ESP Journal of Engineering & Technology Advancements (ESP-JETA)
ISSN: 2583-2646
Special Issue: International Conference on Cloud Security, Cyber governance and Global Impacts (ICCSCGI 2026)

Original Article

AI-Powered Digital Twins for Real-Time Sustainability Tracking in Manufacturing

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Abstract: *As the world moves swiftly towards more environmentally friendly industrial practices, the manufacturing sector, which has traditionally been a major source of carbon emissions and resource use, is under a lot of pressure to adapt. The solution is that combining artificial intelligence (AI) with digital twin technology offers a new technique to keep track of sustainability in real time that might change the game. Digital twins are replicas of things, processes, or even full systems that exist in the actual world. They help manufacturers keep an eye on, copy, and make operations better with incredible accuracy. Adding AI features like machine learning, predictive analytics, and real-time anomaly detection to these digital twins turns them from passive models into smart agents that can not only copy reality but also predict and make it better. This article talks about how AI-powered digital twins could help make manufacturing more environmentally friendly by enabling people keep an eye on things like energy use, emissions, waste, water use, and carbon footprint all the time. Digital twins let you make changes ahead of time and see how things will turn out by connecting the real world with the virtual world. This helps companies make sure their work is in line with global aspirations for sustainability. These systems' best feature is that they can turn data from a variety of sources, such as IoT sensors, production logs, supply chain nodes, and corporate systems, into usable, actionable information. Digital twins employ AI algorithms to learn from this information so they can see problems, try out changes, and make the best choices. For example, a smart factory might use an AI-powered digital twin to keep track of how much power each machine on the floor is using. The twin can tell if the rapid increase in use is due to mechanical wear, bad scheduling, or outmoded processes, and then recommend fixes or even implement them automatically. These skills not only have less of an impact on the environment, but they also make things run more smoothly, make products better, and save money.Companies can also use this technology to run "what-if" scenarios without pausing real production. Before they employ new materials, change the way they create goods, or change the way they receive supplies, they may utilise their digital twin system to assess how each choice would effect the environment. Businesses who have to cope with difficult environmental standards and greater demands from stakeholders for openness and responsibility need to be able to see things ahead of time like this.Digital twins powered by AI have a lot of potential for tracking sustainability, but there are still some issues with using them. Some technical issues include combining data, making ensuring that all of the old systems are following the same standards, and the need for a lot of processing capacity for real-time analytics. You also need to be very careful about moral issues like data privacy, model explainability, and the risk of greenwashing, which is when systems are falsely advertised as being more environmentally friendly than they really are. But it's apparent that this technology gives organisations a strategic edge: those who use it well will not only reach their environmental goals, but they will also defend their business from the future in a market where sustainability and digitisation are swiftly becoming one and the same.This research looks at the structure, features, probable usage, and future prospects of AI-driven digital twins, especially in manufacturing settings that prioritise sustainability. It shows how this new mix of AI and virtual modelling could lead to better, greener, and more adaptable production systems by using case studies from the commercial sector and technical frameworks. This manner, it adds to the growing body of knowledge that is shaping the Fourth Industrial Revolution, when enterprises must be ecologically responsible to stay competitive.*

Keywords: *AI-powered digital twins, sustainability tracking, real-time monitoring, manufacturing industry, industrial IoT, predictive analytics, smart manufacturing, energy efficiency, carbon footprint reduction, cyber-physical systems*

I. INTRODUCTION

This is a highly significant time for the industrial business. It is locked between the inevitable march of the digital revolution and the urgent demand for sustainability around the planet. Manufacturers need to consider about not only what they make, but also how they make it as people become more worried about the environment due to climate change, resource depletion, and government rules. In a society that needs to be able to respond quickly and be open, old means of keeping track of environmental effect, which often employ static reporting, delayed feedback, and walled data systems, are becoming less and less useful. In this high-stakes circumstance, AI-powered digital twins give us a whole new approach to keep track of and improve sustainability performance at all levels of industrial processes. They are smart, work in real time,

and can change. A digital twin is more than simply a digital replica. It's a model of something genuine, like a machine, a manufacturing line, or even an entire factory. It learns and grows over time by gathering data from sensors, IoT devices, and business systems. Adding AI to digital twins makes them able to help make decisions, forecast what will happen in the future, detect problems, and even come up with long-term solutions on their own.

