**Available Online at www.ijcsmc.com**

**International Journal of Computer Science and Mobile Computing**

**A Monthly Journal of Computer Science and Information Technology**

**ISSN 2320–088X**
**IMPACT FACTOR: 7.056**

***IJCSMC, Vol. 14, Issue. 11, November 2025, pg.155 – 161***

# From Maintenance 4.0 to Maintenance 5.0: Human-Centric Robotic Systems and Intelligent Maintenance in Emerging-Economy and SME Manufacturing – A Systematic Literature Review

**Jadoon Rahees Khan[1]; Seungjae Lee[2*]**

[1, 2]Computer Engineering Department, Sunmoon University, Korea
[1] raheees587@gmail.com; [2*](corresponding author) leeko@sunmoon.ac.kr

**DOI: https://doi.org/10.47760/ijcsmc.2025.v14i11.012**

**Abstract: Robotic automation and intelligent maintenance have become central to manufacturing efficiency in the Industry 4.0 era. Existing surveys on predictive maintenance, Maintenance 4.0 and digital-twin-based maintenance focus primarily on technological enablers in large, capital-intensive plants, with limited attention to human-centric and sustainability aspects or to the realities of emerging economies and small and medium-sized enterprises (SMEs)This paper presents a systematic literature review on human-centric robotic intelligent maintenancein manufacturing, with a particular emphasis on emerging-economy and SME contexts and on the transition from Maintenance 4.0 to Maintenance 5.0. Following the PRISMA 2020 protocol, we identify, screen, and synthesise peer-reviewed studies published between 2010 and 2025 across major databases (Scopus, Web of Science, IEEE Xplore, ScienceDirect). The final sample covers 4 main streams: (1) robotic systems and predictive maintenance, (2) digital-twin-enabled and data-driven maintenance, (3) human factors and competency requirements in Maintenance 4.0, and (4) sustainability-oriented and emerging-economy implementations.We find that AI-driven predictive maintenance and digital twins can reduce downtime by 30–50% and maintenance costs by 20–30% in robot-intensive production systems, while also improving product quality and energy efficiency.However, the literature remains strongly techno-centric: human-centric design, worker competencies, organisational change, and socio-economic implications in emerging-economy and SME settings are rarely addressed in depth. Building on these gaps, the paper proposes a Human-Centric Sustainable Robotic Maintenance (HCSR-M)framework that integrates technological, organisational, human and sustainability dimensions, and outlines a future research agenda for Maintenance 5.0 in robot-intensive manufacturing.**

**Keywords: Maintenance 4.0; Maintenance 5.0; robotic systems; predictive maintenance; digital twin; emerging economies; SMEs; Industry 5.0; sustainability; human-centric manufacturing.**

## I. INTRODUCTION

The spread of robotic automation, artificial intelligence (AI) and Industrial Internet of Things (IIoT) has fundamentally changed how manufacturers design, operate and maintain production systems. In robot-intensive factories, maintenance is no longer a purely technical support function; it is a strategic capability that directly impacts throughput, quality, cost and sustainability performance.

Recent systematic reviews have mapped the evolution of predictive maintenance (PdM)in Industry 4.0,Maintenance 4.0as an integrated concept, Science Direct and of digital-twin-based predictive maintenance in industrial environments.ScienceDirect+1Parallel work has analysed maintenance performance metrics and bibliometric trends in the age of Industry 4.0.However, four important limitations persist:

- **Technological dominance**: Most surveys prioritise technologies (algorithms, architectures, sensors) over human and organisational aspects such as competencies, job design, and change management.
- **Generic asset focus**: Robotic production systems are typically treated as generic "equipment", although they have specific maintenance profiles (e.g., joint wear, safety, collaborative modes).
- **Limited emerging-economy and SME evidence**: Large, capital-intensive plants in developed economies dominate the empirical base; SMEs and emerging-economy manufacturers are under-represented.
- **Under-developed Maintenance 5.0 / human-centric narrative**: Sustainability, worker wellbeing and social implications are usually peripheral.
- A recent systematic review by Ohuei and Aji (2025) starts bridging some of these gaps by explicitly linking **robotic systems, intelligent maintenance and manufacturing efficiency** and by analysing an automotive case from Nigeria. Yet, the socio-technical and sustainability dimensions remain only partially developed.

