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Towards Metrology 4.0 in Developing Countries' Manufacturing Industries

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ABSTRACT

A systematic literature review was conducted to unveil the status of the digital transformation of metrology in developing countries, as they are lagging in utilising fourth industrial revolution (IR4.0) technologies to transform manufacturing industries. A PRISMA technique was employed using various keywords to identify, screen, and select the relevant literature. Forty publications were selected for the review, mainly discussing IR 4.0 technologies in metrological operations. The results indicate that the digital transformation of metrology has yet to be initiated in developing countries. However, the employment of IR4.0 technologies in advancing metrological operations in manufacturing industries is mostly discussed in the literature, especially in China and India. It was also evident that African countries lag behind their Asian counterparts in utilising the IR4.0 technologies to advance metrological operations in manufacturing industries. To enable sustainable digital transformation in metrology, national measurement institutes, testing and calibration laboratories, and manufacturing industries should embrace utilising IR 4.0 technologies in metrological operations. This will facilitate coordination and harmonisation of metrological operations within the three entities, eventually leading to sustainable digital transformation in metrology. The transformation in developing countries will enable precision, high-quality, and accurate metrological operations in manufacturing industries, leading to increased product quality and industry competitiveness in the international market. Also, industries could save time and cost while reducing errors in performing metrological operations. Moreover, the description of the phases that the manufacturing industries could go through towards Metrology 4.0 is also provided.

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INTRODUCTION

The world is currently in the fourth industrial revolution (4th IR), which differentiates itself from the preceding revolutions, considering the associated technologies are disruptive (Kumar et al., 2021). The technologies such as Internet of Things (IoT), artificial intelligence (AI), machine learning, cloud computing, big data analytics, augmented reality, virtual reality, and 3D printing, to mention a few have already proven their effectiveness in several fields including business, manufacturing, medical, construction and agriculture (Serrano-Ruiz et al., 2022; Ullah et al., 2021; Nkosi and Agholor, 2021; Ngowi, 2020). In the manufacturing industries, the technologies of IR4.0 continue to impact their supply chain, including design, production process, metrological operations, quality control, management, procurement, sales and marketing, as well as customer-centeredness (Grandinetti et al., 2020; Psarommatis and Bravos, 2022; Maganga & Taifa, 2024). Metrology in the manufacturing industries plays a substantial role as it caters to product quality and enables cost reduction and productivity during production (Schmitt & Moenning, 2006). The product's quality can be attributed to several factors, including the painting industry (James & Taifa, 2023; Gambi & Taifa, 2023) and material removal processes when optimising parameters (Deshpande et al., 2021).

With the technologies of the IR4.0, metrological operations in manufacturing industries are significantly enhanced in several ways, including in-line metrology, digital calibration certificate, smart sensors for real-time inspection, real-time data analytics, cloud metrology, and virtual measurement process (Fedorko et al., 2021; Wieczorowski et al., 2023; Lazzari et al., 2017). Therefore, the employment of IR4.0 technologies in the digital transformation of metrology can be referred to as metrology 4.0 (M4.0) (Wieczorowski and Trojanowska, 2023; Cunha and Santos, 2020). There are currently several initiatives in the digital transformation of metrological operations in manufacturing industries, especially in developed countries. These include using a scanner embedded with a robotic arm to enhance the remote measurement process, employing a laser scanner for rapid inspection of geometric features, and in-line verification of parts (Wieczorowski & Trojanowska, 2023). Upgrading quality infrastructure (QI) for digital metrology innovations, accreditation, conformity assessment, norms and standards, and market surveillance is an ongoing project undertaken by the National Metrology Institute of Germany (Eichstädt, 2020). Moreover, the EMPIR SmartCom and GEMIMEG are ongoing European projects aimed at developing digital calibration certificates to document calibration information, enabling communication between instrument owners and calibration laboratories (Nummiluikki et al., 2021).

The fourth industrial revolution

The industrial revolution is the technological advancement of processes, operations and systems, leading to improved quality, efficiency, and effectiveness while decreasing cost and resources and increasing profit (Taifa et al., 2025; Ashgar et al., 2020). The world has already witnessed three different kinds of industrial revolutions since the 18th century, considered the 1st industrial revolution (IR1.0). The advent of IR1.0 brought significant improvements in production, where steam power replaced human muscle power in manufacturing. Other associated benefits of the revolution include increased production and consumption, improved transportation systems such as roads, canals and railways, and improved finance and banking (Mohajan, 2019). The invention of electricity, assembly lines, mass production and the replacement of iron with steel were the notable developments during the 19th century, which is referred to as the second industrial revolution (IR2.0) Taifa & Mwakagamba, 2025; Nhelekwa et al., 2024). This was considered a US industrial revolution following numerous inventions in the USA, including electrical communication technologies, plumbing, medical instruments, medicine, chemical and petroleum industries (Mohajan, 2020). In the 20th century, the invention of computers, information technology (IT), programmable logic controllers, and industrial automation were witnessed in several parts of the world, which is referred to as the 3rd industrial revolution (IR3.0) (Mohajan, 2021). It was considered to be a transition from analogue and mechanical technologies into digital electronics in the manufacturing industries associated with several technologies, including robotics, 3D printing, and artificial intelligence (Nhelekwa et al., 2022; Mohajan, 2021).