This study says that AI-powered digital twins are not just a better technology; they are also a significant tool for making production more sustainable in real time. Digital twins can employ AI techniques like machine learning, deep learning, and reinforcement learning to analyse intricate environmental data in real time. They can discover spikes in energy use, figure out when maintenance will be needed to avoid waste, model emissions from the supply chain, and modify the flow of resources in real time to reduce the damage to the environment. These talents aren't simply things that could happen in the future; they're growing more and more likely due of better edge computing, 5G connections, and cloud-based platforms. Even while AI-powered digital twins are growing better, they are still not used sufficiently to help with sustainability goals. This is especially true for small and medium-sized enterprises who don't know how to use these systems or don't have the right tools. This paper seeks to address that gap by looking at the main parts, benefits and downsides, and moral difficulties of employing AI-driven digital twin technology to keep track of sustainability in manufacturing settings.

There are many conceivable ramifications of this technology. As the world moves towards carbon neutrality, circular economy models, and ESG (Environmental, Social, and Governance) reporting, manufacturers need tools that are both accurate and adaptable. Digital twins powered by AI can do this by giving you extensive, real-time information about everything from how much energy and water you use to how you manage your waste. More importantly, they let companies shift from reactive compliance to proactive sustainability leadership, making sustainability a business benefit instead of just a checkbox. But making this modification isn't simple. There are huge concerns that need to be fixed, such making sure data can work together, keeping AI safe, making sure AI can be explained, and the risk of digital greenwashing. The upcoming chapters of this article will go into more depth regarding these things. It describes a plan for how digital twins with AI could become a fundamental aspect of sustainable industrial innovation in the Fourth Industrial Revolution.

II. UNDERSTANDING DIGITAL TWINS AND AI INTEGRATION

Digital twins are one of the most important new technologies that are transforming how things are manufactured now. They are in between the real world and the digital world. At first, people conceived of digital twins as virtual models that might explain how things in the actual world work. Now, they are more than simply simple, unchanging simulations. They are now dynamic, real-time reflections of machines, processes, and complex industrial systems. Sensors, IoT devices, and operational records incorporated into real-world settings give data to these digital models all the time, which are then updated. Digital twins are not like ordinary modelling tools because they may give and receive data in both directions. The digital twin shows changes in the real world, and what you learn from it can change what you do in the real world. With the addition of Artificial Intelligence (AI), this model becomes more than just a reflection of operations; it becomes a living, breathing thing that can learn and reason.

Adding AI to digital twin technology makes a major difference in how manufacturers fix problems. Digital twins that use AI may predict problems, offer solutions, and even make decisions on their own instead of waiting for them to happen. Machine learning helps systems find patterns in data and guess what will happen next. Deep learning is good for looking at complicated signals like machine vibrations or pictures from visual inspections. Reinforcement learning makes the system better at what it does based on feedback it gets in real time. By adding these algorithms to digital twin systems, manufacturers may make their processes better, reduce downtime, increase product quality, and keep track of sustainability measures in great detail and at great speed.

This integration becomes even more crucial and useful when it comes to sustainability. You can set up digital twins that use AI to watch and respond to things like how much energy, carbon, trash, and water are used. These ideas can help with everything from adaptive control systems that adjust how machines run in real time to cut down on waste to strategic planning models that indicate how changes in operations will effect long-term sustainability goals. For example, a digital twin of a factory's HVAC system might estimate that the system will use too much energy if the air temperature rises and suggest a better configuration or maintenance schedule. Digital twins can also try out different materials, product designs, or shipping routes in a virtual world to see how they influence the environment before they are used.

The most essential point is that incorporating AI turns digital twins from tools that describe things into systems that tell you what to do and what will happen. This means that they don't just tell you what's going on; they also tell you why it's happening, what might happen next, and what you should do about it. To measure sustainability in real time, you need to have this level of insight. It helps businesses go from just following environmental standards to being leaders in safeguarding

the environment. Digital twins driven by AI give manufacturers a single, smart platform that can assist them make choices about productivity, sustainability, and digital innovation. This is the start of a new age in smart, long-lasting production.

