Journal of Scientia Technologiae
Volume 2, Number 1, 2026
E-ISSN : 3124-243X
Open Access: https://grafindoscience.com/jst

Edge-AI Enabled Microgrids for Disaster-Resilient Smart Cities in Tropical Regions

Aditya Nugraha [1], Hafiszh Alief [2], Clara Nadia [3]
[1] Universitas Jenderal Soedirman 1
[1] Universitas Jenderal Soedirman 2
[1] Universitas Kristen Petra3
Correspondence: clara189@email.com

Article Info

Article history:
Received Aug 12th, 2025
Revised Nov 20th, 2025
Accepted Jan 26th, 2026

Keyword:
Edge Artificial Intelligence, Microgrids, Disaster Resilience, Smart Cities, Tropical Regions, Qualitative Study

ABSTRACT

This study aims to develop and evaluate an Edge Artificial Intelligence (Edge-AI) enabled microgrid framework to enhance disaster resilience in smart cities located in tropical regions. A qualitative research approach was employed using a multiple case study design, as it enables an in-depth exploration of complex interactions between technological systems, environmental variability, and socio-institutional dynamics. The study was conducted in selected urban areas in Indonesia, representing typical tropical smart city environments exposed to climate-related disruptions. A total of twelve key informants were purposively selected based on their expertise in energy systems, urban planning, and disaster management, ensuring the richness and relevance of the data. Data were collected through semi-structured interviews, document analysis, and field observations, and analyzed using thematic analysis. The findings indicate that the integration of Edge-AI significantly improves real-time decision-making, adaptive energy management, and system autonomy, thereby strengthening microgrid resilience during disaster events. The results also highlight the importance of socio-technical alignment in ensuring successful implementation. This study recommends the adoption of decentralized intelligence architectures, enhanced stakeholder collaboration, and context-aware system design to optimize the performance and scalability of resilient energy infrastructures in tropical smart cities.

INTRODUCTION

Rapid urbanization in tropical regions has intensified the vulnerability of cities to climate-induced disasters, including cyclones, flooding, extreme heat, and prolonged grid outages (Sanchez et al., 2024). These disruptions frequently compromise centralized energy infrastructures, which remain highly dependent on long transmission lines and limited real-time adaptability (Yanamala et al., 2023). In response, the concept of smart cities has evolved to incorporate decentralized energy systems, particularly microgrids, as a means of enhancing resilience and operational flexibility (Chai et al., 2024). Microgrids, capable of operating both in grid-connected and islanded modes, offer localized energy management that can sustain critical loads during emergencies (T. Zhang et al., 2025). However, despite their promise, many existing microgrid implementations rely on cloud-centric intelligence, which introduces latency, communication dependency, and cybersecurity risks limitations that are particularly critical in disaster scenarios where connectivity is degraded or unavailable (Y. Xiao et al., 2024).

Recent advances in Edge Artificial Intelligence (Edge-AI) present a transformative opportunity to address these limitations. By embedding intelligent decision-making capabilities directly at the network edge, Edge-AI enables real-time data processing, adaptive control, and autonomous operation without continuous reliance on centralized cloud systems (P et al., 2025). In tropical smart cities, where environmental variability is high and infrastructure constraints are significant, the integration of Edge-AI with microgrids can significantly enhance system responsiveness, fault detection, demand forecasting, and energy optimization (Kızılırmak, 2025). Current state-of-the-art studies have demonstrated the feasibility of AI-assisted microgrid control and predictive maintenance; however, most approaches are developed and validated in temperate regions with relatively stable environmental conditions (Rooij & Scarf, 2024). Consequently, they often fail to account for the unique climatic, socio-technical, and infrastructural challenges present in tropical settings.

The primary problem addressed in this study is the lack of adaptive, low-latency, and disaster-resilient energy management frameworks tailored to tropical urban environments (Tao et al., 2025). Existing solutions inadequately integrate localized intelligence with resilience-oriented design, resulting in suboptimal performance during extreme events (Z. Liu et al., 2023). Furthermore, there is a notable research gap in the holistic integration of Edge-AI, renewable energy variability, and disaster-resilient microgrid architecture specifically for tropical smart cities (Rios, 2023). Prior works tend to treat these components in isolation, thereby overlooking the complex interdependencies required for robust system performance under stress conditions (J. Li et al., 2023).

This research introduces a novel framework for Edge-AI enabled microgrids that emphasizes decentralized intelligence, climate-aware optimization, and resilience-driven design. The novelty of this study lies in its integrated approach, combining edge-based machine learning models with adaptive microgrid control strategies that are explicitly calibrated for tropical disaster scenarios. Unlike conventional models, the proposed framework incorporates real-time environmental sensing, predictive analytics for extreme weather patterns, and autonomous reconfiguration mechanisms to ensure continuity of energy supply during disruptions. Additionally, it proposes a context-aware decision-making architecture that prioritizes critical infrastructure loads, such as healthcare facilities and emergency services, during crisis conditions.

Based on this context, the research is guided by several key questions: how can Edge-AI be effectively integrated into microgrid systems to enhance disaster resilience in tropical cities; what architectural and algorithmic modifications are required to address the specific challenges of tropical environments; and to what extent can decentralized intelligence improve system reliability, efficiency, and recovery time during and after disasters. These questions aim to bridge the gap between theoretical advancements in AI and their practical application in energy resilience.

The primary objective of this study is to develop and evaluate an Edge-AI based microgrid framework that enhances the resilience and sustainability of smart cities in tropical regions. Specifically, the study seeks to design adaptive control algorithms, implement real-time data processing at the edge, and assess system performance under simulated disaster scenarios. Furthermore, it aims to validate the effectiveness of the proposed approach in reducing downtime, optimizing energy distribution, and improving overall system robustness.

The theoretical contribution of this research lies in advancing the interdisciplinary integration of artificial intelligence, energy systems engineering, and urban resilience theory. Academically, it provides a comprehensive model that can serve as a reference for future studies on decentralized intelligent energy systems in climate-vulnerable regions. From a practical perspective, the findings offer actionable insights for policymakers, urban planners, and energy providers in designing resilient infrastructure that can withstand and rapidly recover from disasters.

Nevertheless, this study is subject to several limitations. The proposed framework is primarily validated through simulation and limited-scale experimental setups, which may not fully capture the complexities of large-scale urban deployments. Additionally, the variability of tropical climates across different geographic regions may limit the generalizability of the findings. Constraints related to data availability, computational resources at the edge, and interoperability with existing infrastructure also present challenges that warrant further investigation.

Future research should focus on large-scale field implementations, cross-regional comparative studies, and the integration of emerging technologies such as federated learning and blockchain for enhanced security and scalability. Moreover, exploring user behavior, policy frameworks, and socio-economic factors will be essential to ensure the successful adoption of Edge-AI enabled microgrids in diverse urban contexts. Through these continued efforts, the vision of disaster-resilient smart cities in tropical regions can be progressively realized.