The IR4.0 was first introduced in Germany by representatives from different fields such as business, manufacturing, academics and politics in 2011 under the initiative "to improve German manufacturing industries competitiveness" (Islam et al., 2018). In contrast to the preceding revolution, IR4.0 is disruptive, impacting the entire value chain in manufacturing industries and businesses through the employment of advanced technologies (Nzumile et al., 2024). These technologies are considered the revolution's driving forces as they digitally connect products, value chains, business models, and physical and virtual environments (Kumar et al., 2021). Generally, the built-in technologies which drive the IR4.0 technologies include big data analytics, cloud computing, machine learning, 3D printing, artificial intelligence (AI), internet of things (IoT), augmented reality (AR), virtual reality (VR), simulation, cyber-physical system (CPS), and blockchain (Nzumile et al., 2024; Maganga & Taifa, 2023a; 2023c; 2023b; Kumar et al., 2021). The IR4.0 is currently underway in several developed countries, Germany being the most advanced country in terms of IR4.0 development in its manufacturing industries. Experts believe it is currently in level IR3.8 and will take a decade or less to reach 100%, i.e. IR4.0 (Islam et al., 2018). With this development, several fields continue to be impacted by these disruptive technologies, leading to numerous neologisms including but not limited to metrology 4.0, quality 4.0, construction 4.0 and procurement 4.0.

Metrology 1.0 to Metrology 4.0

Metrology, in particular, is the science of measurement applicable in various fields of science and business (Nzumile *et al.*, 2024). Generally, metrology has existed since ancient times and was deliberately used to support human economic activities in several aspects, including business, manufacturing, transportation and medicine (Fanton, 2019). Since ancient times, metrology has continued to evolve, and the advent of industrial revolutions in the 18th century significantly led to massive development in measurement, calibration and traceability. During the IR1.0, the first vernier calliper was developed, the decimal metric system was introduced, and the metre as length unit was introduced, which can be termed metrology 1.0 (Wieczorowski & Trojanowska, 2023). Metrology 2.0 pertains to the development of Interferometers, measuring microscopes and an industrial bail micrometre during the IR2.0 as well as the signing of the metre convention (Wieczorowski and Trojanowska, 2023; Fanton, 2019). The advent of automation in manufacturing industries necessitates the need for fast and accurate measurement instruments capable of measuring large amounts of products with different features within a short period of time. This led to the advent of metrology 3.0, where the development of the first coordinate measuring machine (CNN) for 2D and later 3D measurement was witnessed and continues to evolve to date (Majstorovic et al., 2019).

With the advent of advanced digital technologies, which drives IR4.0, the digital transformation of metrology, referred to as metrology 4.0, in manufacturing industries is currently underway, though its transformation is slow compared to other fields

(Nummiluikki et al., 2021). The transformation has been hindered by the complexity of the infrastructure required to maintain the trust between parties involved across different areas, which needs due attention to ensure its achievement (Nummiluikki et al., 2021; Cunha and Santos, 2020). Since 2018, several initiatives and notable developments have been achieved in metrology 4.0 within manufacturing industries and other sectors, especially in developed countries, by employing IR4.0 technologies, as discussed in the subsequent session.

IR4.0 technologies and metrology 4.0

Generally, the development of metrology has been influenced by industrial development since the first to the Fourth Industrial Revolution. This is because the associated technologies in the respective industrial revolutions are being used to improve metrological operations in the manufacturing industries (Wieczorowski & Trojanowska, 2023). Therefore, the digital transformation of metrology, i.e. metrology M4.0, is significantly reliant on employing the IR4.0 technologies, including the IoT, AI, cloud computing, big data analytics, and cyber security (Garg et al., 2021). These technologies have already found their way into digitally transforming metrology, especially in developed countries, and there is still ongoing research regarding the employment of IR4.0 technologies in metrological operations. The digital calibration certificate (DCC) has already been in place since 2020 in Germany and was developed by the German National Metrology Institute (PTB) in which the calibration data are digitally stored and sent to the client lab for further processing (Oppermann et al., 2022).

Metrological traceability is enhanced using the DCC, and manufacturing and quality monitoring are enabled to guarantee the reliability and quality of measurement instruments used in manufacturing industries (Oppermann et al., 2022). The employment of IoT, augmented and virtual reality, has enabled the development of high-precision measurement systems capable of taking measurements in real-time while the manufacturing process is on (Junaid et al., 2022). The use of robotic arms embedded with cameras also enabled the remote participation of a technician in the measurement process, which reduces human errors and operation costs, especially during the pandemic period (Wieczorowski & Trojanowska, 2023). Moreover, virtual metrology has already gained popularity in manufacturing industries, enabling product quality estimation directly from a production process without undertaking physical measurement on the product in question. The employment of virtual metrology in manufacturing has enabled the achievement of zero-defect manufacturing through various elements, including data processing, quality estimators, drift detection systems, and sampling decision systems (Dreyfus et al., 2022).

Despite these achievements in metrology, the potential of IR4.0 technologies is still yet to be fully utilised in transforming metrology digitally. Notable development has been made on the digital calibration certificate (DCC), a project initiated by PTB, which has already been in use in Germany since 2020, though its widespread adoption is still a challenging part (Oppermann et al., 2022; Gadelrab and Abouhogail, 2021). However, most of the literature focuses on the proposition of various ways to employ IR4.0 technologies in the digital transformation of various metrology aspects such as measurement, calibration of measurement instruments, traceability, inspection and testing, which requires their realisation in real working environments in the near future (Carmignato et al., 2020; Cunha and Santos, 2020; Andonov and Cundeva-Blajer, 2018) It is also noted that developed countries, especially Europe and the USA, are increasingly investing in advanced digital technologies to transform metrological operations in manufacturing industries compared to developing countries. Considering the disruptive nature of the IR4.0 technologies, vibrant economy, and boundaryless international market, manufacturing industries in developing countries should not lag behind in grasping the potential of the digital transformation of metrology, as witnessed in developed countries. In view of this, the study aimed to unveil the status quo of digital transformation in metrology as well as the proposition of a conceptual framework enabling developing countries' manufacturing industries in achieving sustainable digital transformation in metrology.

