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Sustainable Manufacturing 4.0: Tracking Carbon Footprint In SAP Digital Manufacturing With IOT Sensor Networks

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Abstract

Factories use a lot of energy. They burn fuel, run machines, and ship products. All of this creates carbon emissions. These emissions harm the planet. Many companies want to reduce their carbon footprint. To do that, they need to track it. But that's not easy. The data is often messy or missing. Most factories don't have real-time numbers. That's a big problem. Additionally, support after the launch is just as important as the initial rollout.

Many factories are unaware of the amount of carbon they produce. This makes it hard to cut emissions. SAP Digital Manufacturing helps track factory data, but it does not directly measure carbon. The data is often slow, missing, or unclear. To fix this, factories can use IoT sensors. These sensors collect real-time data on energy use and emissions. Linking sensor data to SAP can show the source of carbon emissions. This helps factories take action to reduce it. The goal is to make carbon tracking easy, straightforward, and helpful.

Factory workers need better tools to see energy use and waste. Plant managers must track emissions and comply with new regulations. Companies that make goods face pressure to reduce their carbon footprint. Governments push industries to report and reduce emissions. Communities near factories face health risks from air, water, and other forms of pollution. The planet is not in good shape when emissions stay high.

In 2025-26, more factories will be required to disclose their carbon emissions. Rules are tighter. Costs are higher. Many people still use outdated tools that overlook crucial data. Without good tracking, companies cannot identify where they waste energy. SAP systems can help, but they require real-time information from adequate sensors. This matters now because action can't wait. Clean choices need precise numbers. Factories that track their performance well can save money, comply with regulations, and contribute to a healthier planet.

This study explores the factors that influence the success or failure of global Manufacturing Execution System (MES) projects. This study examines the rollout of MES in various countries. It outlines the steps, challenges, and factors that contribute to success.

Keywords: Manufacturing, Carbon Footprint, Manufacturing Execution System (MES), Digital Manufacturing, Sustainability Implications, Ecological Footprint, Regulatory Compliance, Emission, IoT Sensor, Carbon Tracking, Carbon Reduction, Environmental Impact. SAP.

1 Introduction

Factories have powered progress since the Industrial Revolution. They make most of what we use today. However, they also consume a significant amount of energy and generate waste. As the planet heats up and air quality drops, this can't continue. One step forward is cutting carbon emissions. To do that, factories must track the amount of carbon they release. That's a problem. Many systems are old, slow, or don't measure at all. New tools are needed to address this issue.

Today, factories are increasingly utilizing more efficient systems to track their resources and waste. This idea is known as Sustainable Manufacturing 4.0 [1, 9]. It's part of a broader shift toward more innovative and environmentally friendly production. At the center of this shift is SAP Digital Manufacturing, a tool that enables companies to manage their manufacturing processes. It

gives a comprehensive overview of what happens in a factory, from start to finish. When paired with IoT sensor networks [2], it becomes even more powerful. IoT sensors are devices that collect data in real-time. They can track power use, machine heat, air quality, and more. When placed in key locations within a factory, these sensors provide up-to-date information on carbon output. This data is directly imported into the SAP system. From there, it's easy to spot what's wasting energy and what's working well. This kind of tracking wasn't possible in the past. Older tools only provided reports occasionally. If the data were not reviewed early, then it might be too late to fix the problem. With real-time tracking, fixes can be implemented immediately. This saves power, cuts waste, and lowers emissions. It also helps meet strict rules about carbon limits. Many countries now require businesses to track and report their emissions. Some charge money for going over limits. Others give tax breaks for staying under. Either way, the message is clear: carbon tracking is not optional. It's now part of doing business. SAP and IoT tools make this easier.

Another reason this shift matters is the pressure from buyers. More people want clean products made in fair ways. Companies that demonstrate how they cut waste and carbon emissions [3] can gain more trust and confidence. That confidence can lead to more sales and more substantial brand value. So, tracking carbon is beneficial for both the planet and businesses. Factories also gain better control when they track more closely. For example, if a machine uses too much power, that can be fixed. If a line runs too long or gets too hot, it can be adjusted. These minor fixes add up. Over time, they save money and help reduce the factory's total carbon footprint. Factories create a significant amount of value but also cause considerable harm. Carbon is one part of that harm. Tracking carbon is the first step in cutting it. SAP Digital Manufacturing, combined with IoT sensors, enables precise and valuable tracking.