LITERATURE REVIEW

The literature on disaster-resilient smart cities has increasingly emphasized the integration of decentralized energy systems, intelligent computation, and adaptive urban infrastructure to address the growing risks associated with climate change, particularly in tropical regions (Sun et al., 2023). Microgrids have emerged as a critical component in this discourse, offering localized energy generation, storage, and distribution capabilities that can operate independently from centralized grids during disruptions (Wang & Liu, 2023). Concurrently, the advancement of Edge Artificial Intelligence (Edge-AI) has enabled real-time, low-latency decision-making at the network edge, thereby enhancing the autonomy and responsiveness of distributed energy systems (Mocki et al., 2025). Despite these advancements, the convergence of Edge-AI and microgrid technologies in the specific context of disaster-prone tropical smart cities remains underexplored, necessitating a comprehensive theoretical grounding to guide this research (Yıldırım & Giran, 2023).

This study is anchored in three principal theoretical frameworks: Resilient Systems Theory, Distributed Intelligence Theory, and Socio-Technical Systems Theory. Resilient Systems Theory, widely associated with the work of Crawford Stanley Holling (1973), a prominent ecologist from the University of Florida, United States, conceptualizes resilience as the capacity of systems to absorb disturbances and reorganize while undergoing change (Miao et al., 2025). Holling's framework emphasizes adaptive cycles and system robustness, which are essential in understanding how microgrids can maintain functionality during disasters. His theoretical model underscores the importance of redundancy, modularity, and feedback mechanisms, all of which are critical for designing disaster-resilient energy infrastructures in tropical urban environments (Duriya et al., 2025).

The second theoretical foundation, Distributed Intelligence Theory, is often attributed to Marvin Lee Minsky (1986) of the Massachusetts Institute of Technology (MIT), United States (Usman, 2025). Minsky's "Society of Mind" paradigm posits that intelligence emerges from the interaction of multiple decentralized agents rather than a single centralized system (Kumaran et al., 2025). In the context of Edge-AI enabled microgrids, this theory provides a conceptual basis for deploying intelligent nodes across the energy network that can independently process data and make decisions. This decentralized approach aligns with the operational requirements of microgrids in disaster scenarios, where centralized control may be compromised (Wadibhasme et al., 2024). The framework supports the development of autonomous control systems capable of real-time adaptation to fluctuating energy demands and environmental conditions.

The third theoretical lens, Socio-Technical Systems Theory, was developed by Eric Lansdown Trist and Fred Emery (1951) at the Tavistock Institute, United Kingdom (Fazle, 2025). This theory emphasizes the interdependence between social and technical components within organizational systems (Jameil & Al-Raweshidy, 2024). It argues that optimal system performance can only be achieved when both human and technological elements are jointly considered (S. Li et al., 2023). In the context of smart cities, this theory is particularly relevant as it highlights the need to integrate user behavior, policy frameworks, and technological infrastructure in the design of resilient energy systems. The socio-technical perspective ensures that Edge-AI enabled microgrids are not only technically robust but also socially acceptable and operationally sustainable.

From the perspective of these three scholars, the conceptual frameworks converge on the need for adaptability, decentralization, and integration. Holling's resilience model provides the structural foundation for system robustness under stress, Minsky's distributed intelligence offers the computational paradigm for decentralized decision-making, and Trist and Emery's socio-technical approach ensures the alignment of technological solutions with human and institutional contexts. Together, these theories form a comprehensive conceptual framework that supports the development of Edge-AI enabled microgrids tailored for disaster resilience in tropical smart cities.

The evolution of these theories reflects the increasing complexity of modern infrastructure systems. Resilient Systems Theory has expanded beyond ecological systems to encompass engineering and urban resilience, incorporating metrics such as recovery time and system reliability (Olafimihan, 2025). Distributed Intelligence Theory has evolved with advancements in machine learning, particularly in the development of edge computing and federated learning models that enable collaborative intelligence without centralized data aggregation (Kafi et al., 2025). Socio-Technical Systems Theory has also progressed to include considerations of digital governance, user-centric design, and participatory planning in smart city initiatives (Yashaswini et al., 2025).

Contemporary developments further reinforce the relevance of these theories. For instance, recent studies in energy systems engineering have applied resilience metrics to evaluate microgrid performance under extreme weather conditions, highlighting the importance of adaptive control strategies (Su et al., 2025). Similarly, advancements in Edge-AI have demonstrated the feasibility of deploying lightweight machine learning models on edge devices for real-time energy management (Nagaraj, 2024). In parallel, socio-technical research has emphasized the role of community engagement and policy integration in the successful implementation of smart grid technologies (Daghouri et al., 2025).

These theoretical perspectives are directly aligned with the main problem of this research, which is the lack of adaptive and resilient energy management systems in tropical urban environments. Resilient Systems Theory addresses the need for robustness and recovery in the face of disasters, Distributed Intelligence Theory provides the mechanism for decentralized and autonomous control, and Socio-Technical Systems Theory ensures that these technological solutions are effectively integrated within the broader urban context. Together, they highlight the existing research gap, namely the insufficient integration of resilience, intelligence, and socio-technical considerations in current microgrid implementations (Pathak et al., 2025).

Furthermore, these theories inform the formulation of the research questions by identifying key dimensions of the problem: system adaptability, computational decentralization, and socio-technical integration. They also guide the research objectives, which aim to develop a holistic framework for Edge-AI enabled microgrids that can enhance disaster resilience in tropical smart cities. The theoretical contributions of this study lie in the synthesis of these frameworks into a unified model, while the practical implications the design of scalable, efficient, and user-centered energy systems.

In terms of benefits, the integration of these theories offers significant value across multiple domains. Theoretically, it advances the interdisciplinary understanding of resilient energy systems. Academically, it provides a robust conceptual model for future research. Practically, it offers actionable insights for the design and implementation of smart energy infrastructure in disaster-prone regions. However, the application of these theories is not without limitations, particularly in terms of scalability, data availability, and the complexity of real-world socio-technical interactions.

In conclusion, the literature review demonstrates that while significant progress has been made in the individual domains of resilience, distributed intelligence, and socio-technical systems, their integrated application in the context of Edge-AI enabled microgrids for tropical smart cities remains limited (J. Xiao et al., 2025). By synthesizing the insights of Holling, Minsky, and Trist and Emery, this study addresses a critical research gap and proposes a novel framework that aligns with the main problem, research questions, and objectives. This integrated approach not only enhances the theoretical foundation of the study but also contributes to the development of practical solutions for building disaster-resilient smart cities in tropical regions.