METHODS AND MATERIALS

This research employed a systematic literature review to obtain pertinent information regarding the research objective. It was conducted by defining the keywords, searching the relevant literature on the subject in question, and finally performing the analysis and discussion. Web of Science and ScienceDirect were identified as the search database considering the fact that they are the most extensive abstract and citation databases which contain multiple peer-reviewed journals in multiple fields, including science, technology, medicine as well as social science (Athuman et al., 2024; Pamba & Taifa, 2024; Kamble et al., 2018). The selected articles were published by Elsevier, Taylor & Francis, and Springer publishing houses in these two databases. The keyword selection was made to obtain the most relevant articles pertaining to metrology 4.0. Since metrology 4.0 is enabled by the technologies of the fourth industrial revolution, articles which describe the linkage between IR4.0 and M4.0 were also highly considered during the search. Based on that, the following keywords were used to search the relevant articles: (i) Metrology, (ii) "Metrology 4.0", (iii) Industry 4.0 AND Metrology, (iv) "Manufacturing AND Metrology 4.0". The search was conducted sequentially, whereby each keyword with its associated identified articles was recorded for the analysis.

During the preliminary search, a total of 104 publications were identified from the aforementioned databases using the defined keywords. The authors ensured that different aspects of metrology 4.0 in manufacturing and Industry 4.0 were deliberately covered during the search. Exclusion and inclusion criteria were considered to enable effective analysis and select the most relevant publications. Articles, book chapters, and conference proceedings published in English were the inclusion criteria. Moreover, metrology 4.0 concepts started to be discussed in the literature in 2016; thus, the articles published from 2016 to 2024 during which the research was undertaken were included. On the other hand, non-English published articles, reports, books, and white papers were not included in this review. Finally, a total of forty (40) articles were selected for the final review for findings and discussion. Figure 1 presents a complete Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) flowchart for selecting the relevant articles.

The statistical analysis of the identified articles was performed based on several aspects, including keyword statistics, which was conducted to unveil the distribution of articles obtained based on keywords used. This enabled the authors to identify the most frequent keyword that resulted in a large number of articles published regarding metrology 4.0. Articles were also statistically analysed based on the publication time frame, enabling the identification of the year in which many articles were published, which provides trending on the metrology 4.0 concepts around the world. The continental publication was also analysed to unveil the status quo of metrology 4.0 concepts globally, which will provide information regarding the advancement of metrology in various countries located on a specific continent. The analysis based on the research type was also conducted to uncover the subject areas under which metrology 4.0 concepts were centred. This is paramount, especially in providing key information on how the digital transformation of metrology could be achieved and where effort should be concentrated to accomplish the transformation in manufacturing industries. The research type where metrology 4.0 concepts were published included the general concepts, i.e. conceptual studies, experimenting with the metrology 4.0 application, simulation of the formulated concept or system, and case studies involving metrology 4.0 concepts and proposition.

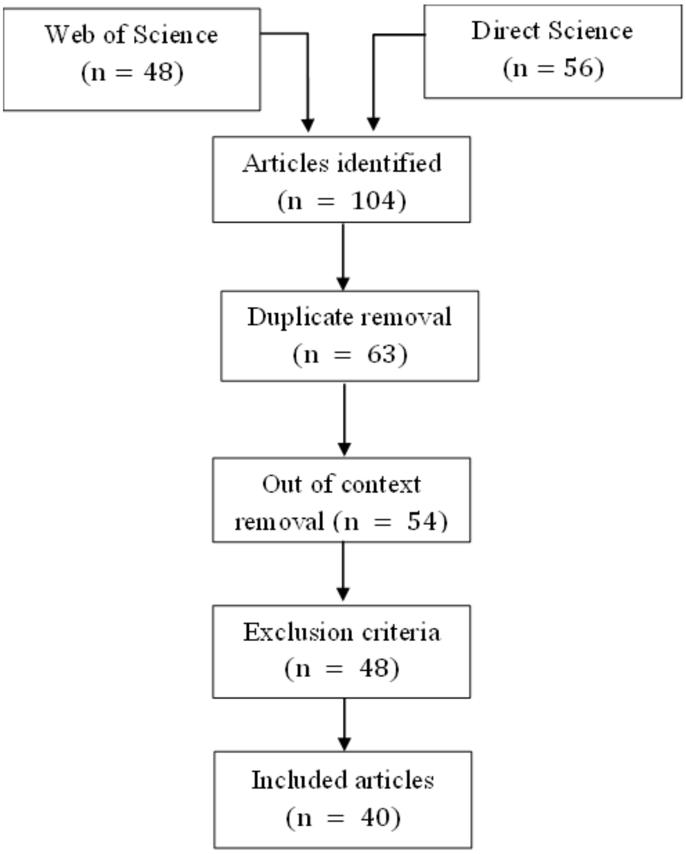

Figure 1: A PRISMA flowchart for articles selection (Nzumile et al., 2024)**.**

The literature content analysis was also performed through thematic and content analysis. The analysis was done to unveil the status of the digital transformation of metrology in various developing countries' manufacturing industries. It was also done to identify the key stakeholders and their contributing factors in enabling the achievement of sustainable digital transformation of metrology in manufacturing industries. The analysis provides the linkage between key stakeholders and how they should collaborate to ensure that manufacturing industries transform metrological operations digitally.