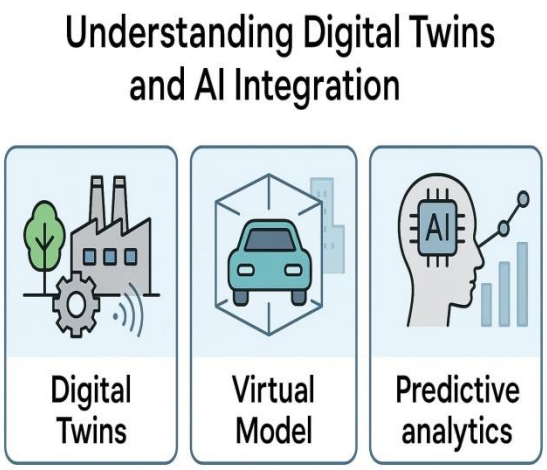

Figure 1: Understanding Digital Twins And Ai Integration

III. SUSTAINABILITY METRICS IN MANUFACTURING

Sustainability in manufacturing is no longer just a side problem; it is now a fundamental strategic goal that is driven by environmental legislation, global climate goals, investor expectations, and customer desire for responsible production. In this case, the first step towards doing something useful is to understand and correctly measure sustainability metrics. We can use these measurements to find out how well we are doing for the environment, where we may be more efficient, and set goals based on facts. Energy use, carbon emissions, water use, material waste, process efficiency, air pollution, and how well resources are used are some of the most important sustainability measures in manufacturing. Tracking these indications the old-fashioned manner, either by reporting on them every so often or inputting data by hand, takes a lot of effort. Most of the time, insights are out of date by the time they are found. AI-powered digital twins are the best option here since they help you keep an eye on and analyse sustainability parameters in real time at any step in the manufacturing value chain. For instance, you might be able to see how much energy is consumed not just at the facility level, but also at the level of particular machines and even certain production cycles. Digital twins with AI might be able to study trends, find spikes in energy demand, connect them to how things are made, and suggest methods to make things better, like recalibrating equipment, shifting loads, or undertaking predictive maintenance. People all around the world are keeping a close eye on carbon emissions. We can always measure and estimate them using data about the types of fuel used, the outputs of machines, the logistics of transportation, and the design of facilities. You can then compare these emissions to the standards used in your business or the targets for net-zero emissions. Then, the algorithm will suggest ways to lower emissions, such restructuring operations, employing green energy, or making items go in a circle.

Also, pipes and tanks with sensors can measure how much water is being used in real time, which is very significant in places where water is hard to find. Digital twins can explain how recycling water will change things, discover leaks or waste, and help make cleaning cycles or cooling systems work better so that less water is needed. Another key issue is how to deal with garbage, which includes both solid and dangerous waste that is created during production. Digital twins that employ AI can keep track of how much waste is created at each phase, suggest other materials to use, or even simulate adjustments to the process to cut down on trash and increase yield. In more advanced uses, these systems can also help with life cycle assessment (LCA) by looking at how things influence the environment from the time they are manufactured until they are thrown away. This helps designers develop things that will last longer from the beginning. Process efficiency, or how well energy, time, and resources are transformed into finished goods, is another crucial but often overlooked metric of sustainability. Digital twins with AI can detect problems with production lines by always checking for bottlenecks, steps that take too long, and machines that aren't working right. All of these things are bad for the environment and squander resources. These ideas are good for the environment, but they also cut costs and make operations more flexible. Digital twins are significant because they help companies see how new technology, supply chain choices, or changes in the law might effect sustainability before they really happen. The fact that you can view, measure, and respond to sustainability data in real time is a big difference from monitoring the environment in a static way. It changes producers from passive reporters to

active strategists for sustainability. Digital twins powered by AI alter sustainability from something you have to do to something that is integrated into how modern manufacturing operates in real time.

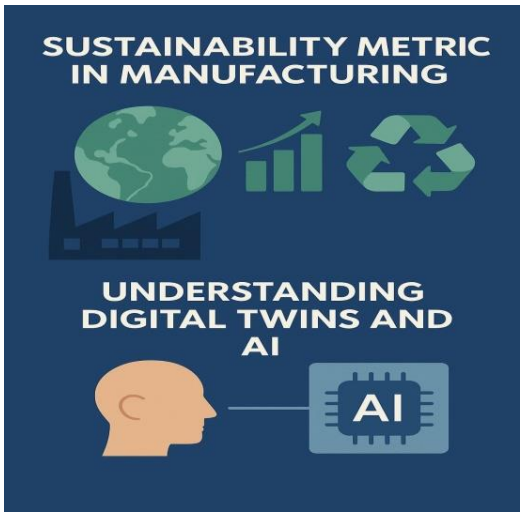

Figure 2: Sustainability Metrics in Manufacturing

IV. SYSTEM ARCHITECTURE AND DATA FLOW

The system design and data flow of AI-powered digital twins have a big impact on how well they can be used to assess sustainability. These two things determine how fast, correctly, and widely the solution can be used. There are numerous layers in the design of a digital twin system, and each one has a different but related job. These professions include detecting and gathering data, analysing it, making judgements, and sending feedback to the real world. The initial portion of the foundation is the physical layer, which contains IoT devices, sensors, actuators, and machines that are already in the production environment. These devices are always gathering information, such as temperature, energy use, vibration, emissions, throughput, water flow, and trash output. This information goes to the connectivity layer. There, high-speed, low-latency communication networks, usually powered by 5G or industrial Wi-Fi, make it easier for data to be delivered to the digital twin's computational core without any interruptions.