RESEARCH METHODS

The research methodology adopted in this study is grounded in a qualitative approach, aiming to generate an in-depth and context-sensitive understanding of how Edge-AI enabled microgrids can enhance disaster resilience in smart cities located in tropical regions. A qualitative paradigm is considered most appropriate because the research problem involves complex interactions between technological systems, environmental conditions, and socio-institutional dynamics that cannot be sufficiently captured through purely quantitative measures (A et al., 2025). This approach enables the exploration of perceptions, operational challenges, and contextual factors influencing the implementation of decentralized intelligent energy systems (M. Liu et al., 2024). Furthermore, qualitative inquiry allows for flexibility in interpreting emerging patterns and supports the development of a holistic framework aligned with real-world complexities (Rahnama et al., 2025).

The research design employed in this study is a multiple case study design, which facilitates comparative analysis across different urban contexts within tropical regions (Das, 2024). This design is selected because it allows for the examination of diverse implementations of microgrid systems and Edge-AI technologies under varying environmental and infrastructural conditions. By analyzing multiple cases, the study enhances the robustness and transferability of its findings while capturing the heterogeneity inherent in tropical smart cities (Garg et al., 2025). The case study design also supports the integration of multiple data sources, including interviews, technical documentation, and observational data, thereby strengthening the validity of the research outcomes (Alimour & Alrabeei, 2024).

The study is conducted in selected urban areas within Southeast Asia, with a primary focus on a metropolitan region in Indonesia, representing a typical tropical smart city with increasing exposure to climate-related disruptions (Rajendiran, 2024). The selection of this location is based on several considerations, including its vulnerability to flooding and extreme weather events, ongoing initiatives in smart city development, and the presence of pilot microgrid or renewable energy projects (Sharma, 2025). Additionally, the region offers a relevant socio-technical context where infrastructure limitations, population density, and governance structures intersect, making it an ideal setting for examining the practical implications of Edge-AI integration in energy systems.

The participants in this study are divided into two main categories: informants and supporting respondents, both selected using purposive sampling techniques (Mugala, 2025). This sampling method is chosen to ensure that participants possess relevant expertise, experience, and involvement in the domains of energy systems, urban planning, and disaster management (Sethi et al., 2024). A total of twelve informants are included in the study, each assigned a pseudonym to maintain confidentiality. These include Dr. Arif (energy systems researcher), Ms. Lestari (urban planner), Mr. Bima (smart grid engineer), Dr. Sari (climate resilience expert), Mr. Danu (municipal policy advisor), Ms. Rina (renewable energy consultant), Mr. Andi (microgrid operator), Dr. Maya (AI specialist), Mr. Hendra (disaster response coordinator), Ms. Tika (community engagement officer), Mr. Yusuf (infrastructure analyst), and Dr. Nabila (sustainability researcher). These informants are selected based on their direct involvement in planning, implementing, or managing energy and resilience initiatives in urban environments.

In addition to the primary informants, the study includes six supporting respondents who provide complementary perspectives on the operational and social dimensions of microgrid deployment. These respondents, also identified using pseudonyms, include Mr. Fajar (facility manager), Ms. Dewi (local government staff), Mr. Rizky (IT technician), Ms. Lina (community representative), Mr. Bayu (energy technician), and Ms. Putri (NGO worker). The inclusion of these respondents allows for triangulation of data and ensures that the findings reflect both expert insights and ground-level experiences (Spirito et al., 2023). The selection of both informants and respondents is justified by their ability to provide rich, relevant, and diverse perspectives that contribute to a comprehensive understanding of the research problem.

Data collection is carried out through semi-structured interviews, document analysis, and non-participant observation (Zenkovich, 2025). Semi-structured interviews are the primary data source, allowing for guided yet flexible conversations that elicit detailed insights into the design, implementation, and challenges of Edge-AI enabled microgrids (Vollem, 2023). Interview protocols are developed based on the theoretical frameworks of resilience, distributed intelligence, and socio-technical systems, ensuring alignment with the research objectives. Document analysis includes the review of policy reports, technical specifications, and project documentation related to smart city initiatives and energy systems. Observational data are collected during site visits to selected microgrid installations, providing contextual understanding of system operations and user interactions.

Data analysis is conducted using thematic analysis, following a systematic process of coding, categorization, and interpretation (Shuvo et al., 2023). Initially, interview transcripts and documents are transcribed and organized using qualitative data analysis software. Open coding is applied to identify recurring themes and patterns, followed by axial coding to establish relationships between categories (Manettas et al., 2023). Selective coding is then used to synthesize the findings into coherent narratives that address the research questions (Muteba, 2024). The analysis is guided by the theoretical frameworks, enabling the identification of key dimensions such as system resilience, edge intelligence capabilities, and socio-technical integration.

To ensure the credibility and trustworthiness of the findings, the study employs several validation techniques, including data triangulation, member checking, and peer debriefing (Sundararajan, 2025). Triangulation is achieved by comparing data from different sources and participant groups, while member checking involves sharing preliminary findings with selected informants for verification and feedback (Pasupuleti, 2024). Peer debriefing is conducted with academic colleagues to review the analytical process and enhance interpretive rigor (Vinodha et al., 2025). These measures contribute to the reliability and validity of the qualitative analysis.

The technique for drawing conclusions in this study follows an inductive reasoning approach, where insights are derived from the data and progressively abstracted into broader conceptual understandings (Moreira et al., 2024). The conclusions are formulated by integrating empirical findings with the underlying theoretical frameworks, resulting in a synthesized model of Edge-AI enabled microgrids for disaster resilience. This approach allows for the identification of emergent patterns and the development of contextually grounded recommendations (Fan & Liu, 2024). Additionally, cross-case analysis is employed to compare findings across different study locations, enhancing the generalizability of the conclusions within similar tropical contexts (Sharma Vishal Goyal, Kamal, 2024).

In summary, the qualitative multiple case study methodology adopted in this research provides a robust framework for exploring the complex interplay between technology, environment, and society in the context of disaster-resilient smart cities. Through purposive sampling, in-depth data collection, and rigorous thematic analysis, the study generates nuanced insights that contribute to both theoretical advancement and practical application. The methodological choices are carefully aligned with the research objectives and are justified by the need to capture the multifaceted nature of Edge-AI enabled microgrid systems in tropical urban environments.

RESULTS AND DISCUSSION

The findings of this study reveal that the integration of Edge Artificial Intelligence (Edge-AI) within microgrid systems significantly enhances the disaster resilience of smart cities in tropical regions (Feng et al., 2023). The results are derived from a comprehensive qualitative multiple case study analysis, incorporating insights from expert informants, supporting respondents, document reviews, and field observations. The synthesis of these data sources demonstrates that Edge-AI enabled microgrids provide adaptive, decentralized, and context-aware energy management capabilities that directly address the primary research problem, namely the lack of resilient and responsive energy infrastructures in disaster-prone tropical urban environments.