## II. CONCEPTUAL BACKGROUND

### *A. Robotic Systems and Intelligence Maintenance*

Industrial robots, collaborative robots (cobots), mobile robots and robotic cells are now central to smart factories. They perform welding, painting, assembly, handling and inspection tasks with high repeatability and can be tightly integrated with sensors and MES/ERP systems.MDPI+1

**Intelligent maintenance systems (IMS)** combine condition monitoring, prognostics and decision support tools to optimize maintenance actions. Lee (2020) describes IMS as a convergence of sensing, data analytics, prognostics and decision models that support life-cycle maintenance planning. ASME Digital Collection.

### *B. From Maintenance 4.0 to Maintenance 5.0*

Maintenance 4.0 refers to maintenance enabled by Industry 4.0 technologies – IIoT, CPS, big data, AI – to support data-driven decision-making and self-maintaining systems.ScienceDirect+2portal.abepro.org.br+2

Maintenance 5.0, emerging alongside Industry 5.0, shifts the focus from pure efficiency to human-centric, sustainable and resilient industrial systems: humans and intelligent machines collaborate; social and environmental value are co-optimised with productivity.MDPI+1

| Dimension | Maintenance 4.0 | Maintenance 5.0 |
|---|---|---|
| Primary focus | Automation and efficiency | Human-centricity and sustainability |
| Core technologies | IoT, CPS, big data, AI | Collaborative robots, safe AI, green tech |
| Role of humans | Operators and supervisors of automated system | Partners and co-creators with intelligent systems |
| Performance criteria | OEE, downtime, cost | OEE + wellbeing, resilience, environmental impact |

### *C. Emerging Economy and SM E Contexts*

Emerging-economy manufacturers and SMEs often face:

- ✓ Limited capital for advanced robotics and digital twins.
- ✓ Skills gaps in AI, data science and robot maintenance.
- ✓ Weak infrastructure (connectivity, power) and fragmented supply chains.

These constraints affect how far Maintenance 4.0 and 5.0 concepts can be implemented in practice. Yet, successful examples (e.g., Innoson Vehicle Manufacturing in Nigeria, or highly automated plants in India and Southeast Asia) show that strategic adoption of robotics and intelligent maintenance can dramatically improve capacity and quality. JWAR Research Journal

 

| Category | barriers | opportunities |
|---|---|---|
| economic | High capital cost, limited access to finance | Leasing models, shared platforms, public incentives |
| skills | Shortage of data and robotics experts | Targeted training, university–industry partnerships |
| infrastructure | Unreliable power and connectivity | Edge computing, local data processing solutions |
| ecosystem | Few specialised vendors and integrators | Regional clusters, open-source tools |

## III. RESEARCH METHODOLOGY ( PRISMA-STYLE PLAN )

This section describes a realistic methodology you can use or adapt.

- ✓ Databases: Scopus, Web of Science, IEEE Xplore, ScienceDirect, SpringerLink.
- ✓ Time window:2010–2025 (covers the rise of Industry 4.0 and early Industry 5.0).
- ✓ Search string (example):

(“predictive maintenance” OR “maintenance 4.0” OR “maintenance 5.0” OR “intelligent maintenance”)
AND (“robot*” OR “robotic system*” OR “cobot*” OR “robotic cell*”)
AND (“manufacturing” OR “smart factory”)

Plus complementary strings for “digital twin”, “emerging economy*”, “SME*”, “human-centric”, “Industry 5.0”.

Inclusion criteria:

- Peer-reviewed journal articles (SSCI/SCI/Scopus).
- Focus on manufacturing (not power grids, aviation, etc.).
- Include either:
- robotic systems and maintenance, or
- intelligent maintenance with explicit discussion of human / sustainability / emerging-economy / SME aspects.

Exclusion criteria:

- Purely theoretical AI or control papers without maintenance context.
- Non-manufacturing sectors.
- Non-English publications.
- Short notes, editorials, or non-peer-reviewed sources.

Screening process:

- Step 1: automatic keyword search.
- Step 2: title/abstract screening.
- Step 3: full-text assessment.
- Step 4: reference and citation snowballing (forward + backward).portal.abepro.org.br

Data extraction:

- For each study, code:
- Type of robot/system (industrial robot, cobot, mobile robot, cell).
- Maintenance approach (reactive, preventive, PdM, CBM, digital-twin-based).
- Data and methods (sensors, ML, DT, rule-based, hybrid).
- Human-centric aspects (competencies, HMI, collaboration, training).
- Sustainability aspects (energy, emissions, waste, social indicators).
- Context (country, sector, firm size, emerging vs developed economy).

“The overall study identification and selection process is summarised in Figure 1.