RESULTS AND DISCUSSION

Keywords statistics

As mentioned in the methodology, four different keywords were used to search the relevant articles. The distribution of articles obtained after keyword execution is indicated in Figure 2. 'Industrial 4.0 AND metrology' keywords resulted in 16 (40%) articles for review, which is the highest compared to the rest. It was followed by

"Manufacturing AND Metrology 4.0", which contributed 12 (30%) articles for review, 'Metrology' with 10 (25%), while "Metrology 4.0" is the least contributing keyword with only 2 (5%) reviewed articles. The highest contributions of the keywords 'Industry 4.0 AND Metrology' as well as "Manufacturing AND Metrology 4.0" are mainly due to the fact that metrology development has always been driven by the industrial revolution and modern manufacturing technology within which various associated technologies are employed to improve metrological operations (Wieczorowski & Trojanowska, 2023). Therefore, most of the articles discuss metrology aspects within the bounds of Industry 4.0 and modern manufacturing technology, thus their highest contribution.

On the other hand, the "Metrology 4.0" keyword is observed to contribute less to the number of reviewed papers because the literature has hardly identified 'Metrology 4.0' as a stand-alone concept. Thus, few articles discussed Metrology 4.0 concepts rather than being discussed within IR4.0 and modern manufacturing technologies. This observation can also be underscored by the fact that the digitalisation of metrology has been slowly progressing compared to other sectors, as pointed out by Nummiluikki et al. (2021).

Publication based on time frame

The digitalisation of metrology began to be discussed in the literature in 2016, though the concept of digitalisation or IR4.0 began in 2011. The number of published articles regarding metrology 4.0 concepts is unequally distributed from 2016 to 2024, during which this research was undertaken, as indicated in Figure 3. The highest publication year, as indicated in Figure 3, was during 2019, in which a total of ten (10) publications were identified. During 2019, the need for virtual and remote control of various processes, including metrological operation, sharply increased because of the impact of the pandemic. This was due to the fact that there were many restrictions regarding human interaction, which impacted manufacturing organisations, leading to various innovations such as a robotic arm embedded in the inspection machine to allow operators to remotely control the inspection process as well as the virtual measurement process (Wieczorowski and Trojanowska, 2023; Hsieh et al., 2019).

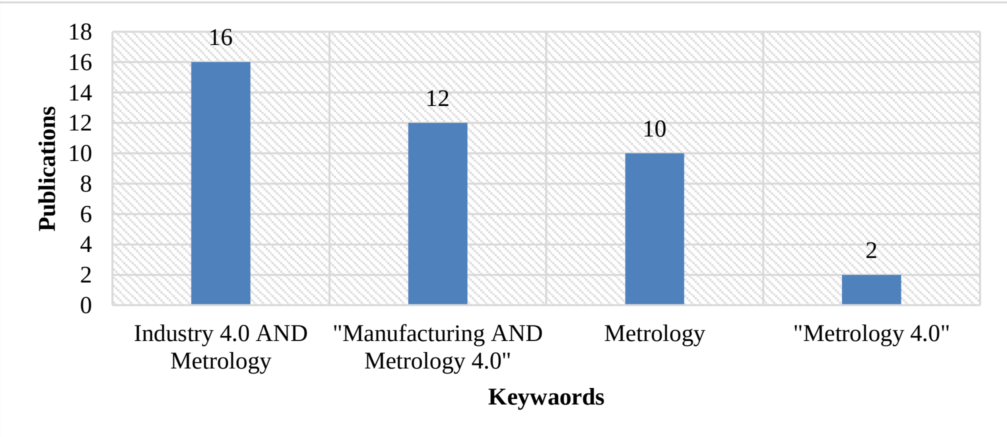

Figure 2: Publication based on keywords used.

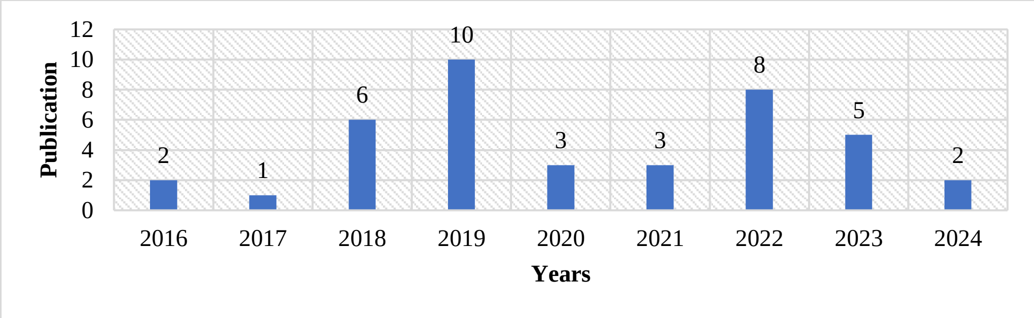

Figure 3: Year-wise publication details.

Continental metrology 4.0 publications distribution

Publications also vary from continent to continent, following countries' awareness and technological development within the respective continents. Figure 4 indicates the distribution of publications based on continents, whereby Europe is the continent most contributed to with regard to the digitalisation of metrology, with twenty (20) publications. This is mainly due to the fact that the concept of digitalisation brought by the fourth industrial revolution was first discussed in Europe, especially in Germany in 2011, to improve German manufacturing industries' performance (Cunha & Santos, 2020). The technological advancement in America, especially the USA and some of the Southern American countries such as Brazil and Argentina, also contributed to the highest number of publications, which are twelve (12) publications in the American continents, as indicated in Figure 2. Asia and Africa seem to lag, with Africa being the worst as it contains only two publications, while Asia has a total of six (6) publications, indicating that the technological development and the awareness regarding IR4.0 are still low.