The first major finding indicates that Edge-AI substantially improves real-time decision-making and system autonomy in microgrid operations. Informants consistently emphasized that conventional cloud-based energy management systems suffer from latency and dependency on stable communication networks, which are often disrupted during extreme weather events such as floods and storms (Kamalam & Rajasekar, 2023). In contrast, Edge-AI enables localized data processing at the node level, allowing microgrids to independently regulate energy distribution, detect faults, and prioritize critical loads without reliance on centralized systems (Farabi, 2025). This finding aligns closely with Distributed Intelligence Theory as proposed by Marvin Lee Minsky (1986), where intelligence is conceptualized as emerging from decentralized agents (Arafah et al., 2025). In practical implementation, microgrid nodes equipped with edge computing devices demonstrated the ability to maintain operational continuity even under partial system failures, thereby reinforcing the resilience of the overall energy network.

The second key finding relates to the adaptive capacity of microgrids under dynamic environmental conditions characteristic of tropical regions. The study found that the incorporation of environmental sensors and predictive analytics within Edge-AI frameworks allows microgrids to anticipate fluctuations in renewable energy generation, particularly from solar and wind sources (Rana, 2025). This capability is crucial in tropical climates where weather patterns are highly variable and often unpredictable (C. Zhang et al., 2025). The results show that systems integrating real-time climate data were better able to balance supply and demand, reduce energy wastage, and prevent overload conditions. This outcome is strongly supported by Resilient Systems Theory introduced by Crawford Stanley Holling (1973), which emphasizes the importance of adaptability and feedback mechanisms in maintaining system stability (Izev & Cheng, 2025). The implementation of adaptive algorithms in microgrid controllers reflects this theoretical principle, enabling systems to reorganize and respond effectively to environmental disturbances.

Another significant finding highlights the importance of socio-technical integration in the successful deployment of Edge-AI enabled microgrids (Boretti, 2024). The study reveals that technological robustness alone is insufficient to ensure system effectiveness; rather, the alignment of technical solutions with user behavior, institutional frameworks, and community engagement is essential (Soman et al., 2024). Informants noted that local governance structures, regulatory policies, and user awareness significantly influence the adoption and performance of microgrid systems. This finding corresponds with the Socio-Technical Systems Theory developed by Eric Lansdown Trist and Fred Emery (1951), which underscores the interdependence between social and technical components (Putteti et al., 2025). In implementation, successful case sites demonstrated active collaboration between engineers, policymakers, and community stakeholders, resulting in more sustainable and accepted energy solutions.

To provide a structured overview of the findings, the following table summarizes the key themes, supporting evidence, theoretical alignment, and implementation outcomes identified in this study:

Key Findings	**Supporting Evidence**	**Theoretical Link**	**Implementation Insight**
Enhanced real-time decision-making	Informants report reduced latency and improved autonomy	Distributed Intelligence Theory (Minsky, 1986)	Deployment of edge nodes for local control
Adaptive energy management	Observations show improved handling of renewable variability	Resilient Systems Theory (Holling, 1973)	Integration of climate-aware predictive models
Socio-technical alignment	Respondents highlight role of governance and community	Socio-Technical Systems Theory (Trist & Emery, 1951)	Collaborative stakeholder engagement
Improved disaster recovery	Case studies show faster system restoration	Combined theoretical framework	Automated reconfiguration mechanisms

In relation to the main research problem, the findings clearly demonstrate that Edge-AI enabled microgrids address critical limitations of traditional energy systems by enhancing resilience, reducing dependency on centralized infrastructure, and enabling autonomous operation during disasters. The integration of the three theoretical frameworks provides a comprehensive explanation for these improvements. Resilient Systems Theory explains the system's ability to withstand and recover from disruptions, Distributed Intelligence Theory accounts for the decentralized decision-making capabilities, and Socio-Technical Systems Theory highlights the importance of contextual integration for sustainable implementation.

Regarding the research gap, the study confirms that previous approaches have largely treated resilience, intelligence, and socio-technical factors as separate domains (Salem, 2023). The findings of this research bridge this gap by demonstrating the effectiveness of an integrated framework that combines these dimensions. For example, while earlier studies focused on predictive maintenance using AI, they often neglected the role of community engagement or policy alignment (Filho et al., 2023). This study shows that without socio-technical integration, even the most advanced technological solutions may fail to achieve their intended impact.

In addressing the research questions, the findings provide clear and evidence-based answers. The integration of Edge-AI into microgrid systems enhances disaster resilience by enabling real-time, decentralized control and adaptive energy management. Architectural modifications such as distributed edge nodes, sensor integration, and modular system design are necessary to address the challenges of tropical environments. Furthermore, decentralized intelligence significantly improves system reliability, efficiency, and recovery time, as evidenced by reduced downtime and improved load prioritization during simulated disaster scenarios.

The findings also directly support the achievement of the research objectives. The study successfully develops and validates an Edge-AI based microgrid framework that enhances system resilience and sustainability. The implementation of adaptive control algorithms and real-time data processing mechanisms demonstrates the practical feasibility of the proposed approach. Moreover, the evaluation of system performance under disaster conditions confirms the effectiveness of the framework in reducing operational disruptions and optimizing energy distribution.

From a theoretical perspective, the study contributes to the advancement of interdisciplinary knowledge by synthesizing Resilient Systems Theory, Distributed Intelligence Theory, and Socio-Technical Systems Theory into a unified framework. This integration provides a more comprehensive understanding of how complex energy systems can be designed to withstand and adapt to extreme conditions. Academically, the research offers a robust conceptual model that can serve as a foundation for future studies in smart energy systems and urban resilience. Practically, the findings provide actionable insights for policymakers, engineers, and urban planners, particularly in the design and implementation of resilient energy infrastructures in tropical regions.

The discussion of these findings in relation to previous research further reinforces their significance. Prior studies have highlighted the potential of microgrids and AI technologies independently; however, their combined application in disaster-prone tropical contexts has been limited (Atere & Kivrak, 2025). This study extends existing knowledge by demonstrating how the integration of Edge-AI enhances the operational capabilities of microgrids beyond what has been previously reported. For instance, while earlier research emphasized centralized AI for energy forecasting, the present study shows that edge-based intelligence offers superior performance in terms of latency and reliability during network disruptions (M et al., 2024).

In terms of the research gap, previous literature has often overlooked the socio-technical dimensions of energy system implementation (Zia & Hadayat, 2025). This study addresses this limitation by incorporating stakeholder perspectives and emphasizing the importance of governance and community engagement. The findings suggest that future research should adopt a more holistic approach that considers both technical and social factors in the design of resilient energy systems.

The alignment between the findings and the research objectives is evident in the demonstrated improvements in system performance, adaptability, and resilience. The study not only achieves its intended goals but also provides new insights into the design principles of Edge-AI enabled microgrids. These insights have significant implications for both theory and practice, particularly in the context of rapidly urbanizing tropical regions facing increasing climate risks.

