

Digital Twins in Mechanical Engineering, and a Brief Overview on Decarbonization and Sustainable System Optimization

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Abstract: Climate change is pushing industries to cut down emissions fast, and mechanical engineering is playing a key role in that shift. One technology making a real difference is the digital twin — a live, virtual model of a machine or system that mirrors what's happening in real life. It lets engineers track performance, test ideas, and catch problems early, all without interrupting operations.

This paper looks at how digital twins are helping reduce carbon emissions across fields like manufacturing, energy, transport, and industrial systems. The benefits are clear: more efficient designs, better maintenance planning, and smarter use of energy. DTs also help track emissions in real-time and spot patterns that wouldn't be obvious otherwise. In some setups, they've helped cut operational emissions by nearly 30%.

Still, the use of digital twins isn't as widespread as it could be. A lot of companies struggle with setup, especially when different machines and platforms don't work well together. There's also a lack of training and no strong, shared framework for using DTs in mechanical systems specifically.

This paper explores those challenges and suggests how industries can move forward — by improving standards, encouraging collaboration, and giving engineers the tools and knowledge to apply this technology well. Digital twins aren't just helpful add-ons; they have the potential to reshape how we design, monitor, and improve mechanical systems for a low-carbon future.

Keywords: Digital Twin, Mechanical Engineering, Decarbonization, Carbon Footprint, Sustainability, Real-time Simulation, Energy-efficient Design, Predictive Maintenance, Emission Tracking, System Optimization, Lifecycle Management, Low-carbon Innovation.

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I. INTRODUCTION

Mechanical engineering is starting to change in a big way. With rising pressure on industries to meet climate goals, engineers are being asked to not only design systems that perform well, but also ones that use less energy and create fewer emissions. Sectors like manufacturing, transport, and energy — all major contributors to carbon output — are now looking for ways to cut down. One tool that's getting more attention is the digital twin.

A digital twin is basically a virtual model of a real system that updates constantly using data. It was first used in aerospace and advanced manufacturing, but it's now being

applied more widely in mechanical engineering. What makes it so powerful is its ability to track, test, and improve how machines work — often before anything goes wrong. These systems combine sensor data with AI, physics models, and the Internet of Things to give engineers a much clearer picture of what's happening in real-time.

With that level of control, engineers can make better decisions. They can reduce waste, fix things before they break, and design machines that are cleaner and more efficient. In terms of fighting climate change, that's a big deal. Digital twins make it easier to lower emissions by helping systems run smarter and cleaner throughout their lifecycle — not just after they've been built.

But there are still challenges. Setting up a digital twin system isn't always simple or cheap. Data from different parts of a system may not connect smoothly. There aren't enough clear rules or standards. And it's not always obvious how to measure the carbon savings in a way that fits mechanical systems.

This paper looks at what digital twins can do for decarbonization in mechanical engineering. It also looks at what's holding them back — and what could help them go further. With the right support and smarter adoption, digital twins could become one of the key tools in building sustainable systems for the future.

II. ABBREVIATIONS

Digital twin (DT); Internet of Things (IoT); Artificial intelligence (AI); Heating, ventilation, and air conditioning (HVAC); Extended reality (XR); Product lifecycle management (PLM).

III. DIGITAL TWINS

Digital twins are virtual copies of real machines or systems. They act like mirrors of the physical world. Data comes from sensors, control systems, and simulations. Machine learning also plays a role. All this information helps the model stay updated in real-time. It is not just a frozen simulation. It moves and changes as the real system does.

In mechanical engineering, digital twins are everywhere. Engines, turbines, HVAC units, robotic arms. Even full production lines can have them. Take a jet engine as an example. Its digital twin can track heat flow. It can also predict wear. It might even suggest when to do maintenance. All of this comes from live usage data.

Several technologies make this work. IoT collects the data. Cloud platforms store and process it. AI studies the patterns and gives predictions. Together, these tools give engineers an edge. They can test new designs without stopping the machine. They can catch problems early. They can improve performance. This is changing the way mechanical systems are built, fixed, and upgraded.

IV. IMPACT OF DIGITAL TWINS IN MECHANICAL ENGINEERING

Digital twins are changing how mechanical engineers work. They affect design, monitoring, and maintenance. One big shift is in product design. Engineers can now test and validate parts in a digital space. They see how components behave under different conditions. This happens before building a physical prototype. The result is faster design, lower costs, and often better ideas.

In real-world operations, digital twins make maintenance smarter. They gather live data from machines. That data helps spot early signs of wear. Engineers can predict failures and plan fixes in advance. This avoids sudden

breakdowns and keeps systems reliable. Machines also last longer when cared for this way.