The networking layer is below the processing layer. It conducts the heavy work of collecting, cleaning, storing, and getting data ready for real-time or batch analysis. This processing can happen on the edge, near the source (such on embedded devices or edge gateways), or in the cloud, where there is a lot of storage and computing power for advanced analytics and long-term sustainability tracking. It all depends on how significant and important the operation is. More and more manufacturing organisations are embracing hybrid architectures that integrate cloud and edge capabilities. These designs let people make decisions quickly (at the edge) and learn more deeply (via cloud-based learning models). The intelligence layer is at the top of the stack. It uses AI algorithms to change raw data into valuable knowledge. Machine learning models can detect faults with how machines perform or consume energy, figure out what's not working right, forecast how the environment will change in the future, and offer fixes straight immediately. Reinforcement learning models might potentially adjust system settings on their own to make them better for sustainability metrics like carbon footprint or resource utilisation.

This architecture relies heavily on the two-way data flow that connects the digital twin to its physical twin. The system not only collects and analyses data from the real world, but it also sends commands or adjustments to machines based on that data. This makes a closed loop of feedback. This loop helps systems make themselves better based on environmental goals, including using less energy during off-peak hours or modifying the way they make things to cut down on emissions. Also, connecting the system to enterprise-level platforms like ERP (Enterprise Resource Planning), MES (Manufacturing Execution Systems), and SCADA (Supervisory Control and Data Acquisition) makes sure that the organization's overall strategy and operations are affected by the sustainability insights from digital twins.

Powerful digital twin architecture also lets manufacturers use simulation modules to see how alternate production methods or environmental policies would work without actually using them. This feature is highly significant for planning for the future since it helps firms make choices that are less hazardous. Data governance and cybersecurity are also very significant components of architecture, especially when operational and environmental data are so private. Encryption, role-based access, and audit trails are all things that the system needs to make it safe from breaches and abuse. AI-powered

digital twins can be clever partners in Composite in sustainable Anonymous manufacturing because they can easily and in real time coordinate data across different layers.

V. REAL-TIME TRACKING AND PREDICTIVE CAPABILITIES

One of the coolest things about AI-powered digital twins for eco-friendly manufacturing is that they can keep track of things in real time and make predictions. AI-driven digital twins work in a dynamic loop, taking in data from machines, sensors, and production settings, analysing it, and then acting on it as it comes in. This is not like older systems that depend on reports that come in at certain times or indicators that are behind. This capability allows producers detect problems immediately away, keep a watch on environmental performance indicators right away, and respond swiftly and correctly. The digital twin does more than just keep track of what's going on. It also understands it, puts it in context, and recommends or even carries out solutions right away. For instance, it can determine if a production line is consuming too much energy, if water use suddenly goes up, or if an equipment that emits a lot of pollution is getting less efficient over time. Digital twins can utilise AI to sort problems by how bad they are, how they affect sustainability, and what has happened in the past. This gives plant managers and decision-makers a sophisticated dashboard that shows environmental diagnostics in real time.

You can only view production operations in real time on one side of the coin. The other is predictive intelligence, which makes the digital twin a change agent that acts before the change occurred. Digital twins can figure out when problems with sustainability might develop before they do by using machine learning, time-series forecasting, and data from past operations. For instance, a predictive model can start maintenance on a crucial compressor before emissions or waste levels rise if it knows that the compressor generally starts leaking oil after 2,000 hours of use. The system can also try out different scheduling strategies to smooth out the energy curve if energy use data reveal that a peak load event is likely to place during the next production shift. This kind of predictive foresight lets producers make the greatest decisions about what to do now and what to do next, all while doing the least amount of damage to the environment.

The AI model can also learn from every operational choice in real time, which helps it keep improving. The digital twin gets smarter over time because it goes through this iterative cycle, which teaches it how a facility functions and modifies its forecasts and suggestions to match. For example, it might first recommend slowing down the machines to save energy, but after analysing how that impacts throughput and waste output, it might change its mind and suggest a new strategy that balances both environmental and economic goals. AI-powered digital twins may learn from their mistakes and adapt how they act, unlike static analytics dashboards or rule-based automation systems.

Tracking and predicting environmental performance in real time makes it visible, actionable, and manageable, which are all critical for meeting today's stringent carbon reduction objectives, ESG commitments, and legal obligations. These features also make data available to everyone in the firm. Engineers, sustainability officers, plant managers, and executives may all get up-to-date, consistent data that is specific to their jobs and goals. AI-powered digital twins are more than just tools that react; they are strategic advisors incorporated into the industrial ecosystem that help organisations run greener by offering them immediate insights and accurate predictions. The future of sustainable manufacturing is really being made in this blend of what is and what could be.