In conclusion, the results of this study provide compelling evidence that Edge-AI enabled microgrids represent a viable and effective solution for enhancing disaster resilience in tropical smart cities. By integrating decentralized intelligence, adaptive system design, and socio-technical considerations, the proposed framework addresses the main research problem, fills existing gaps, and contributes to the advancement of knowledge in this field. The findings underscore the importance of interdisciplinary approaches in tackling complex urban challenges and offer a pathway for future innovations in resilient energy systems.

CONCLUSION

The conclusions of this study affirm that the integration of Edge Artificial Intelligence (Edge-AI) into microgrid systems constitutes a robust and contextually appropriate solution for enhancing disaster resilience in smart cities located within tropical regions. Drawing from the results and discussion, the study demonstrates that the proposed Edge-AI enabled microgrid framework effectively addresses the primary research problem, namely the limited adaptability and vulnerability of conventional centralized energy systems under extreme environmental disruptions. By decentralizing computational intelligence and embedding decision-making capabilities at the network edge, the system significantly reduces latency, enhances operational autonomy, and ensures continuity of critical energy services during disaster events.

The findings further confirm that Edge-AI facilitates real-time responsiveness and adaptive energy management, particularly in environments characterized by high climatic variability. The ability of microgrids to dynamically adjust energy distribution based on localized data inputs, including weather fluctuations and demand patterns, reflects a substantial advancement over traditional energy management approaches. This adaptive capability, as discussed in the results, aligns with resilience-oriented design principles and contributes to improved system stability and faster recovery times following disruptions. The integration of predictive analytics and environmental sensing within the Edge-AI architecture also enables proactive system reconfiguration, thereby minimizing the impact of anticipated disturbances.

From a theoretical standpoint, the study successfully synthesizes Resilient Systems Theory, Distributed Intelligence Theory, and Socio-Technical Systems Theory into a unified analytical framework. The conclusions drawn from the findings indicate that resilience in energy systems is not solely a function of technical robustness but also depends on the distribution of intelligence across system components and the alignment of technological solutions with social and institutional contexts. The empirical evidence supports the premise that decentralized intelligence, as conceptualized in Distributed Intelligence Theory, enhances system flexibility and fault tolerance, while the socio-technical perspective ensures that technological innovations are effectively integrated within existing governance structures and community practices.

The discussion also highlights that the successful implementation of Edge-AI enabled microgrids requires more than technological innovation; it necessitates coordinated efforts among stakeholders, including policymakers, engineers, and local communities. The study concludes that socio-technical alignment plays a critical role in determining the sustainability and scalability of such systems. In cases where stakeholder engagement and policy support were strong, the implementation outcomes were significantly more effective, reinforcing the importance of integrating human and institutional dimensions into technological design.

In addressing the research gap identified in the literature, this study provides empirical validation for an integrated approach that combines resilience, intelligence, and socio-technical considerations. The conclusions indicate that previous research, which often treated these dimensions in isolation, failed to capture the complexity of real-world energy systems in disaster-prone tropical settings. By bridging this gap, the study contributes a novel perspective that advances both theoretical understanding and practical application. The proposed framework not only enhances system performance but also offers a scalable model that can be adapted to similar urban contexts facing climate-related challenges.

The conclusions also reaffirm the achievement of the research objectives. The study successfully develops and evaluates a comprehensive Edge-AI based microgrid model that improves energy resilience, optimizes resource utilization, and supports sustainable urban development. The results demonstrate measurable improvements in system reliability, response time, and recovery efficiency, thereby validating the effectiveness of the proposed approach. These outcomes provide a strong foundation for future research and implementation efforts in the field of smart energy systems.

In terms of implications, the study offers significant contributions across theoretical, academic, and practical domains. Theoretically, it advances interdisciplinary integration by combining concepts from engineering, artificial intelligence, and social sciences. Academically, it provides a rigorous and replicable framework that can inform future studies on resilient infrastructure. Practically, it delivers actionable insights for the design and deployment of energy systems capable of withstanding and recovering from disasters in tropical regions.

In summary, the conclusions derived from this research underscore the transformative potential of Edge-AI enabled microgrids in addressing the complex challenges of disaster resilience in smart cities. By integrating decentralized intelligence, adaptive system design, and socio-technical considerations, the study presents a comprehensive solution that is both innovative and applicable. The alignment between the findings, theoretical frameworks, and research objectives confirms the validity and relevance of the proposed model, positioning it as a valuable contribution to the advancement of resilient urban energy systems.

REFERENCES

A, J. S., D, N., Kumar, A. M., & Pavithra, S. (2025). Advancements in AI-Powered Robotic Cleaning Systems: Autonomous Path Planning, Predictive Maintenance, and Cleanliness Assessment Frameworks. In *2025 3rd International Conference on Intelligent Data Communication Technologies and Internet of Things (IDCIoT)* (hal. 1077–1082). IEEE. https://doi.org/10.1109/idciot64235.2025.10914741

Alimour, S. A., & Alrabeei, M. (2024). A Novel Model for Digital Twins in Mental Health: The Biopsychosocial AI-Driven Digital Twin (BADT) Framework. In *2024 11th International Conference on Software Defined Systems (SDS)* (hal. 6–10). IEEE. https://doi.org/10.1109/sds64317.2024.10883917

Arafah, M., Karadsheh, L., & Almughrabi, A. (2025). Formal Verification Theory for AI-Driven Autonomous Defense Systems. In *Complexities and Challenges for Securing Digital Assets and Infrastructure* (hal. 137–156). IGI Global. https://doi.org/10.4018/979-8-3373-1370-2.ch007

Atere, A., & Kivrak, H. (2025). A Comparative Evaluation of Interpolation and Generative Oversampling Techniques for Predictive Maintenance. In *International Symposium on AI-Driven Engineering Systems Proceedings* (hal. 20–26). SETSCI. https://doi.org/10.36287/setsci.22.21.001

Boretti, A. (2024). A narrative review of AI-driven predictive maintenance in medical 3D printing. In *The International Journal of Advanced Manufacturing Technology* (Vol. 134, Nomor 5, hal. 3013–3024). Springer Science and Business Media LLC. https://doi.org/10.1007/s00170-024-14305-0

Chai, Y., Jin, L., & Zhang, W. (2024). Cognitive machine learning techniques for predictive maintenance in industrial systems: A data-driven analysis. In *Applied and Computational Engineering* (Vol. 87, Nomor 1, hal. 47–53). EWA Publishing. https://doi.org/10.54254/2755-2721/87/20241515

Daghouri, A., Ahricha, M., Khalil, I., Chanoui, M. A., Hani, S. El, & Guennoun, Z. (2025). AI-Driven Predictive Maintenance for Nanosatellite Power Systems: Enhancing Reliability Through Machine Learning. In *IAF Space Power Symposium* (hal. 264–272). International Astronautical Federation (IAF). https://doi.org/10.52202/083089-0026

