry, particularly in the context of the fourth industrial revolution.
[17]	Big Data (BD)	By far one of the most dominant fields over the past decade, data science plays a crucial role by using scientific tools and processes to analyse high volumes of data and extract meaningful insights hidden in the data. Industries generate large amounts of data that are too complex to be processed and analysed by conventional computing infrastructure, hence the need for dedicated data processing, transmission and storage facilities that can handle the unique characteristics of big data. Key advancements include big data analytics and exploring ways of reducing data overload.
[18]	Edge Computing (EC)	Edge computing is an emerging computing paradigm that processes data at the edge of the network, and close to data sources, which differs from traditional cloud computing, where centralised computing clusters largely perform processing. The edge can be colloquially defined as any computing device along the path between the data source and the cloud. Key benefits of processing data on the edge include low cost, reduced energy consumption, and lower bandwidth requirements, as the data is not uploaded to the cloud. This is advantageous in 4IR systems that are envisaged to generate large amounts of data in a few hours of operation. Key advancements include addressing energy and security challenges, as well as advancing AI algorithms to run on resource-constrained edge devices.
[19]	3D Printing (3DP)	3D printing is an innovative additive manufacturing technology that creates physical objects from a 3D geometric representation through successive addition of material, layer by layer. It has been demonstrated that traditional manufacturing methods are wasteful, expensive, time-consuming, and require expert artisanal knowledge and skill. 3D printing appears to be reasonable since it is not wasteful. Instead, manufacturing is performed layer by layer, eliminating the need for subtractive manufacturing. This enables the construction of intricate parts that may be challenging to manufacture using conventional methods. Research trends are focusing on 3D printing materials, developing faster printers, and expanding the application of 3D printed materials to industries such as healthcare, sport, aviation and manufacturing.
[20]	Cloud computing (CC)	The term cloud computing has been coined to describe computing infrastructure and applications that can be accessed via the internet with various pricing models. This has eliminated the need for businesses and organisations to install applications or have powerful computing resources locally. IT services, including web hosting, data storage, data analytics, networking, and security, can be offered by global commercial providers such as Google, among others. The focus of cloud computing is to minimise the cost of IT infrastructure and provide access to a wide range of opportunities, especially in developing economies.
[21]	Self-driving cars (SDC)	Autonomous vehicles use remote sensing technology to operate completely without human intervention. They incorporate actuators and sensors such as cameras, radar, lidar, and GPS to navigate and avoid obstacles on the road. The technology was mainly developed for self-driving cars to complement human drivers. However, continual sensor development, superior signal processing methods, and breakthroughs in machine learning and deep learning have motivated full automation, and hence the complete removal of the human driver. This technology is poised to transform 4IR through self-awareness, independence and autonomy in the industry. Research directions involve the development of algorithms for sensor integration, object detection, recognition and obstacle avoidance in industries.
[22]	Autonomous robots (AR)	Autonomous robots represent a significant technological leap on two fronts: (*i*) robots and *(ii)* autonomy. These are machines programmed to perform specific repetitive tasks. In addition to replacing humans, autonomous robots perform tasks independently without human supervision or effort. Differing from pre-programmed machines, autonomous robots are self-sufficient robotic systems that offer several advantages, especially in the 4IR industries. Research directions in this field include learning adaptation and multi-robot systems.
[23]	System integration (SI)	System integration refers to the technological process of combining all these technologies to work seamlessly in the 4IR. The aim is to develop systems capable of sharing data and processes to achieve a singular, unified goal of an efficient 4IR, all supported by high-speed internet access.

interviews with educators and captains of industry to develop a relevant framework for upskilling for the 4IR. The following steps are adopted: (i) identifying the research questions, (ii) literature search, (iii) inclusion and exclusion criteria, (iv) selecting the studies, (v) analyzing data, and (vi) identifying gaps and proposing a context-specific framework. The search was limited to articles covering the scope of 4IR, with particular emphasis on emerging technologies reported in Scopus, Web of Science, and Google Scholar.