Figure 3: Real-Time Tracking and Predictive Capabilities

VI. CASE STUDIES IN INDUSTRY

It may sound like something from the future, yet many large organisations in different areas are now utilising AI-powered digital twins to make their operations more eco-friendly, and the effects are both measurable and positive. One of the most famous examples is Siemens, which is a world leader in industrial automation. Siemens utilised an AI-powered

digital twin at its electronics factory in Amberg, Germany, to model and keep a watch on manufacturing processes in real time. The system uses thousands of sensors and edge devices across the facility to keep an eye on energy use, equipment performance, and emissions into the air. As a result, the company utilised 20% less energy and made all of its equipment (OEE) 30% more efficient. The digital twin's AI algorithms not only made processes that use a lot of energy more efficient, but they also made predictive maintenance possible. This cut down on material waste and unplanned downtime. These changes are good for the environment and save money at the same time.

General Electric (GE) is another fantastic example in the aviation business. Digital twins help GE keep an eye on the life cycles of jet engines while they are being constructed and while they are in service. These AI-powered twins use sensor data to display how engines wear down, how much fuel they use, and how much pollution they produce when they fly in different conditions. This method helps GE make engines that are better for the environment and consume less fuel. This helps airline clients follow tight emissions requirements and save money on operational costs. The digital twin also helps create maintenance schedules that are better for the environment and save waste and unnecessary replacements.

In the chemical production business, BASF has employed digital twins to model how resources are used across the facility and how sophisticated chemical processes happen. BASF might utilise AI to add to these digital models to find out how changing the circumstances of the reaction influences how much energy is used and how many by-products are generated. This helps them use resources better while having the least impact on the environment. Their Ludwigshafen business, which is one of the largest integrated chemical complexes in the world, has used AI-driven digital twin simulations to cut down on CO_2 emissions and get less fresh water by enhancing recycling procedures.

Unilever, a big corporation that manufactures things for people to use, has also utilised similar technologies in its facilities around the world to help with its environmental aims. As part of its "Factory of the Future" project, Unilever constructed AI-powered digital twins to keep track of and cut down on carbon emissions, water use, and waste in its operations. Thanks to the technology, they have already met significant sustainability goals ahead of time. For instance, all of their production sites now acquire all of their electricity from renewable sources, and since 2008, they have lowered CO_2 emissions from energy by more than 65%.

These real-world examples show that AI-powered digital twins can be used in a lot of different production environments and can be made to work in even more. The underlying value proposition is the same for all types of production, whether it's discrete manufacturing like electronics, process-intensive industries like chemicals, or high-precision sectors like aerospace. These include enhanced visibility, predictive control, operational efficiency, and actual sustainability benefits. These case studies show that digital twins are more than just ideas in textbooks or tech prototypes. They are genuine systems that are now earning money for some of the world's most difficult manufacturing businesses. These examples also show small and medium-sized enterprises how to be both environmentally friendly and innovative at the same time.

VII. BENEFITS AND COMPETITIVE ADVANTAGES

There are several benefits to using AI-powered digital twins in industrial systems, and monitoring the environment is just one of them. It makes businesses rethink how they measure success, come up with new ideas, and stay ahead of the competition. One of the best things about it is that it makes things go more smoothly. Digital twins give manufacturers real-time information about how machines are working, where processes are stalled, and how resources are being used. This helps companies enhance workflows and cut down on waste at multiple levels. This means that less energy is used, fewer materials are wasted, and production goes faster, all of which make operations more efficient and good for the environment. For instance, an AI-enhanced digital twin may tell when a machine is using too much power due of wear and tear or misalignment by always checking production cycles and environmental data. This allows you undertake targeted maintenance before it costs a lot of money or causes too many emissions. These predictive skills help the environment and the enterprise by reducing unexpected downtime, extending the lifespan of assets, and lowering the costs of reactive maintenance.

Another important benefit is that it leads to innovation that is good for the environment. Digital twins help manufacturers test and try out new materials, energy sources, or process changes that are beneficial for the environment without having to change the manufacturing line. This safe testing cuts down on expensive trial-and-error methods and speeds up the development of products and processes that are better for the environment. It also helps with life cycle analysis, which helps companies think about how their decisions might influence the environment from the time they develop something to the time they throw it away. Not only does this kind of proactive planning make operations more sustainable, it also makes products better, helps the company follow environmental rules, and boosts the brand's reputation.

Digital twins that use AI are also very useful for following the regulations. Governments and international groups are setting laws regarding how much energy people may use, how they can get rid of rubbish, and how much pollution they can generate. An AI-powered digital twin system may keep an eye on key performance indicators that are vital to these rules, deliver data in real time, and even sound warnings when the operation is about to break the rules. This real-time compliance monitoring decreases the likelihood of legal problems, helps firms avoid fines, and makes sure they are always ready for an audit.