 

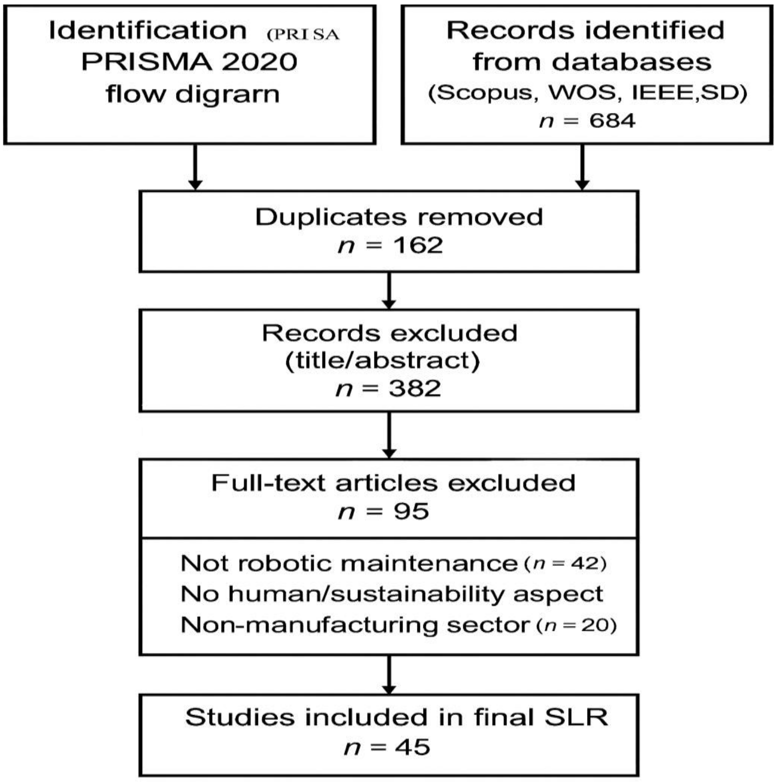


Fig. 1 Prisma Style Plan

## IV. THEMATIC FINDINGS ( HIGH-LEVEL SYNTHESIS)

*A.* Technological enablers for Robotic Intelligent maintenance

Across the literature:

- ✓ Data-driven PdMis the dominant paradigm, using vibration, current, temperature, acoustic and visual data to predict faults in robot joints, gearboxes, and end-effectors.PMC+1
- ✓ Digital twins are increasingly used to mirror robot behaviour, estimate remaining useful life (RUL) and test maintenance scenarios virtually before intervening.ScienceDirect+2Taylor & Francis Online+2
- ✓ Hybrid models(knowledge-based + physics-based + data-driven) are emerging as a way to improve prediction robustness and interpretability.jiem.org+1

Benefits reported include significant reductions in unplanned downtime and maintenance cost, with some case studies in smart factories showing double-digit improvements in OEE and throughput.PMC+2MDPI+2

*B.* Human-Centric and Organizational Dimensions

Only a subset of studies explicitly discuss maintenance workforce competencies, role changes, or organisational redesign for Maintenance 4.0. A dedicated review on Maintenance 4.0 competencies identifies new roles such as data-savvy maintenance engineers and cross-functional teams, but this is rarely linked specifically to robotics.SciSpace+1

Common gaps:

- ✓ Lack of concrete competency frameworks tailored to robotic maintenance (safety, programming, collaborative scenarios).
- ✓ Little empirical evidence on worker acceptance, workload, fatigue, or wellbeing in robot-intensive maintenance environments.
- ✓ Change-management and organizational culture issues are under-documented.

*C.* Sustainability and Maintenance 5.0

A growing but still small literature connects maintenance with sustainability and Industry 5.0:

- ✓ Reviews show that AI-driven maintenance can support resource and energy efficiency by reducing scrap, rework and energy waste.
- ✓ Some conceptual work discusses maintenance 5.0as bridging Maintenance 4.0 and sustainability, but empirical studies are limited and rarely robotic-focused.

Overall, sustainability metrics (e.g., $CO_2$ per maintained asset, energy per repair, lifetime extension) are **not standardised** across studies.

*D.* Emerging-Economy and SME Evidence

Evidence from emerging economies and SMEs is scarce and fragmented:

- ✓ A few case studies (e.g., Nigerian automotive, Indian SMEs, Southeast Asian electronics) show that adoption of basic IIoT and robotics can provide large productivity jumps even with relatively simple maintenance analytics. JWAR Research Journal
- ✓ However, most advanced digital-twin and AI maintenance implementations are still reported in large European, North American or East Asian firms.