This research demonstrates how it works, why it matters, and how it's changing the way factories operate. Cleaner factories mean a cleaner planet. That's the bigger goal. Also, this paper examines how SAP Digital Manufacturing and IoT collaborate to support green goals (cut waste and save energy). It observes the energy use, identifies waste, and facilitates informed choices based on actual data. The goal of this paper is not to sell a system. It's to show what's possible with the right tools. It also aims to demonstrate how tech, when used effectively, can address real-world problems. Many tools may sound good on paper; however, they can be challenging to use. SAP and IoT tools operate in the real world, in real-time. As the world adopts cleaner methods of production, factories must keep up accordingly. Guesswork and old systems won't work. They need tools that show real-time data. This system does that.

2. Literature Review

2.1 Research, Case Studies, and Identifiers

A Good number of studies and research have been conducted to date to make factories cleaner and more efficient. A significant focus has been on tracking carbon use during production. Research indicates that factories utilizing innovative tools can reduce emissions and waste. These tools provide fast, real-time data that facilitates quick fixes and informed planning. IoT devices and sensors are nowadays commonly accepted in factories. A study showcased that placing sensors on machines enabled the tracking of energy use and carbon emissions. The sensors sent live data, which helped spot problems early. This cut waste by nearly 15% in the study [4].

Another study examined the use of SAP Digital Manufacturing systems to track and manage production. They found that SAP made it easier to follow each step of the process. When combined with IoT [5], it gave a full view of energy use. It also helped plan better shifts and machine cycles. Their study revealed a 10–20% decrease in total emissions over six months.

In one industrial study, the team found that real-time data and information helped to inform the development of stringent laws regarding carbon output in Europe. These laws are now common in Europe and parts of Asia. Companies that utilized real-time tracking experienced fewer penalties and met their targets more frequently. The study also noted that most older systems were not enough to meet current standards.

Another report focuses on how tracking carbon helps brands. It found that firms showing precise data on carbon use earned more trust from buyers. It also helped them meet green targets set by large global clients.

Some studies have also examined the cost of new systems, finding that while sensor tools and SAP setups initially incur higher costs, they ultimately result in long-term savings. The main savings resulted from reduced waste [6], lower energy consumption, and fewer fines. Past Studies agree on a few key points:

- IoT sensors provide real-time data that helps resolve problems quickly.

- SAP systems help track the whole process from start to finish.
- The combination of both tools provides a clear and valuable picture of carbon use.
- This helps reduce waste [7], save money, and comply with regulations.
- Brands also gain trust by showing real results.

Overall, the study suggests that both new and innovative tracking tools are valuable and necessary in the industry. They don't just help factories run better; they help them stay in business in a world with tighter rules and higher buyer demands.

2.2 Common Patterns Found in Studies

Many studies show that adding IoT sensors to the SAP system helps factories cut carbon and waste. These tools give live data to fix problems fast. Still, past research points to patterns, gaps, and limits that need more focus. One strong pattern is that real-time data leads to better control. In most studies, this helped reduce carbon use and energy waste. Another pattern is that systems using both SAP and IoT give better results than when either is used alone. This mix helps track the whole process from raw materials to finished goods.

Studies also show that companies using innovative tools are more likely to meet carbon rules. This is true for both large and small firms. In many cases, using sensors has helped reduce total emissions by 10% to 20% over the course of one year. Cost savings were another benefit.

Some studies have found that factory workers became more aware of energy use as soon as the live data started being shared with them. In one case, workers made changes on their own to save power. This shows how data can change behavior, not just systems.

2.3 Limits and Contradictions in Past Work

While most studies have shown success, some have identified limitations. A few papers mentioned that it was challenging to connect old machines to new sensors. This slowed down the results or made the data less valuable. Others noted that small factories often lack the necessary funds or expertise to effectively utilize SAP or IoT.