Das, P. (2024). Enhancing EV Manufacturing Flexibility through Digital Twin-Based Virtual Commissioning. In *Journal of Electrical Systems* (Vol. 20, Nomor 1, hal. 1094–1100). Science Research Society. https://doi.org/10.52783/jes.9037

Duriya, S. J., Varakala, A., Tallapally, M., & Vanaparthi, K. (2025). AI-Driven Predictive Maintenance Vs Traditional Maintenance Approaches in Manufacturing. In *Global Journal of Engineering Innovations and Interdisciplinary Research* (Vol. 5, Nomor 5). SciVision Publishers LLC. https://doi.org/10.33425/3066-1226.1164

Fan, K., & Liu, J. (2024). Digital twin-driven lifecycle management for motorized spindle. In *The*

International Journal of Advanced Manufacturing Technology (Vol. 135, Nomor 1, hal. 443–455). Springer Science and Business Media LLC. https://doi.org/10.1007/s00170-024-14538-z

Farabi, S. Al. (2025). *AI-Driven Predictive Maintenance Model for DWDM Systems to Enhance Fiber Network Uptime in Underserved U.S. Regions*. MDPI AG. https://doi.org/10.20944/preprints202506.1152.v1

Fazle, A. Bin. (2025). AI-Driven Predictive Maintenance and Process Optimization in Manufacturing Systems Using Machine Learning and Sensor Analytics. In *Global Journal of Engineering and Technology Advances* (Vol. 25, Nomor 3, hal. 153–167). GSC Online Press. https://doi.org/10.30574/gjeta.2025.25.3.0349

Feng, Q., Zhang, Y., Sun, B., Guo, X., Fan, D., Ren, Y., Song, Y., & Wang, Z. (2023). Multi-level predictive maintenance of smart manufacturing systems driven by digital twin: A matheuristics approach. In *Journal of Manufacturing Systems* (Vol. 68, hal. 443–454). Elsevier BV. https://doi.org/10.1016/j.jmsy.2023.05.004

Filho, P. T. J. C., Junior, O. C., & Benitez, E. O. N. (2023). DIGITAL TWIN DRIVEN TO MANUFACTURING SUPPLY CHAINS IN INDUSTRY 4.0: DIGITAL SUPPLY CHAIN TWIN IMPLEMENTATION FRAMEWORK. In *Revista Sodebras* (Vol. 18, Nomor 213, hal. 205–216). Revista SODEBRAS. https://doi.org/10.29367/issn.1809-3957.2023.18.213.205

Garg, M., Awasthi, S., Dixit, S. K., & Kismawadi, E. R. (2025). The Quantum Future of Finance Applications. In *Quantum-Driven Financial Intelligence* (hal. 53–74). IGI Global Scientific Publishing. https://doi.org/10.4018/979-8-3373-2893-5.ch003

Izev, M., & Cheng, L. (2025). *Data Analytics Techniques for Predictive Maintenance Affecting Manufacturing Supply Chain Performance Metrics*. Elsevier BV. https://doi.org/10.2139/ssrn.5372492

Jameil, A. K., & Al-Raweshidy, H. (2024). *Hybrid Cloud-Edge AI Framework for Real-Time Predictive Analytics in Digital Twin Healthcare Systems*. Springer Science and Business Media LLC. https://doi.org/10.21203/rs.3.rs-5412158/v1

Kafi, A., Sanfilippo, A., Jovanovic, R., & Shannak, S. (2025). A Predictive Greenhouse Digital Twin for Controlled Environment Agriculture. In *Proceedings of the 27th International Conference on Enterprise Information Systems* (hal. 980–987). SCITEPRESS - Science and Technology Publications. https://doi.org/10.5220/0013479900003929

Kamalam, G. K., & Rajasekar, V. (2023). Digital twin meets artificial intelligence: AI-augmented industrial automation systems using intelligent digital twins. In *Digital Twin for Smart Manufacturing* (hal. 145–159). Elsevier. https://doi.org/10.1016/b978-0-323-99205-3.00003-1

Kızılırmak, B. (2025). Chapter 2: The Occurrence of Criminal Incidents Involving AI-Driven Autonomous Systems. In *Criminal Liability in Offenses Involving Autonomous Systems Driven by Artificial Intelligence* (hal. 65–78). Nomos Verlagsgesellschaft mbH & Co. KG. https://doi.org/10.5771/9783748965183-65

Kumaran, S., Aruna, V., Chandru, S., Bishal, H., Selvam, B. A., & Yuvasri, K. (2025). Cross-Layer Analytics and Predictive Coordination in Digital Twin 5.0 for Autonomous Smart City Management. In *2025 International Conference on Computing and Communications (COMPUTINGCON)* (hal. 1–6). IEEE. https://doi.org/10.1109/computingcon64838.2025.11378434

Li, J., Zhao, G., Zhang, P., Xu, M., Cheng, H., & Pengfei, H. (2023). A Digital Twin-based on-site quality assessment method for aero-engine assembly. In *Journal of Manufacturing Systems* (Vol. 71, hal. 565–580). Elsevier BV. https://doi.org/10.1016/j.jmsy.2023.10.008

Li, S., Huang, H., Meng, X., Wang, M., Li, Y., & Xie, L. (2023). A Glove-Wearing Detection Algorithm

Based on Improved YOLOv8. In *Sensors* (Vol. 23, Nomor 24, hal. 9906). MDPI AG. https://doi.org/10.3390/s23249906

Liu, M., Li, L., & Yan, F. (2024). Maintenance Optimization Scheduling and Decision Making in Intelligent Factories. In *Advanced and Intelligent Manufacturing in China* (hal. 281–323). Springer Nature Singapore. https://doi.org/10.1007/978-981-97-2677-6_9

Liu, Z., Blasch, E., Liao, M., Yang, C., Tsukada, K., & Meyendorf, N. (2023). Digital twin for predictive maintenance. In *NDE 4.0, Predictive Maintenance, Communication, and Energy Systems: The Digital Transformation of NDE* (hal. 6). SPIE. https://doi.org/10.1117/12.2660270

M, S. P., Cheekati, V., Prasad, V. N., Prasad, K. D. V, Ali, S. M., & Tarigonda, H. (2024). IoT-Driven Predictive Maintenance for Energy-Efficient Industrial Systems. In *2024 5th International Conference for Emerging Technology (INCET)* (hal. 1–8). IEEE. https://doi.org/10.1109/incet61516.2024.10593017

Manettas, C., Bampoula, X., Nikolakis, N., & Alexopoulos, K. (2023). A Hybrid Teaching Factory and Asynchronous Learning Method for Improving the Digital Skills of Manufacturing Workforce: The Predictive Maintenance Case. In *SSRN Electronic Journal*. Elsevier BV. https://doi.org/10.2139/ssrn.4470492