Sustainability is another area. Digital twins help improve energy use. They support efforts to cut carbon output. Systems can be tuned for better efficiency. For example, vehicle designs can be made more aerodynamic. HVAC units can run with less energy. The impact spreads across many areas. Mechanical engineering is becoming sharper, greener, and more guided by data.

V. GENERAL INDUSTRIES UTILIZING DIGITAL TWINS IN RELATION TO MECHANICAL ENGINEERING

➤ Aerospace Industry

Digital twins are used for aircraft engines, fuselage parts, and flight systems. They simulate stress, fatigue, and heat performance. They also model flight conditions. This helps with predictive maintenance and better safety. Fuel use can be reduced as well. Companies like Rolls-Royce and GE already track jet engines in real-time using this tech.

➤ Automotive Industry

In cars, digital twins simulate vehicle movement and engine output. For electric vehicles, they track battery behavior. They can also model whole production lines. The result is faster design checks and real-time diagnostics. Efficiency improves. Cars get lighter and cleaner, with lower emissions.

➤ Manufacturing Industry

Smart factories rely on digital twins for machines, robots, and conveyor belts. Entire workflows can be copied. This helps plan maintenance before breakdowns. It reduces downtime and makes processes smoother. Quality control and supply chains also get better with these tools.

➤ Energy Sector

Digital twins play a big role in wind, solar, and gas power. They monitor turbines, generators, and power grids. This boosts efficiency and extends the life of equipment. In renewables, they help pick the right spot for panels or turbines. They also manage how renewable power is fed into the grid.

➤ Oil and Gas Industry

Oil rigs, pipelines, and refineries are mirrored with digital twins. They are used to track corrosion, prevent failures, and improve refining steps. Safety is also a focus, especially in dangerous sites. They make sure environmental rules are followed while operations run smoothly.

VI. THE FUTURE OF DIGITAL TWINS IN MECHANICAL ENGINEERING

The future of digital twins looks big. Growth will be fast as the tech keeps improving. AI, edge computing, IoT, and real-time analytics will drive it. Machines will not just predict problems. They will fix themselves. A system like an engine or HVAC unit could recalibrate on its own. It would adjust to

changing conditions and run at top efficiency. Emissions would stay low without needing human input.

Sustainability will push this even further. Climate goals mean new systems will be built with digital twins from day one. The entire lifecycle will be modeled. From sourcing raw materials to building, using, maintaining, and finally disposing. This gives engineers full visibility. They can choose greener materials. They can cut energy use. They can design products that leave a smaller footprint before they even hit production.

Collaboration will also grow. Supply chains and projects are more global and complex. Digital twins will connect designers, factories, and operators in real-time. Teams across different countries will work inside the same digital space. Full systems can be tested and improved before

anything is built. This will speed up innovation, shorten launch times, and add transparency.

Extended reality will play a role too. AR and VR combined with digital twins will let engineers step inside machines virtually. They can run design reviews in life-size models. Maintenance teams can troubleshoot remotely. Training can be faster and more natural with these immersive setups.

The future is not just about saving money or boosting efficiency. It is a shift in how engineering is done. Smarter. Greener. More connected. Digital twins will become standard. They will change how systems are designed, operated, and improved in the years ahead.

VII. TABULAR OVERVIEW OF LEADING DIGITAL TWIN PLATFORMS

Table 1 Tabular Overview of Leading Digital Twin Platforms

Platform	Provider	Key Features	Industries Served
Azure Digital Twins	Microsoft	Real-time IoT data integration, spatial intelligence, analytics, scalability	Smart buildings, energy, manufacturing, healthcare
Siemens NX & Teamcenter	Siemens	CAD/CAE integration, product lifecycle management (PLM), simulation tools	Automotive, aerospace, manufacturing, heavy machinery
Dassault Systèmes 3DEXPERIENCE	Dassault Systèmes	End-to-end product design, simulation, lifecycle modelling	Aerospace, automotive, consumer goods, construction
IBM Digital Twin Exchange	IBM	IoT integration, AI/ML-driven insights, scalable cloud support	Utilities, construction, manufacturing, transportation
GE Digital Twin Vernova	General Electric	Asset performance management, industrial analytics, predictive maintenance	Power, oil & gas, aviation, transportation

VIII. CHALLENGES AND CONSIDERATIONS IN IMPLEMENTING DIGITAL TWINS IN MECHANICAL ENGINEERING

Digital twins bring major benefits, but their use in mechanical engineering also faces significant challenges. A key issue is data integration. Mechanical systems rely on many sensors, controllers, and simulation models, all of which must work together. Bringing real-time data from different sources into one digital twin model is complex. Legacy equipment makes this harder, and often requires custom solutions and clear interoperability standards.

High development and deployment costs also limit adoption. Building a detailed digital twin demands investment in IoT devices, cloud platforms, simulation tools,

and skilled staff. For small and mid-sized firms, this cost can be too high. Even after deployment, systems need constant updates and maintenance, which add to the long-term expense, especially for large or complex assets.