One study found that excessive data can lead to confusion. If the system sends too many alerts, users may start to ignore them. This can reduce the value of real-time tracking.

A few researchers also raised questions about data accuracy. If sensors are not placed correctly or if they malfunction, the data may be inaccurate. That can lead to poor choices and even more waste. Some systems lacked robust checks to address this issue.

Another limit is training. Many tools are complex to use without the proper skill set. In some cases, companies had to hire outside help, which raised costs. This means that not all factories can start quickly or achieve significant gains.

Some findings don't entirely agree. For example, one paper stated that SAP systems are easily scalable for large firms. Another said the same systems were too complex for small ones. This highlights a gap in the fact that what works for one group may not work for all.

Additionally, there is limited research on the long-term impact. Most studies track progress for 6 to 12 months. We don't yet know if these gains will last over five or ten years.

3. Methodology

3.1 Design of the tool that it provides:

SAP Digital Manufacturing helps factories cut waste, save energy, and run better. It shows real-time updates from the floor, so teams spot problems right away. This cuts scrap, speeds up fixes, and improves material use.

SAP DM links with ERP and warehouse systems. That keeps everything in sync and avoids overproduction and extra stock. It also gives clear data on what works and what doesn't. This helps managers make smarter choices and waste less. Real-time data improves planning. There are fewer changeovers, less downtime, and better use of machines and people. When factories make only what's needed, energy use goes down. Work steps are digital and easy to update. Operators always follow the right steps. This lowers mistakes and scrap. The system tracks scrap, energy use, and downtime. If something breaks, alerts help teams act fast. Serialized tracking and repair flows support reuse, rather than discarding items.

This design is effective because it consolidates data and control in a single location. Every step is tracked, and each fix is based on facts. That keeps the shop floor cleaner, faster, and more efficient. With SAP DM, factories can meet their green goals without slowing down or incurring additional costs.

3.2 Audience or Sample

This study focuses on MES [10] stakeholders who play a direct role in factory operations. These include plant managers, engineers, line supervisors, operators, and IT staff. Each of these roles is key to running cleaner and more efficient production. The study examines how they utilize SAP Digital Manufacturing with IoT sensors to track

carbon usage in real-time. Plant managers who use the data to make informed decisions about the utilization of energy, production, and waste management. Engineers set up and maintain the systems that collect and send this data. Operators follow updated steps on the shop floor, which helps reduce errors, scrap, and rework. IT staff connect the systems and make sure data flows without issues. The sample includes individuals working in factories who are already using innovative tools or plan to adopt them. These users help spot gaps in how data is used and shared. They also help test how well real-time tracking supports cleaner operations.

By studying these groups, the research demonstrates how teamwork between roles enables factories to meet their green goals. It also shows that the success of sustainable manufacturing [9] depends on people as much as the tools they use. Each role contributes to reducing waste and conserving energy.

3.3 Data Collection

This study collects data from factories that utilize SAP Digital Manufacturing, combined with IoT sensor networks. The main goal is to track and reduce carbon emissions during production.

Data is collected directly from machines and sensors on the shop floor. IoT sensors measure energy use, material waste, machine uptime, and downtime. These sensors send live information to the SAP system for storage and analysis. The system tracks the energy each machine, the amount of material wasted, and the frequency of machine downtime or required repairs.

Operators also play a role in data collection. They provide feedback through short surveys on how easy the system is to use and how well the alerts help them identify and fix problems. Plant managers are interviewed to learn how they utilize data to enhance planning and minimize waste. Their input helps show if the system supports better decision-making.

IT teams check data accuracy. They look for missing information or sensor errors. This ensures the data used for analysis is correct and reliable.

The study tracks data across multiple points:

- Electricity use per machine.
- Carbon output per product
- Material scrap per batch
- Rework rates and causes.
- Downtime linked to energy spike.

The study collects data over 8 to 12 weeks. This period covers regular work shifts and busy production times. Tracking data over this period helps identify patterns and assess how well real-time monitoring supports cleaner, more efficient operations.