IV. Curriculum Design for 4IR Upskilling

The 4IR curriculum is offered in tertiary education institutions and focuses primarily on preparing university graduates and reskilling industry professionals in various fields of engineering. Learning for undergraduate students typically spans a period of four years, with delivery primarily being face-to-face, including lectures, practical sessions, and examinations. For professionals already in the field who cannot afford reskilling on a full-time basis, a block-based mode of study can be implemented, where they will conduct fast-paced, face-to-face contact for practical sessions. Their lectures can be offered through an online mode of study. Upon completion of the studies, participants will be awarded an academic certificate or degree in either a Bachelor's degree or a post-graduate certificate to enhance career opportunities in 4IR. Like any taught curriculum, learning for the 4IR is based on several tried-and-tested pedagogical approaches. In this curriculum, three teaching and learning approaches will be implemented: lecture-based learning [24], problem-based learning [24], and project-based learning [25]. In the literature, it has been widely stated that a combination of these teaching approaches is effective in producing the desired outcomes, and the evidence is summarised in various reviews [26]. Finally, evaluation methods include assignments, practical reports, project presentations, group presentations, tests, and a final exam, usually administered at the end of the semester.

Next, the skills and competencies required in the 4IR era have been widely proposed by various researchers in the literature, highlighting the need for graduates and employees to update their technical capabilities, especially in hard technical skills. We summarise the technologies highlighted in the literature [27] [28] [29], and identify nine key technologies that form the backbone of 4IR. These are the Internet of Things (IoT), cybersecurity, augmented reality, big data, edge computing, 3D printing, cloud computing, autonomous vehicles, autonomous robots, and system integration, as presented in Table 2. On top of all that, high-speed internet access will be the key to ensuring 4IR success [28]. In summary, these are the technologies that should be included in any curriculum that targets the 4IR.

We argue that the components of 4IR are not new. In fact, these technologies have been taught independently in tertiary institutions worldwide. Only the recent emergence of 4IR converges all of these technologies together. In response, the taught curriculum should also incorporate these technologies within a unified framework. However, the result is a curriculum that encompasses a substantial amount of content. For example, subjects such as IoT, AI, and Data Science, among others, are so vast that they can individually cover the university curriculum for the entire 4-year period. Hence, in this work, we develop a streamlined curriculum that encompasses all aspects of study within the specified period while maintaining a relatively moderate workload.

Figure 3 illustrates the conceptual framework for developing 4IR skills in learners, as well as the role that industry and tertiary educational institutions play in this process. The industry sets the necessary skills required by the workforce, while educational institutions administer the education. Then the learners will acquire those skills and earn competence in the 4IR. The technical skills cover the specialised knowledge and the necessary expertise required for students to excel in any area [30], and in this case, 4IR. The end goal of teaching such skills is for the learners to develop critical technical competence [30]. [31], outlined a technical skills development framework that consists of three steps: perception, integration, and automation. These are a series of skills that improve the employability of students. On the other hand, soft skills relate to interpersonal skills that enable learners to interact professionally with other team members. Skills such as time management, effective communication, and collaboration, although unmeasurable, play a key role in the workplace. Industry and academia do not exist in a vacuum, there needs to be a feedback mechanism that supports continuous development. Finally, this study develops a context-specific framework that differs from existing 4IR upskilling frameworks by shifting the focus to student capabilities and the adoption of adaptive learning modes at tertiary education institutions.

V. The Way Forward: Policy Recommendations and Future Research

A. Summary of research findings

The research identified nine key hard skills that students need to succeed in the 4IR economy. The research also analysed six degree programs from the Faculty of Science and Technology at Midlands State University to determine if the 4IR skills are offered at the university. The following are the six qualifications that were analysed.

- BSc Degree in Industrial Physics and Instrumentation
- BEng Degree in Telecommunication Engineering
- BSc Degree in Software Engineering
- BSc Degree in Computer Systems Engineering
- BSc Degree in Cyber Security
- BSc Degree in Mathematics and Statistics

100% of the hard skills are already included in the existing curricula of the six degree programs. However, the curriculum needs more soft skills that teach students to deal with emotional and social issues in the workplace.