Using AI-powered digital twins in your firm also gives you an edge over your competitors. Companies that can show real-time, data-driven sustainability performance have a strategic edge as customers, investors, and supply chain partners become more interested in sustainability. Manufacturers that can set up and grow these systems well may market their company as being not just smart and efficient, but also beneficial for the environment. This is a trait that is getting more and more popular in global markets that care about ESG indicators and sustainability indices. This competence also lets a company receive green funding, loans tied to sustainability, and carbon credits, all of which can help the company become even more solid financially.

Digital twins can connect shop floor workers, engineers, sustainability officers, and executives in real time on a single platform. This also encourages a culture of openness and shared responsibility. Everyone has the same information, knows the same goals, and is always working to make things better. This shared knowledge helps people come up with new ideas, speeds up the process of making decisions, and makes sure that sustainability is always a part of the company's DNA.

Digital twins that use AI are more than just tools for sustainability; they are also important business tools. They assist the environment and the financial line, which is a rare win-win that places adopters at the front of the next industrial revolution, when intelligence, adaptability, and sustainability are no longer optional. They are needed.

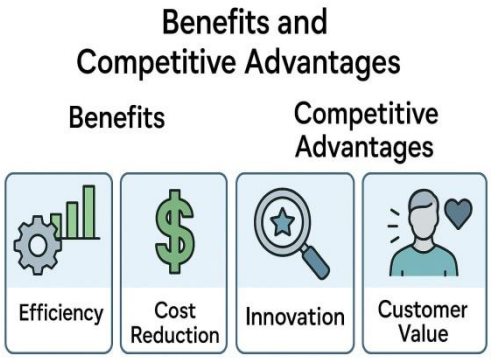

Figure 4: Benefits and Competitive Advantages

VIII. CHALLENGES AND ETHICAL CONSIDERATIONS

AI-powered digital twins have a lot of potential for sustainable production, but it will be challenging to get them to be extensively employed because of problems with technology, organisations, and ethics. The first problem is that it's hard to put data together. In manufacturing, it's common to have old systems, proprietary software, and data repositories that were never supposed to function together. Factories need more than simply strong infrastructure to aggregate real-time data from multiple sources, such as PLCs, SCADA systems, IoT sensors, ERP platforms, and environmental monitors. They also need better interoperability standards. Sadly, a lot of factories still don't have these. If a digital twin doesn't have clean, continuous, and contextually correct data, it won't perform well, much alone deliver useful information about sustainability.

Second, the high cost and lack of skills are huge problems, especially for small and medium-sized firms (SMEs). You need to invest a lot of money on sensor networks, edge or cloud computing resources, AI experts, and cybersecurity solutions to construct and maintain AI-powered digital twin ecosystems running. Many small and medium-sized firms don't produce a lot of money, thus they might not be able to pay the initial costs, even though they will save money in the long term. There is also an increasing lack of expertise at the intersection of AI, industrial operations, and sustainability science. When workers don't have skills that cross departments, attempts to put systems into place can fail. This means that the systems may not be used sufficiently or may not be set up effectively to reach sustainability goals.

When it comes to ethics, issues about who owns and has access to data are quite crucial. Digital twins need a steady flow of data that includes not only information about machines but also information about humans, like how well they work, when they work, and even biometric markers in more complicated situations. If this data isn't handled properly, it could be

used for harmful things, which makes people worry about privacy, getting authorisation from employees, and the misuse of private information. A lot of companies still don't have strong data governance policies, mechanisms to keep data anonymous, and clear ways to gain consent, even though they are all highly crucial.

There is also a rising chance that algorithms will be hard to understand and unfair. Digital twins with AI models may make suggestions or forecasts that look right at first, but they could be based on training data that is biassed or erroneous assumptions. If these models employ biassed data to make decisions regarding sustainability, including how to use resources or how to choose suppliers, they could unintentionally keep environmental injustice going or encourage results that seem "optimal" but are ethically wrong. A lot of AI systems are like black boxes, which makes this issue even worse because it's hard for those who care to know how judgements are made.

Another huge problem is that IT companies use digital twins to make their attempts to be more environmentally friendly sound better than they really are. Just putting in a digital doppelganger doesn't mean that a factory is sustainable. It's important to know how it will be used, how open the process is, and whether an outside party can evaluate and verify improvements in sustainability. If this method isn't kept under check, it could make people lose faith in AI-driven sustainability as a whole.

Lastly, we are always worried about risks to cybersecurity. Digital twins are getting more and more connected and able to work on their own. However, this also makes them more vulnerable. If a digital twin system were to be hacked, it might interrupt operations, change environmental data, or even report emissions and compliance metrics falsely. This would affect the company's reputation and make it harder for it to obey the standards.