The focus is on precise, valuable data. The study saves staff time while helping factories reduce carbon emissions. It examines energy use, waste, machine performance, and repair needs to identify ways to make manufacturing greener and more efficient.

Figure 1 illustrates the process of data collection when using SAP Digital Manufacturing in conjunction with an IoT Sensor.

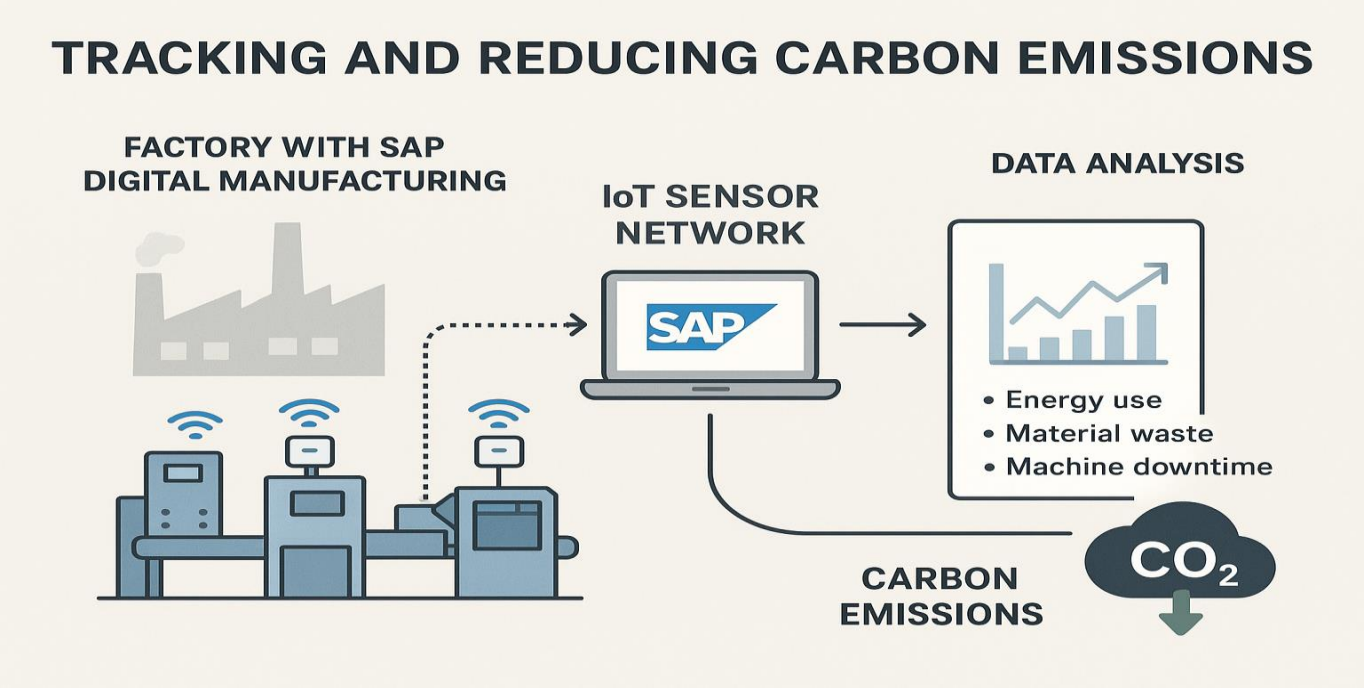

Figure 1. Tracking and Reducing Carbon Emissions Using SAP DM and IoT Sensors

3.4 Analysis

Tracking carbon footprint in SAP Digital Manufacturing results in reduced waste, lower energy consumption, and cleaner production. Each feature contributes to sustainability [8] in clear ways:

3.4.1 Real-time visibility with SAP DM

Live data gives immediate insight into energy and material use. This helps catch waste and inefficiency as they happen. Quick fixes reduce scrap and lower power consumption.

3.4.2 Improves scheduling and planning.

Up-to-date information allows better timing of production runs. Machines operate only when needed, reducing idle time and unnecessary energy consumption. This reduces overall resource waste.