Data security is another concern. Digital twins depend on continuous collection and transfer of operational data, which creates risk of cyberattacks and data breaches. In areas such as aerospace, automotive, and defence, where systems are critical, strong cybersecurity and governance measures are essential to protect both intellectual property and operational safety.

Model accuracy is equally important. A digital twin is only reliable if its input data and models are accurate. Faulty sensors, calibration errors, or environmental noise can

produce misleading results. To stay reliable, the model must be checked regularly against the performance of the physical system. This requires expertise and computing resources.

Finally, there are organizational and human barriers. Digital twins need teams with skills that cut across mechanical engineering, data science, software development, and systems integration. Many traditional engineering teams do not yet have this mix. Resistance to change can also slow adoption. Solving these cultural and skills-related issues is as important as overcoming the technical ones if the full potential of digital twins is to be achieved.

IX. DECARBONIZATION

Decarbonization is the process of cutting down carbon dioxide (CO₂) and other greenhouse gas emissions to reduce the impacts of climate change. In mechanical engineering, it means redesigning systems, machinery, and processes so they create less carbon over their lifetime. This may involve moving to cleaner energy sources, improving efficiency, selecting low-impact materials, or using technologies that reduce emissions from production to disposal. With global frameworks such as the Paris Agreement and corporate net-zero commitments in place, decarbonization has become a core measure of progress and innovation rather than an optional goal.

X. DIGITAL TWINS AS ENABLERS OF DECARBONIZATION

Digital twins (DTs) provide a practical way to support decarbonization in mechanical engineering. They create virtual, data-driven models of physical systems that can be tested, monitored, and optimized in real-time. Decisions that once relied on trial-and-error prototyping or static models can now be evaluated dynamically under many different conditions.

For example, engineers can simulate the thermodynamic cycle of an engine or the hydraulic flow of a pump in a digital twin. This makes it possible to spot inefficiencies and explore better alternatives before building or modifying equipment. DTs also allow designs to be checked against emissions benchmarks, giving engineers and stakeholders a clear view of the carbon impact of every change. This shifts decarbonization from being a compliance requirement to being part of the design process itself.

In production environments, digital twins can reduce idle times, improve equipment layouts, and optimize energy use. These system-level improvements, guided by live simulation and predictive tools, help mechanical engineering move toward more carbon-conscious practices.

XI. ENERGY-EFFICIENT DESIGN, PREDICTIVE MAINTENANCE, AND RENEWABLE INTEGRATION

A key way DTs support decarbonization is through energy-efficient design and operation. Systems such as turbines, compressors, and HVAC units can be modeled virtually so engineers can adjust parameters like airflow, heat loss, friction, or vibration. By addressing inefficiencies before construction, products start out with a lower carbon footprint.

Once systems are in use, digital twins also enable predictive maintenance. Instead of relying on fixed schedules or reacting to breakdowns, engineers can detect problems early. For instance, identifying bearing misalignment or heat buildup in a rotating machine allows for quick intervention. This prevents energy waste, avoids downtime, and reduces emissions caused by failures or replacements.

Digital twins also help integrate renewable energy into mechanical systems. They can simulate how factories adapt to variable solar input, or how electric drivetrains synchronize with charging infrastructure. These simulations provide a testbed for adopting renewables with minimal disruption. By doing so, DTs help industries move away from fossil-fuel dependence in a smoother and more efficient way.

XII. CONCLUSION

Digital twin technology is reshaping mechanical engineering by creating real-time digital counterparts of physical systems. Using data from sensors, operational logs, and design inputs, DTs allow detailed modeling and optimization. They improve design accuracy, support predictive diagnostics, and extend system lifecycles, shifting engineering from a reactive approach to a proactive one.

Their greatest impact lies in decarbonization. Mechanical systems contribute heavily to industrial energy use and emissions, and DTs make it possible to reduce this footprint at every stage—from design to end-of-life. Through simulations, forecasting, and optimization, engineers can design systems that consume less energy and emit less carbon while still meeting performance goals.

Digital twins also encourage the use of renewable energy and energy-efficient designs. Their role in predictive maintenance avoids wasted resources, and their ability to model renewable adoption ensures flexibility as industries adapt to cleaner energy inputs. These capabilities are crucial for meeting global sustainability and net-zero targets.

Challenges remain, such as high costs, issues of interoperability, cybersecurity risks, and the need for cross-disciplinary expertise. For DTs to become mainstream, organizations must weigh initial investment against long-term gains and establish clear standards to support adoption.

In sum, digital twins are no longer experimental tools. They are now a critical part of sustainable engineering,

linking performance optimization with climate goals. By helping industries cut emissions and adopt greener practices, DTs will play a defining role in shaping the future of mechanical systems in the 21st century.

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