Metrology 4.0 articles based on research type

The reviewed articles were categorised into four different research types: conceptual, case study, simulation, and experimentation. As indicated in Figure 5, conceptual articles emerge to dominate the list with twenty-one (21) articles, which is above half of the total articles reviewed. This indicates that currently, researchers are primarily focusing on conceptualising the application of IR4.0 technologies in the digital transformation of metrology in manufacturing industries. The case study also seconded the conceptual research articles, with ten (10) articles reviewed, indicating that the newly developed concepts for the digital transformation of metrology were also tested and validated through empirical studies using case studies. The last but one, nine (9) articles experiment with the developed Measurement systems, for example, the Cyber-Physical Manufacturing Metrology Model (CPM^3) and vision-based systems for use in manufacturing for error identification and compensation. Simulation is the last, with only one article reviewed indicating that the technology is not adequately employed to transform metrology digitally; thus, the need for more future research on the subject is significant.

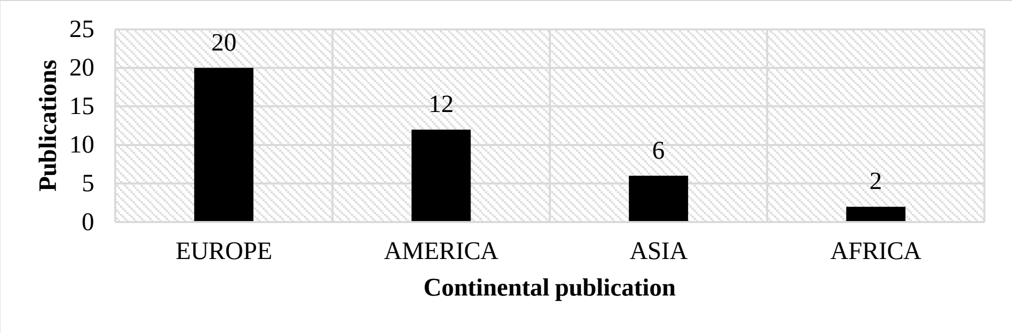

Figure 4: Continental publications distribution.

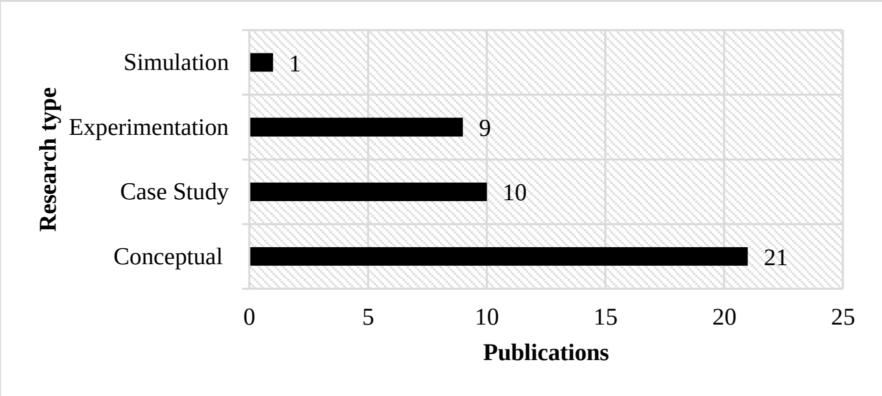

Figure 5: Publications based on research type.

Status of Digital transformation of metrology in developing countries' manufacturing industries

Digital transformation in metrology encompasses the employment of contemporary technologies of the IR4.0 linking various processes through cyber-physical systems, enabling the interconnected process, data-driven and efficient (Wieczorowski and Trojanowska, 2023; Garg *et al.*, 2021). As indicated in Figure 4, in Africa and Asia, where most of the developing countries are located, the digital transformation in metrology has almost not yet been taken into consideration. In Asia and India specifically, the realisation of digital transformation in metrology has yet to be initiated; only the conceptualisation and proposition of how the transformation could be achieved are discussed in the literature. For example, the proposition and conceptualisation of paradigms Metrology Cloud and Digital Quality Infrastructure in India and various attributes of digital transformation in metrology were discussed (Garg et al., 2021).

It has also been found that in developing countries, extensive research is being conducted focusing on the employment of IR4.0 technologies in advancing metrological operations. For example the employment of IoT technology in designing a machine vision system for defect detection in holes milled on a workpiece, the use of AI to enhance defect detection in laser semiconductor manufacturing, the employment of cloud technology to enable automatic virtual metrology as well as the employment of AI in developing a vision-based system for labelling and dimensional measurement on a shop floor (Singh et al., 2023; Saif et al., 2022; Hou et al., 2019; Hung et al., 2016). It is evident that the developing countries in Asia are a bit awakened in making an effort toward a digital transformation of metrology compared to their counterpart in Africa, where the concepts of both industry 4.0 and metrology 4.0 are nascent. Most of the contribution in Africa's developing countries focuses on unveiling the potential of the IR4.0 in various fields as exemplified by Nzumile et al. (2024). This is because most of the manufacturing industries operates within the IR3.0 as pointed out by Nhelekwa et al. (2022).

Although developing countries in Asia have already started employing IR4.0 technologies in the digital transformation of metrological operations, the standardisation challenges have yet to be resolved. This means that calibration of newly developed measurement systems and their traceability to international standards will not be feasible, leading to multiple unstandardised systems and procedures. In developed countries, despite the fact that they are also developing new measurement systems by employing IR4.0 technologies, there are also initiatives to combat the standardisation challenges, such as the European Metrology Cloud (Garg *et al.*, 2021). The cloud will be used as a metrology core platform for member states aimed at supporting and streamlining regulatory processes within the member states to get rid of technical barriers across Europe. In view of this, developing countries should focus on developing new metrology systems using the IR4.0 technologies and ensure the development of a centralised platform to harmonise and standardise various developed systems across the countries.