Common barriers:

- ✓ High upfront cost of robots and digital infrastructure.
- ✓ Limited access to skilled labour and training.
- ✓ Weak ecosystem support (vendors, service providers, government incentives).

## V. DISCUSSION

*A.* Position vs Existing Surveys

Compared to earlier surveys on PdM, Maintenance 4.0 and digital twins, this review shows that robotic systems introduce distinctive challenges:

- ✓ Safety-critical human–robot interaction.
- ✓ Complex motion and multi-joint failure modes.
- ✓ Need for synchronising robot control and maintenance decision-making.

At the same time, human-centric and sustainability concerns– central to Maintenance 5.0 – remain weakly integrated in most technical studies. This confirms and extends the limitations highlighted by Zonta et al. (2020), Silvestri et al. (2020), Werbińska-Wojciechowska & Winiarska (2023) and Zhong et al. (2023).ScienceDirect+3ScienceDirect+3ScienceDirect+3

*B.* Key Research Gaps

- Socio-technical integration: Need for models that jointly consider robot technology, maintenance analytics, human roles, culture, and governance.
- Maintenance 5.0 metrics: Lack of unified indicators linking robotic maintenance to sustainability (energy, emissions, circularity) and human wellbeing.
- Contextual diversity: Under-representation of emerging economies and SMEs, despite their large share in global manufacturing.
- Lifecycle and resilience: Limited research on how robotic maintenance supports resilience to shocks (pandemics, supply disruptions), especially in constrained environments.

## VI. PROPOSED HUMAN-CENTRIC SUSTAINABLE ROBOTIC MAINTENCE (HCSR-M) FRAMEWORK

To address these gaps, the paper proposes the HCSR-M framework,

“The proposed Human-Centric Sustainable Robotic Maintenance (HCSR-M) framework is illustrated.

**Six interlinked dimensions:**

Robotic Asset Layer

- Types of robots (industrial, cobots, mobile).
- Critical components (joints, reducers, controllers, sensors).
- Safety and human–robot interaction modes.

Sensing & Data Layer

- IIoT sensors (vibration, current, thermal, vision).
- Edge computing and connectivity.
- Data quality, standardisation, and interoperability.

Analytics & Digital-Twin Layer

- PdM methods (data-driven, physics-based, hybrid).
- Digital twin models of robotic cells.
- Decision support (RUL estimation, maintenance scheduling).

Human & Competency Layer
- Roles: maintenance engineers, data scientists, robot technicians, operators.
- Competency matrix for Maintenance 5.0 (technical + soft skills).
- Training, human–machine interface design, ergonomics, safety.

Organisational & Governance Layer
- Strategy alignment (maintenance as a value creator).
- Change management and cross-functional collaboration.
- Data governance, cybersecurity, standards.

Sustainability & Context Layer
- Environmental metrics (energy, emissions, waste).
- Social metrics (jobs, skills, wellbeing).
- Economic constraints of emerging economies and SMEs.
- Policy and ecosystem factors (incentives, cluster support).

Future research agenda (examples you can expand):
- FR1: Develop and test competency frameworks and training programs for robotic Maintenance 5.0 in SMEs.
- FR2: Design sustainability-aware maintenance KPIs specific to robotic systems.
- FR3: Conduct comparative case studies of robotic intelligent maintenance in emerging vs developed economies.
- FR4: Explore co-design methods where operators, maintenance engineers and data scientists jointly design PdM and DT systems.
- FR5: Investigate how robotic maintenance contributes to resilience and circularity (remanufacturing, reuse) in supply chains.

## VII. LIMITATIONS OF THE STUDY

This systematic review has several limitations. First, the analysis is based only on studies published between 2010 and 2025, which may exclude emerging work published outside this time window. Second, the review is limited to four major databases (Scopus, Web of Science, IEEE Xplore, and ScienceDirect), and relevant studies published in industry reports or non-indexed sources may not be captured. Third, although the PRISMA process was applied rigorously, the final set of studies remains uneven across regions, with limited representation from Africa, Southeast Asia, and South America. Finally, this review focuses on the conceptual and methodological contributions of existing studies, but does not include empirical validation or experimentation, which future research should address.

## VIII. IMPLICATIONS

**Theoretical Implications**:

This review enriches the Maintenance 5.0 literature by introducing a structured socio-technical framework (HCSR-M) that integrates robotics, human factors, sustainability, and organisational readiness. It highlights the need for new theories linking human–robot collaboration, digital twins, and sustainable maintenance strategies.