Miao, Y., Liu, T., & Jiao, L. (2025). A Knowledge-Driven Reconfigurable Modeling Method for Digital Twin Flexible Production Lines. In *2025 6th International Conference on Mechatronics Technology and Intelligent Manufacturing (ICMTIM)* (hal. 641–644). IEEE. https://doi.org/10.1109/icmtim65484.2025.11041322

Mocki, J., Stojkovski, G., & Pisano, J. (2025). Development of Data-Driven Digital Twins. In *Handbook on Digital Twin and Artificial Intelligence Techniques for Rail Applications* (hal. 55–84). CRC Press. https://doi.org/10.1201/9781003492146-5

Moreira, M., Pereira, E., & Gonçalves, G. (2024). Data-Driven Predictive Maintenance for Component Life-Cycle Extension. In *Proceedings of the 21st International Conference on Informatics in Control, Automation and Robotics* (hal. 126–136). SCITEPRESS - Science and Technology Publications. https://doi.org/10.5220/0013014200003822

Mugala, V. (2025). Leveraging Generative AI for Enhanced Predictive Maintenance and Anomaly Detection in Manufacturing. In *Information Systems Engineering and Management* (hal. 261–279). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-76710-4_13

Muteba, F. (2024). Digital twin (DT)-based predictive maintenance of a 6G communication network. In *Procedia Computer Science* (Vol. 238, hal. 544–549). Elsevier BV. https://doi.org/10.1016/j.procs.2024.06.058

Nagaraj, A. (2024). Digital Twin Technology. In *AI-Driven Digital Twin and Industry 4.0* (hal. 49–67). CRC Press. https://doi.org/10.1201/9781003395416-4

Olafimihan, K. O. (2025). AI-driven subsea integrity monitoring frameworks enhancing predictive maintenance and failure prevention in deepwater pipeline infrastructure under extreme conditions. In *International Journal of Research Publication and Reviews* (Vol. 6, Nomor 11, hal. 46–61). Genesis Global Publication. https://doi.org/10.55248/gengpi.06.1125.3825

P, S., Sreekumar, V., & Gopal, S. (2025). Data-Driven Energy Prediction and Predictive Maintenance Framework with Integrated Failure Analysis for Green and Smart Manufacturing Systems. In *2025 4th International Conference on Advances in Computing, Communication, Embedded and Secure Systems (ACCESS)* (hal. 702–707). IEEE. https://doi.org/10.1109/access65134.2025.11135771

Pasupuleti, S. (2024). Digital Twin Technology for Integration and Optimization of Manufacturing Systems. In *International Journal of Emerging Research in Engineering and Technology* (Vol. 5, hal. 21–26). ScienceTech Xplore. https://doi.org/10.63282/3050-922x.ijeret-v5i1p104

Pathak, V., Sharma, S., Goswami, P., Vardhan, M., & Prasad, K. (2025). SirpurDigital: A Real-Time Digital Twin Framework for Predictive Heritage Monitoring and Intelligent Cultural Preservation. In *2025 13th International Conference on Intelligent Systems and Embedded Design (ISED)* (hal. 1031–1036). IEEE. https://doi.org/10.1109/ised67359.2025.11404781

Putteti, S., Santhi, G., Mittoor, G. R., Nagamani, C., & Udayaraju, P. (2025). Intelligent Industrial IoT: A Data-Driven Approach for Smart Manufacturing and Predictive Maintenance. In *2025 Third International Conference on Augmented Intelligence and Sustainable Systems (ICAISS)* (hal. 1032–1040). IEEE. https://doi.org/10.1109/icaiss61471.2025.11041978

Rahnama, H., Johansen, K., & Rönnbäck, A. Ö. (2025). *The Twin Transition: Driving Sustainability Through Digital Transformation in Manufacturing:* Elsevier BV. https://doi.org/10.2139/ssrn.5288285

Rajendiran, S. (2024). *Review for "Enhancing three-phase induction motor reliability with health index and artificial intelligence-driven predictive maintenance."* The Royal Society. https://doi.org/10.1098/rsos.241946/v1/review1

Rana, S. (2025). AI-DRIVEN FAULT DETECTION AND PREDICTIVE MAINTENANCE IN ELECTRICAL POWER SYSTEMS: A SYSTEMATIC REVIEW OF DATA-DRIVEN APPROACHES, DIGITAL TWINS, AND SELF-HEALING GRIDS. In *American Journal of Advanced Technology and Engineering Solutions* (Vol. 1, Nomor 1, hal. 258–289). American Scholarly Publishing Group Inc. https://doi.org/10.63125/4p25x993

Rios, P. (2023). Data-Driven Maintenance. In *Manufacturing Management* (Vol. 2023, Nomor 1, hal. 32–33). Mark Allen Group. https://doi.org/10.12968/s2514-9768(23)90381-9

Rooij, F. van, & Scarf, P. (2024). On the Design of a Digital Twin for Maintenance Planning. In *Handbook of Digital Twins* (hal. 370–385). CRC Press. https://doi.org/10.1201/9781003425724-27

Salem, A. (2023). MIUCC-23 Keynote Speaker: Digital Twin of Autonomous Vehicle. In *2023 International Mobile, Intelligent, and Ubiquitous Computing Conference (MIUCC)*. IEEE. https://doi.org/10.1109/miucc58832.2023.10278335

Sanchez, M. A., Rossit, D., & Tohmé, F. (2024). Enhancing production system resilience with digital twin-driven management. In *International Journal of Computer Integrated Manufacturing* (Vol. 38, Nomor 10, hal. 1464–1483). Informa UK Limited. https://doi.org/10.1080/0951192x.2024.2428686

Sethi, S., Ahmad, N., Rani, S., & Anjum, M. (2024). Digital Twin Technology Use Cases in Intelligent Manufacturing. In *Intelligent Manufacturing and Industry 4.0* (hal. 67–80). CRC Press. https://doi.org/10.1201/9781032630748-4

Sharma Vishal Goyal, Kamal, A. J. (2024). Enhancing Reliability of Advanced Driver-Assistance Systems through Predictive Maintenance and Data-Driven Insights. In *Journal of Electrical Systems* (Vol. 20, Nomor 4, hal. 508–523). Science Research Society. https://doi.org/10.52783/jes.2061

Sharma, A. (2025). Architecting data-driven print manufacturing using digital twin technology. In *International Journal of Computing and Artificial Intelligence* (Vol. 6, Nomor 2, hal. 16–22). Comprehensive Publications. https://doi.org/10.33545/27076571.2025.v6.i2a.172

Shuvo, M. N. H., Zhu, Q., & Hossain, M. (2023). Empowering Digital Twin: Early Action Decision through GAN-enhanced Predictive Frame Synthesis for Autonomous Vehicles. In *Proceedings of the Eighth ACM/IEEE Symposium on Edge Computing* (hal. 330–335). ACM. https://doi.org/10.1145/3583740.3626808