In short, AI-powered digital twins can help make manufacturing more sustainable, but you need to be very careful about how you utilise them and make sure that you follow the rules and put people first.

IX. FUTURE DIRECTIONS AND RESEARCH OPPORTUNITIES

There is still a lot of room for growth and new ideas in AI-powered digital twins in sustainable manufacturing. As industries aim towards net-zero emissions, circular economies, and smart factories, digital twins will likely progress from being employed in certain situations to being significant pieces of their overall strategy. One thing that needs to happen in the future is the development of standard rules for how to make digital twins more environmentally friendly. There isn't a single standard right now that informs us how to use a digital twin to keep track of, score, or check for sustainability. Cross-industry standards that specify key performance indicators (KPIs) for energy use, emissions, waste reduction, and life-cycle effect can aid with future study. Digital twin systems would be built with these standards in mind. These standards would let manufacturers around the world check and improve their environmental performance by letting different systems work together, setting benchmarks, and making sure they follow the rules.

Learning how to adapt and being aware of what's going on around you are also very essential topics of study. AI algorithms nowadays can look at data from the past and use it to generate predictions. But the next generation of digital twins needs to be able to adjust in real time when things in the environment change, including difficulties in the supply chain that come up out of the blue, legislative changes, or weird weather. Adding transfer learning and zero-shot learning models could make digital twins more flexible in diverse industrial settings without having to train them from scratch. Digital twins also need to make AI models easy to understand so that they are more reliable and open. In the future, systems should be able to properly explain why they make specific suggestions, especially when those proposals affect worker safety, productivity goals, or sustainability goals.

There is also a lot of research going on in the areas of edge AI and distributed intelligence that needs to be done. As 5G and edge computing technologies improve, it is more possible that AI processing will be moved closer to where data is created, such on the shop floor, in sensors, or even inside machines. This decentralisation would speed up decision-making, make it more autonomous, cut latency, and allow for real-time micro-level improvements in sustainability. It will be very vital to look on energy-efficient edge AI models to make sure that the systems that are supposed to be better for the environment don't use too much compute power themselves.

Another essential thing to think about is how to use blockchain technology and digital twins together to check for sustainability and keep track of carbon emissions. Blockchain can make sure that the data used to show compliance or get carbon credits is transparent, immutable, and easy to check. Blockchain and AI-powered twins might be able to work together to create reports on sustainability that can't be edited. Governments and investors want corporations to be more responsible for their environmental, social, and governance (ESG) operations, therefore this will be vital.

Designing digital twins with people in mind is another crucial topic that hasn't been addressed enough. Models of the future need to think about more than simply how effectively machines perform. They also need to think about the

psychological, sociological, and ergonomic elements of the workers. Researchers should look into how digital twins can maintain track of and improve both people's health and the health of the environment at the same time. This will help make sustainability more complete.

Lastly, we can make digital twin technology easier for everyone to use by making open-source platforms, low-code interfaces, and AI-as-a-service models. These would help small and medium-sized firms (SMEs) and developing countries get started more easily. This would spread the benefits of sustainable manufacturing more evenly across all industries around the world. As partnerships between schools and corporations grow, the ecosystem that turns AI-powered digital twins from advanced simulations into the nervous systems of future-proof production will also grow.

X. POLICY IMPLICATIONS AND THE ROLE OF GOVERNANCE

As AI-powered digital twins become increasingly common in sustainable manufacturing, rules and regulations become not only important but also vital. It is important to have clear, moral, and enforceable regulations in place to make sure that this powerful technology is used correctly. This technology could transform the way businesses watch, control, and improve their impact on the environment. Without good governance, the same tools that are supposed to protect the environment can be used for greenwashing, data manipulation, or short-term economic gains that damage long-term environmental goals. So, businesses, government agencies, regulatory bodies, and international organisations need to work together to set standards, define what ethical use is, and come up with measures to make sure that people respect the laws when they utilise digital twins in production.

One of the most critical things that policy needs to do is make sure that all digital twin platforms have the same sustainability indicators. There is no one approach that everyone in the globe agrees on for digital twins to keep track of carbon emissions, energy use, water use, or garbage reduction. This indicates that there is a chance for selective reporting and conflict. The ISO, IEEE, and the UN's Sustainable Development Goals (SDGs) are all examples of governments and organisations that develop standards. They should concentrate on making certification systems and taxonomies that clearly define what an AI-enabled sustainability activity is and how it can be verified. Then, these suggestions might be added to the program's architecture as default settings, making sure that the system is compatible from the start.