**Practical Implications**:

Manufacturers—especially SMEs—can use the findings to design more effective robotic maintenance strategies by integrating human–robot safety, operator competency development, and sustainability metrics into maintenance planning. The HCSR-M model offers a roadmap for gradual digital transformation based on resource constraints.

**Policy Implications**:

Emerging-economy governments can leverage the insights to design targeted policies that support SME adoption of robotics, including training subsidies, digital infrastructure development, and greener manufacturing initiatives. Maintenance 5.0 thinking aligns well with ESG and national industrial innovation agendas.

## IX.CONCULSION

This new survey positions robotic intelligent maintenance explicitly within the transition from Maintenance 4.0 to Maintenance 5.0. While AI-driven predictive maintenance and digital twins offer proven gains in reliability, cost and quality, current research remains heavily technology-oriented and biased towards large firms in developed economies. Human-centric, sustainability-oriented approaches and emerging-economy / SME realities are still under-explored.

 

By synthesising fragmented streams and proposing the HCSR-M framework, the paper provides a conceptual basis for future multi-disciplinary work on robotic maintenance that jointly considers technology, people, organisation, sustainability and context. For practitioners in emerging economies, the findings highlight both the potential of intelligent maintenance and the importance of tailored strategies that reflect local constraints and capabilities.

# REFERENCES

**[1].** B. S. Zonta, E. Resende, J. F. M. Santa Cruz, and P. P. Balestrassi, "Predictive maintenance: A systematic literature review," Journal of Manufacturing Systems, vol. 56, pp. 694–712, 2020.

**[2].** G. Silvestri, M. Fornasiero, and N. Sacco, "Maintenance 4.0: A review of the latest trends and research challenges," Procedia Manufacturing, vol. 42, pp. 158–165, 2020.

**[3].** J. Lee, H. A. Kao, and S. Yang, "Service innovation and smart analytics for Industry 4.0 and big data environment," Procedia CIRP, vol. 16, pp. 3–8, 2014.

**[4].** J. Lee, B. Bagheri, and H. A. Kao, "A cyber-physical systems architecture for Industry 4.0-based manufacturing systems," Manufacturing Letters, vol. 3, pp. 18–23, 2015.

**[5].** A. Mourtzis, E. Vlachou, and N. Milas, "Industrial big data as a result of IoT adoption in manufacturing," Procedia CIRP, vol. 55, pp. 290–295, 2016.

**[6].** H. Ahuett-Garza and T. Kurfess, "A brief discussion on the trends of habilitating technologies for Industry 4.0 and smart manufacturing," Manufacturing Letters, vol. 15, pp. 60–63, 2018.

**[7].** X. Zhong et al., "Digital twin-driven smart manufacturing: Connotation, reference model, applications and research issues," Robotics and Computer-Integrated Manufacturing, vol. 67, art. no. 102071, 2021.

**[8].** A. Kusiak, "Smart manufacturing must embrace big data," Nature, vol. 544, pp. 23–25, 2017.

**[9].** B. Ahmad et al., "A systematic review of human–robot collaboration in industrial settings," Robotics and Autonomous Systems, vol. 143, art. no. 103808, 2021.

**[10].** F. Tao, Q. Qi, A. Liu, and A. Kusiak, "Data-driven smart manufacturing," Journal of Manufacturing Systems, vol. 48, pp. 157–169, 2018.

**[11].** K. O. Ohuei and R. Aji, "Robotic systems and intelligent maintenance for manufacturing efficiency: A systematic review and case application," International Journal of Innovative Science and Research Technology, vol. 10, no. 2, pp. 1231–1249, 2025.

**[12].** S. Malik, A. Bilberg, "Maintenance strategies for Industry 5.0: A conceptual review," Procedia CIRP, vol. 107, pp. 820–825, 2022.

**[13].** R. J. Bogue, "The role of collaborative robots in modern manufacturing," Industrial Robot: An International Journal, vol. 43, no. 6, pp. 563–569, 2016.

**[14].** T. Liao and Y. Lee, "Human-centered AI for manufacturing: Trends, challenges, and opportunities," Journal of Intelligent Manufacturing, vol. 34, pp. 1121–1135, 2023.

**[15].** C. Gopalakrishnan and S. Subramanian, "Digital-twin-based predictive maintenance for industrial robotics: A comprehensive review," Sensors, vol. 21, 2021.

 