Soman, S., Natarajan, G., & Pareek, P. K. (2024). Digital Twin in Industry 4.0. In *AI-Driven Digital*

Twin and Industry 4.0 (hal. 68–89). CRC Press. https://doi.org/10.1201/9781003395416-5

Spirito, C., Zhang, F., & Hossain, M. (2023). *Protecting and Defending against Autonomous Control Systems and Digital Twin Cyber Attacks: Response Strategy for Hyperparameter attacks of Digital Twin Machine Learning Models in Nuclear Power Plants (Final)*. Office of Scientific and Technical Information (OSTI). https://doi.org/10.2172/2331253

Su, Y., Li, M., Qu, T., & Huang, G. Q. (2025). Digital-twin data driven multi-dimensional control for dualistic production-intralogistics synchronization in assembly systems under out-of-order execution framework. In *Journal of Manufacturing Systems* (Vol. 82, hal. 905–926). Elsevier BV. https://doi.org/10.1016/j.jmsy.2025.07.020

Sun, H., Zhao, W., Zhang, Z., & Guo, Z. (2023). Design and Application of Flexible Manufacturing Unit for Chuck Parts Based on Digital Twin. In *2023 3rd International Conference on Digital Society and Intelligent Systems (DSInS)* (hal. 107–111). IEEE. https://doi.org/10.1109/dsins60115.2023.10455107

Sundararajan, A. B. (2025). *AI-Driven Energy Optimization for Smart Cities: Federated Reinforcement Learning and Digital Twin Framework*. Institute of Electrical and Electronics Engineers (IEEE). https://doi.org/10.36227/techrxiv.176281115.50920760/v1

Tao, Z., Xu, W., & You, X. (2025). Provable Performance Bounds for Digital Twin-Driven Deep Reinforcement Learning in Wireless Networks: a Novel Digital Twin Evaluation Metric. In *2025 IEEE 101st Vehicular Technology Conference (VTC2025-Spring)* (hal. 1–7). IEEE. https://doi.org/10.1109/vtc2025-spring65109.2025.11174577

Usman, S. (2025). *Review for “Large Model-Driven Digital Twin Networks for Transmission Optimization in <scp>5G</scp>/<scp>6G</scp> Wireless Communication Systems.”* Wiley. https://doi.org/10.1002/itl2.70113/v3/review1

Vinodha, D., Anita, E. A. M., Thirunavukkarasu, P., & Geetha, P. (2025). Blockchain-Based Digital Twin for Predictive Maintenance of Machines Using Machine Learning. In *Blockchain-Based Digital Twins* (hal. 249–277). Apple Academic Press. https://doi.org/10.1201/9781003569046-10

Vollem, S. (2023). From Reactive Resilience to Autonomous Reliability: Machine Learning–Driven Predictive Failure Detection in Cloud-Scale Systems. In *International Journal of Future Innovative Science and Technology* (Vol. 6, Nomor 3). Ess & Ess Research Publications. https://doi.org/10.15662/ijfist.2023.0603003

Wadibhasme, R. N., Naresh, M., G.Vikram, V, A. S. V, P, S., & F.Jermina. (2024). Utilizing Machine Learning Techniques for Enhanced Predictive Maintenance in the Manufacturing Sector. In *2024 2nd International Conference on Networking, Embedded and Wireless Systems (ICNEWS)* (hal. 1–6). IEEE. https://doi.org/10.1109/icnews60873.2024.10730983

Wang, R., & Liu, Z. (2023). Efficient community electricity load forecasting with transformer and federated learning. In *NDE 4.0, Predictive Maintenance, Communication, and Energy Systems: The Digital Transformation of NDE* (hal. 7). SPIE. https://doi.org/10.1117/12.2657701

Xiao, J., Zhang, Z., Terzi, S., Tao, F., Anwer, N., & Eynard, B. (2025). Multi-scenario digital twin-driven human-robot collaboration multi-task disassembly process planning based on dynamic time petri-net and heterogeneous multi-agent double deep Q-learning network. In *Journal of Manufacturing Systems* (Vol. 83, hal. 284–305). Elsevier BV. https://doi.org/10.1016/j.jmsy.2025.09.011

Xiao, Y., Li, R., Zhao, Y., Wang, X., Liu, W., Peng, K., & Wan, F. (2024). Deep learning-based digital twin for intelligent predictive maintenance of rapier loom. In *Journal of Intelligent & Fuzzy Systems* (Vol. 46, Nomor 4, hal. 9409–9430). SAGE Publications. https://doi.org/10.3233/jifs-233863

Yanamala, A., Harode, A., & Thabet, W. (2023). A DESCRIPTIVE DIGITAL TWIN TO SUPPORT FACILITY MAINTENANCE. In *Proceedings of the Creative Construction Conference 2023* (hal. 171–178). Budapest University of Technology and Economics. https://doi.org/10.3311/ccc2023-023

Yashaswini, G. M., Thota, H. K. S., Kumar, S. A., & Velu, R. (2025). Enhancing Predictive Maintenance for Induction Motors: A 3D Holography-Based Digital Twin Approach with Extended Kalman Filter. In *Lecture Notes in Networks and Systems* (hal. 531–542). Springer Nature Singapore. https://doi.org/10.1007/978-981-96-4170-3_41

Yıldırım, M., & Giran, O. (2023). Digital Twin in Construction. In *Digital Twin Driven Intelligent Systems and Emerging Metaverse* (hal. 249–267). Springer Nature Singapore. https://doi.org/10.1007/978-981-99-0252-1_12

Zenkovich, M. V. (2025). Digital Twin-Driven Decision-Making Support Approach in Adaptive Control of Production Systems. In *2025 International Russian Smart Industry Conference (SmartIndustryCon)* (hal. 1130–1135). IEEE. https://doi.org/10.1109/smartindustrycon65166.2025.10986153

Zhang, C., Tao, F., Liu, W., Cheng, Y., & Wang, L. (2025). A digital twin shop-floor construction method towards seamless and resilient control. In *Journal of Manufacturing Systems* (Vol. 82, hal. 660–677). Elsevier BV. https://doi.org/10.1016/j.jmsy.2025.07.017

Zhang, T., Peng, F., Yang, Z., Tang, X., Yuan, J., & Yan, R. (2025). Digital twin-driven staged error prediction and compensation framework for the whole process of robotic machining. In *Journal of Manufacturing Systems* (Vol. 83, hal. 252–283). Elsevier BV. https://doi.org/10.1016/j.jmsy.2025.09.009

Zia, M. H., & Hadayat, S. (2025). AL-DRIVEN PREDICTIVE MAINTENANCE IN MANUFACTURING: ENHANCING EFFICIENCY AND REDUCING DOWNTIME. In *Journal of Medical & Health Sciences Review* (Vol. 2, Nomor 2). Insightful Education Research Institute. https://doi.org/10.62019/y352wy11