Sustainable digital transformation of metrology in developing countries' manufacturing industries

Sustainable digital transformation of metrology ensures a continued utilisation of the IR4.0 technologies in advancing metrological operations undertaken within the manufacturing industries, taking into consideration economic, social and environmental factors *(Martínez-Peláez et al.,* 2023). Considering the systematic literature review conducted, this study proposes a conceptual framework indicated in Figure 6 as a basis to enable developing countries to achieve a sustainable digital transformation of metrology in the manufacturing industries. The framework constitutes four main components or key players in the accomplishment, such as IR4.0 technologies, National Metrology Institute, testing and calibration laboratories, and Manufacturing Industries, as explained in the following subsections. In addition to the four constituents of the framework, the study also highlights key phases to assist manufacturing industries towards metrology 4.0 achievements.

IR4.0 technologies

The review identified multiple technologies of IR4.0 that are currently employed in the digital transformation of metrology in manufacturing industries, including AI, IoT, big data, cyber security, simulation, cloud computing, 3D printing, robotics, and virtual and augmented reality. Artificial intelligence, which deals with the simulation of human intelligence in machines to enable thinking and learning like humans, has already found its way into digitalising metrological operations. In coordinate metrology, AI is heavily utilised in the analysis of large amounts of data for pattern identification to improve the accuracy and precision of measurement systems through the employment of computer vision algorithms (Wieczorowski et al., 2023). Developing a portable, flexible, accurate and fast image classifier in semiconductor manufacturing for defect detection has already been developed through the employment of deep learning, which improves manufacturing accuracy (Hou et al., 2019). AI, through the employment of deep learning, has enabled the development of a vision-based system for capturing a good quality image of a product or process purposively to identify any variations and maintain their quality throughout the process (Singh et al., 2023). It should also be noted that the sustainable digital transformation of metrology is achieved by ensuring stakeholders involved in metrological operations also employ IR4.0 technologies to enhance their digital transformation. Organisation such as National Measurement Institute (NMI) and calibration laboratories are significantly required to transform their metrological operations digitally. To exemplify this, in developed countries, especially Europe, technologies such as big data, cloud computing, AI, and IoT have already been employed in the creation of digital quality infrastructure referred to as the European Metrology Cloud (Thiel and Wetzlich, 2019; Oppermann *et al.*, 2018). The cloud is purposively formed to harmonise the entire digital metrological operation and services in European nation's metrology institutes, such as conformity assessment, market surveillance, and verification, as well as creating a single digital market within the union (Thiel and Wetzlich, 2019). Therefore, through the IR4.0 principles such as interoperability, service-oriented, virtualisation, modularity, decentralisation, and real-time capability, the digital transformation in metrology within manufacturing industries, calibration laboratories, and National Metrology Institute can be achieved effectively.

National Metrology Institute (NMI)

The NMI is among the key players in enabling the digital transformation of metrology; in fact, it is the epicentre of the transformation. It is the one that coordinates all of the metrological operations within a particular country, coordinates with international metrology organisations, and is the initiator of any changes in the metrology industry (Shunashu and Pastory, 2020). It is generally considered to be a custodian of national measurement standards for products and services, formulates rules and regulations, enforces them to trade and commerce under the legal metrology department, as well as granting accreditation certificates to testing and calibration laboratories in the country (Garg et al., 2021; Shunashu and Pastory, 2020).

The significant role played by the NMI is demonstrated by the National Metrology Institute Germany (PTB) as an example, wherein it is responsible for preparing the quality infrastructure for a digitalised world within which metrology is part and parcel (Eichstädt, 2020). The institute has already begun the transformation, which is centred mainly on accomplishing five activities, including ensuring uniformity in metrology, sustainable usability of research results and data, development of holistic concepts for handling measurement instruments and measurement data, ensuring the sufficient and safe utilisation of digital technologies as well as making sure that there is active participation of employees in the digital transformation (Gadelrab and Abouhogail, 2021; Eichstädt, 2020). Generally, the NMI coordinates, monitors, and ensures effective metrological operations are performed in both testing and calibration laboratories as well as in the manufacturing industries. Therefore, the employment of IR4.0 technologies in the digital transformation of metrology in the institute would drastically promote sustainable transformation across various stakeholders in the country, as indicated in Figure 6.

Testing and calibration laboratories and manufacturing industries

Testing and calibration laboratories, on the other hand, link the NMI and manufacturing industries. The NMI grants accreditation certificates to testing and calibration laboratories, giving them a mandate to calibrate and verify measurement instruments used in manufacturing industries during the production process (Hackel et al., 2023; Garg et al., 2021). In the manufacturing industries, metrological operations such as measurement, testing, and inspection are performed using instruments that are required to be calibrated to maintain their accuracy and precision for quality product and service provision. Therefore, with the digital transformation of metrology, the calibration services from the laboratories will no longer be performed by requiring clients' instruments but rather, virtual and remote calibration will be employed (Cunha and Santos, 2020; Andonov and Cundeva-Blajer, 2018). Thus, the sustainable digital transformation of metrology could effectively be achieved when IR4.0 technologies are effectively employed by the three key stakeholders, such as NMI, testing and calibration laboratories, and manufacturing industries undertaking metrological operations.