B. Recommendations

The programs analysed cover their respective areas of specialisation over four years. However, it is impractical for students to do all these degree programs one after the other, since 4IR demands that students be proficient in the hard skills highlighted in this paper. Based on these findings, the following recommendations are made:

1. There is a need to recast the skills required for the 4IR into a four-year degree program for new students, or
2. Continuous training in the 4IR is vital. Therefore, there is a need to cast the skills required into a 2-year post-graduate diploma for recent graduates or employees already working in the field, or
3. Due to the nature of employees already working in the field, they may not be able to afford to learn on a full-time basis. Self-paced, short courses that cover the entire curriculum should be developed.
4. In addition to the soft skills that are in the existing curricula, there is a need to incorporate more soft skills, such as social, emotional, ethics, and values, that can be offered under the Faculty of Social Sciences or Education.

C. *Future Work*

In the future, we hope to investigate how the introduction of 4IR in Zimbabwean companies affects the already existing workforce. This is necessitated by the disruptive nature of the technologies driving the 4IR. Technologies such as AI and robotics threaten to replace humans. This has negative effects, especially on middle and lower employees engaged in manual labour. We also hope to investigate the uptake of 4IR and related technologies in the Zimbabwean market. We also hope to expand the studies to include other tertiary educational institutions in Zimbabwe to determine how the Modules taught in engineering, science and technology faculties align with the 4IR skill set.

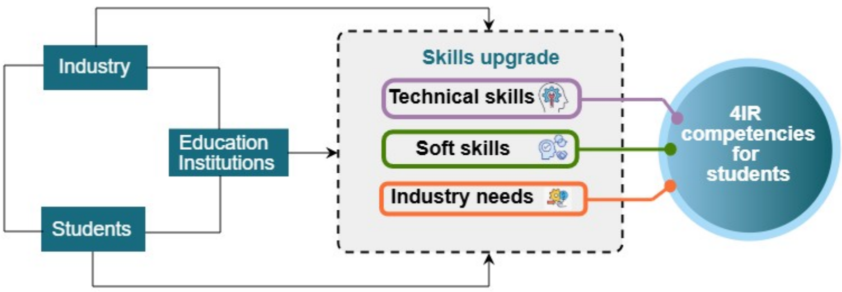

Figure 3: Conceptual framework for developing 4IR skills.

Table 2: OVERVIEW OF THE PROPOSED CURRICULUM.

Curriculum Aims	
Students will be able to: 1. Develop digital literacy skills. 2. Master software, firmware and hardware development skills. 3. Build scalable data analytics and visualisation workflows, and gain competence in cloud computing skills. 4. Develop proficiency in AI and Machine Learning tools. 5. Gain competence in building and operating IoT systems. 6. Acquire automation and robotics skills. 7. Develop cybersecurity and data privacy skills. 8. Use EDA software to build skills in additive manufacturing.	
Topic	**Learning content**
1. Introduction to digital technologies	Overview of 4IR technologies
2. Software development and algorithm design	Designing and implementing algorithms in Python, C/C++, MATLAB and simulation
3. Cloud computing, data processing and data visualisation	Developing cloud-based workflows for data processing and informative visualisations
4. AI and machine learning	Builing end-to-end machine learning models.
5. IoT design and development	o Introduction to IoT design tools and enabling technologies o Implement end-to-end IoT systems for different application
6. Robotics hardware and software development	o Introduction to robotic systems and components o Programming and controlling robots
7. Cybersecurity principles, encryption, and authentication	o Fundamentals of cybersecurity o Identifying and mitigating cyber threats
8. CAD design, 3D printing and CNC machining	o Introduction to CAD Software for 3D Modeling o 3D printing technologies and workflows
9. Prototyping basics	Developing prototypes

VI. CONCLUSIONS

The emergence of 4IR demands well-equipped graduates with diverse skill sets in various areas such as AI, IoT, Data Science, Cybersecurity, and Edge Computing, among others.

As such, educational institutions are required to prepare students for this emerging technology. This study aimed to develop a framework for skilling and reskilling learners and employees with the skills required for employment in the 4IR industries, with a focus on the Zimbabwean landscape. The research developed a skills development framework that highlights the relationships between industry needs, tertiary educational institutions, and the learners. The research also identified nine key hard skills from the literature and consolidated them into a single curriculum. Additionally, the skills were mapped to the modules taught in six degree pr programs in the Faculty of Science and Technology at Midlands State University in Zimbabwe. The study reveals that all the hard skills required in the 4IR are offered separately across different degrees; therefore, there is a need to consolidate and offer these skills either in a single degree program, a postgraduate diploma, or a self-paced short course.

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