Other dimensions of governance include preserving intellectual property, data privacy, and cybersecurity. Digital twins need a lot of operational, environmental, and sometimes even personal data, therefore data governance needs to be very strong. Policymakers need to make sure that the standards are followed that say there must be explicit data use policies, encryption methods, audit trails, and frameworks for user approval. When doing business across borders, this is very significant. For example, manufacturers may send digital twin data to their worldwide headquarters. This makes us think about data jurisdiction and sovereignty. Laws like the GDPR in Europe or India's Digital Personal Data Protection Act might be changed to include industrial AI systems and stop people from utilising data about sustainability in the wrong way.

Incentive-based governance can also get more individuals to utilise it. Small and medium-sized enterprises that can't afford to buy AI-powered digital twins can get aid from green subsidies, tax credits, and ESG-linked financing. You can also use public-private collaborations and sandboxes to try out rules that strike a good mix between keeping an eye on things and letting new ideas flourish. Education and capacity building are also key parts of government. This means that everyone who works in an industry, from factory workers to sustainability officials, needs to know how to understand, manage, and improve digital twin ecosystems in a way that is healthy for people and the environment.

It's equally as important to work with other countries. Everyone should want to be sustainable, and all countries should use digital twins in manufacturing the same way. This includes coming to an agreement on standards, sharing digital infrastructure, and working together on research all across the world. Digital transformation can help groups like the UN, WEF, and WTO make sure that national policies are in line with global efforts to safeguard the environment.

Policy and governance aren't just about control; they're also about giving people the tools they need to do things. They create the trust, responsibility, and structure that AI-powered digital twins need to become useful tools for long-term production at a time when climate change is crucial and industries need to shift.

XI. CONCLUSION

When climate change, resource depletion, and regulatory demands are changing how things are created around the world, the combination of artificial intelligence and digital twin technologies is a big deal. This study paper looks into how AI-powered digital twins could be used to keep an eye on how sustainable manufacturing is in real time. Digital twins are more than just a buzzword in the Industry 4.0 revolution. When used with smart analytics, they become very powerful tools for modelling, keeping an eye on, and improving environmental performance at speeds and accuracies that no other tools

can equal. They build a real-time, learning model of the factory floor that changes all the time depending on data from the real world. This turns sustainability into a natural, continuing activity instead than a job that has to be done.

The wonderful thing about this fusion is that it can turn raw, muddy industrial data into usable, real-time information that helps people make decisions that matter. Digital twins keep track of essential sustainability metrics including energy use, carbon emissions, water use, trash production, and equipment efficiency. This lets you see the whole picture of how well your environment is performing. These systems don't just show what is; they also guess what might happen. They do this by using AI to generate predictions and look for things that are out of the ordinary. Manufacturers can figure out how changes in materials, methods, or ways of doing business will effect the future. This allows them think ahead about difficulties with sustainability and come up with solutions that are good for both the economy and the environment.

Big corporations like Siemens, GE, Unilever, and BASF are already using this technology in the real world. These companies have proved that digital twins powered by AI may help make products that are better for the environment, consume less energy, make less waste, and even keep equipment from breaking down. These case studies show that being environmentally responsible and going digital are not mutually exclusive; they are both vital for staying competitive in the future. Companies who use digital twins to keep track of their sustainability are not only following the law, but they are also protecting their enterprises from the unpredictable nature of environmental dangers and market changes.

But there are complications with the journey. We saw that there are still huge difficulties with things like data integration, cybersecurity, talent development, algorithmic bias, and ethical governance. There is also a lot of work that needs to be done to provide universal rules on how to use digital twins to measure sustainability. This is to keep things from being inconsistent or to stop people from trying to "greenwash." These problems are real, but they shouldn't deter people from working together to make sure that industrial AI has a responsible and fair future. This needs to happen, and policymakers, engineers, ethicists, and business leaders should all work together to make it happen.

Governance will be very crucial in deciding how this technology will be used on a bigger scale. Governments can make sure that digital twins are good for the public as well as for business by developing smart regulatory frameworks that promote their usage, protect privacy, mandate openness, and are in accordance with global sustainability goals. We need to stop thinking about new ideas just for the sake of having them and start thinking about them with a goal in mind. We should not just look at how advanced technology is, but also how much it helps individuals and the globe.

In the future, AI-powered digital twins will be more personalised, decentralised through edge computing, more closely linked with blockchain for traceability, and machines and people will work together more intimately. These smart devices will become the brains of smart factories as the industrial industry strives to find a balance between efficiency and sustainability. They will give everyone in the firm real-time information about the environment that helps them make decisions.

In short, AI-powered digital twins aren't a silver bullet, but they are a really valuable way to make business more environmentally friendly. Their use is a clear move away from reactive sustainability measures and towards a future that is smart, proactive, and based on data. Digital twins not only indicate what can be done, but they also show how to get there as business leaders, policymakers, and researchers work together to protect the environment and make business better.

X. REFERENCE

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