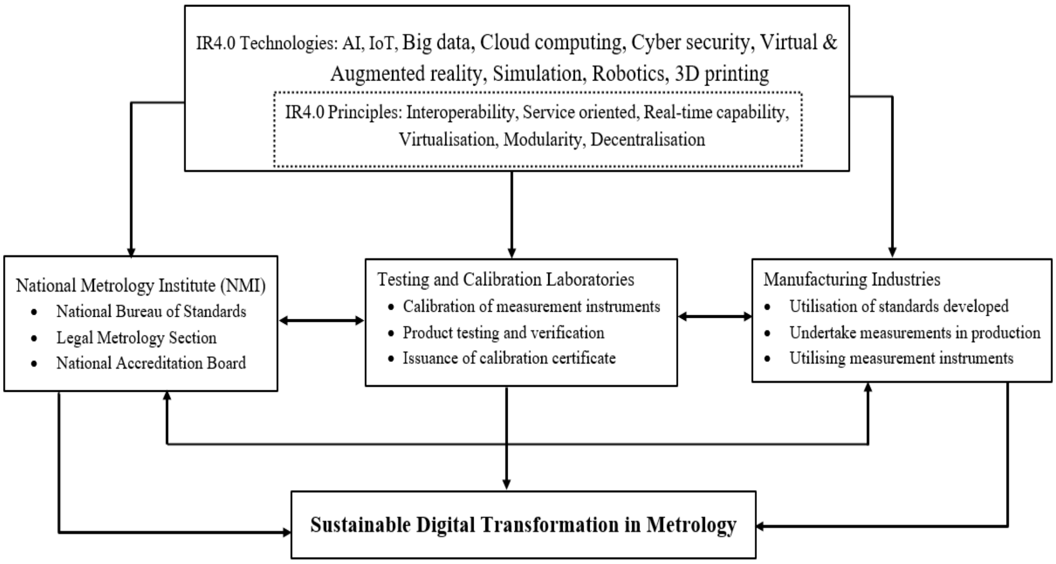

Figure 6: A conceptual Framework for Sustainable Digital Transformation in Metrology.

Phases towards metrology 4.0 in developing countries' manufacturing industries

Both NMI, testing and calibration laboratories, and IR4.0 technologies play substantial roles in achieving metrology 4.0 in manufacturing industries. It should also be noted that the three entities externally promote and influence the achievement of metrology 4.0 because they are mostly involved in modern manufacturing technologies (Wieczorowski & Trojanowska, 2023). Despite these external influences, it is critically important for the manufacturing industries to build their internal capacity and capability towards achieving metrology 4.0 in various phases. The phases include the preliminary phase, the Metrology 4.0 maturing phase and the sustainable metrology 4.0 phase, which are described in the following subsections.

Preliminary phase

Ashgar *et al.* (2020) pointed out that developing countries lag behind in implementing IR4.0 technologies mostly due to a lack of commitment and awareness, poor infrastructure, and a lack of competent workers in the digital technology aspects. The preliminary phase is further divided into two phases: the modern metrology techniques survey and the assessment of the level of preparedness towards metrology 4.0. The two phases will enable the organisation to identify the trends in advancing metrology within manufacturing industries and examine its level of preparedness towards metrology 4.0 in various aspects such as infrastructure, investment capital, labour skills, awareness and commitment. The management will decide whether to go forth with the next phase or to build the organisation's capacity and capability for metrology 4.0 following the findings from the two phases, as indicated in Figure 7.

Metrology 4.0 maturing phase

When the organisation is in good condition in terms of skilled labour, commitment, investment capital and other factors towards Metrology 4.0, the next phase is the Metrology 4.0 maturing phase. It is further divided into three phases, including the initialisation phase, the definition phase and the preparation phase. In the initialisation phase, the organisation should mainly focus on planning for strategies and conditions to implement metrology 4.0 within the organisation, which is followed by confirmation of the availability of expertise to implement the planned strategies in the definition phase. The definition phase should also consider budget allocation for metrology 4.0 implementation and integration of basic digital technologies in organisational metrological operations. In the preparation phase, the organisation has to ensure the sensitisation and dissemination of the metrology 4.0 strategy to employees in order for them to be aware. In this phase, the organisation has to be data-driven in multiple aspects, and data are digitally collected in some areas. Machines and systems should be partially integrated, and cyber security measures should be partially implemented.

Sustainable Metrology 4.0 phase

In the sustainable metrology 4.0 phase, the organisation should ensure consistent digitalisation of metrological operations and keep up to date with modern manufacturing techniques worldwide. The sustainable metrology 4.0 phase includes two phases: implementation and optimisation. In the implementation phase, the organisation has to ensure that humans and AI interact in the decision-making process regarding metrological operations. There should be advanced integration of digital technologies in various metrology aspects as well as the utilisation of autonomous measurement systems. On the other hand, in the optimisation phase, the organisation should establish external links and interfaces with other organisations to consistently share expertise and knowledge, enabling sustainability in achieving metrology 4.0. While in this phase, there should no longer be human involvement in decision-making, the measurement process, instruments and other metrological operations are autonomously accomplished. Self-calibrated instruments, touchless calibration of instruments, real-time product inspection and online conformity assessment, to mention a few, should be implemented. The entire phases to enable organisations towards metrology 4.0 are indicated in Figure 7.

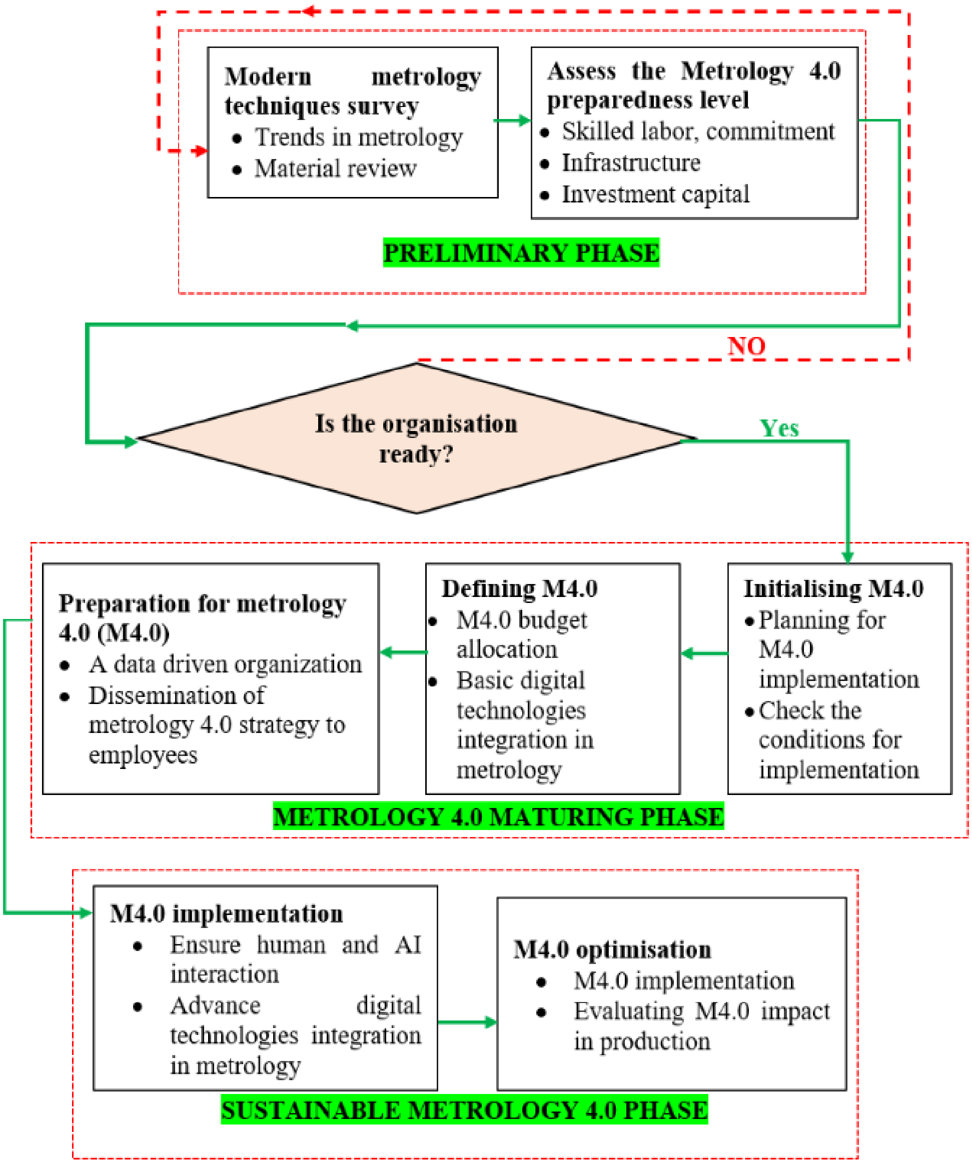

Figure 7: Phases towards metrology 4.0 for manufacturing industries.

CONCLUSION

Concluding remarks: This study aimed to establish a conceptual framework to enable the sustainable digital transformation of metrology in developing countries. A systematic literature review was conducted using the PRISMA technique, in which multiple criteria for article selection were considered, including year of publication, article category, and language used. The digital transformation of metrology in developing countries was observed to be nascent, with Africa being the least developed compared to their Asian counterpart. Even though transformation has not yet been initiated, there is immense and notable progress in digitalising metrological operations within manufacturing industries, which could later positively impact the overall digital transformation of metrology within the countries. In contrast to the developed European countries, the digital transformation of metrology has already been in place since 2017, especially in Germany, and it continues to spread across Europe to achieve a single digital market. It was also noted that for the successful digital transformation of metrology in developing countries, the key players in metrological operations, such as NMI and testing and calibration laboratories, should effectively collaborate. The collaboration should ensure both stakeholders embrace the IR4.0 technologies and utilise the technologies' potential in advancing various metrological operations undertaken by the organisation.

Implications of the Study: Based on the systematic literature review conducted, it is evident that researchers are currently focusing on innovating new techniques that utilise IR4.0 technologies in undertaking metrological operations. The conceptual framework for sustainable digital transformation in metrology contributes to the body of knowledge by revealing the potential of NMI, testing and calibration laboratories, and manufacturing industries to enable the transformation. The proposed framework can also be useful in enabling the harmonisation of metrological operations; for example, when the industry needs to calibrate measurement instruments used in production, there will be no need to move the instrument physically, but to link with the calibration laboratory to undertake calibration digitally. The digital linkage between the NMI and the calibration laboratories enhanced by IR4.0 technologies will also enable traceability of measurement standards between the NMI and calibration laboratories, eventually improving measurement accuracy and quality in developing countries' manufacturing industries.

The study further suggested the continued collaboration in research and other metrological operations between the three entities, especially on how the IR4.0 technologies could be employed in achieving the transformation sustainably. However, despite the goodness and promising future of the IR4.0 technologies adoption in developing countries' manufacturing industries, poor strategies during the adoption phases could result in an intended outcome including hacking of the industrial key competitive information, replacement of huge amounts of human labour, retarding the employee thinking capacity and lowering the innovative ability of the employee.

Study limitations: Much might have been discussed in the literature regarding the digital transformation of metrology in languages other than English, including Indian, Chinese, Japanese and others. This review is limited only to English, which is one of the limitations prompting a further review of other publications in other languages. Other publishing houses, such as Inderscience, Emerald, and Wiley, could have added substantial information to the review in addition to the information obtained from the three publishing houses considered in this study. Hence, researchers may further extend the review by considering vast publications from several publishing houses.

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