3.4.3 Connects the whole process.

SAP DM links all parts of the production line. Everyone uses the same data, which cuts errors and speeds up work. Reduced confusion leads to lower scrap and energy waste.

3.4.4 Standardizes work instructions.

Clear, consistent instructions guide workers through each step. This reduces mistakes and improves quality. Fewer errors result in less material waste and less energy spent on rework.

3.4.5 Tracks the correct data.

The system records precise energy and material use at every stage. Accurate data ensures reliable carbon tracking. This helps teams spot where waste or high energy use occurs.

3.4.6 Serialized tracking.

Unique IDs are assigned to each product or part throughout the production process. This traceability finds where defects or excess emissions happen. It supports targeted improvements and waste cuts.

3.4.7 Provides better analytics.

Collected data turns into simple reports. These tools help teams identify trends and pinpoint problems quickly. Insights guide actions that lower emissions and boost efficiency.

4. Results

The study employed thematic analysis to identify key factors influencing the success of tracking carbon footprints with SAP Digital Manufacturing. This method helped to reveal common patterns in stakeholder experiences and challenges during implementation. It also showed how people viewed system effectiveness over time.

4.1 Sustainability Indicators

Using SAP Digital Manufacturing with IoT sensor networks enables more precise and accurate tracking of carbon output. Real-time data from sensors shows where energy is wasted. Teams can fix issues faster. This results in lower emissions, less scrap, and improved machine utilization. The result is cleaner and more efficient production. As shown in Table 1, the values are presented for each measure.

Table 1: Key Metrics for Sustainable Manufacturing 4.0

Indicator	Value	Impact Measurement	Remarks
Energy Use	12%	kWh per unit made	Less power is used in each production cycle
Material Waste	8%	Scrap Rate	Fewer defects and less wasted material
Machine Downtime	18%	Hours Per Shift	Faster fixes and better machine use
Carbon Emissions	15%	CO_2/ Production Batch	Lower footprint per product made
Production Planning Errors	20%	Missed schedules or overproduction	Fewer reschedules and late runs
Rework Rate	18%	% of items rework	More first-pass quality
Data Accuracy	35%	% of correct readings	Better decisions from trusted numbers
Response Time to Issues	40%	Live Monitoring	Problems are fixed before they grow

4.2 Key Quantitative Result

Carbon Emissions Table used in Sustainable Manufacturing 4.0. This table helps track and analyze emissions at various stages of the production process. The data in Table 2 provides a comprehensive breakdown of emissions against the energy used in every process step, listed in detail.

Table 2: Carbon Tracking Results with SAP DM and IoT

Date	Line	Process Step	Energy Used (kWh)	CO_2 Emissions (kg)	Emission Source	Sensor ID
5/12/2025	A	Pre-Assembly	120	45.6	Welding, PCB	SENS-001
5/12/2025	B	Sub-Assembly	85	32.3	Robot Machine	SENS-002
5/12/2025	B	Final Assembly	70	27	Machine Assembly	SENS-010
5/12/2025	B	Testing	55	18.4	Test Equipment	SENS-005
5/12/2025	B	Packaging	40	14.2	Conveyor Belt Motor	SENS-007

4.3 Key Indicator Comparison: Past and Current

The data in Table 3 [1,8] presents a comparison table focused on a key performance indicator (KPI) for tracking carbon output, highlighting the differences between past methods (manual, no sensors) and the current method (SAP Digital Manufacturing with IoT sensor networks). Capturing data using a sensor and utilizing the right tool, compared to the past method of data collection, will always provide an accurate measurement of carbon footprint.

Table 3: Key Indicator Comparison: Manual Tracking vs. SAP + IoT Sensors

Key Indicator	Past Method (No Sensors)	Current Method (SAP + IoT Sensors)
Carbon Output (kg CO_2/unit)	Estimated using average fuel or power usage per shift/day	Measured in real time per machine, per product, per process
Data Source	Manual meter readings, utility bills, or periodic logs	Direct from sensors on machines and energy lines
Time Resolution	Daily or monthly estimates	Real-time (seconds or minutes)
Measurement Accuracy	Low precision: Rounded figures, manual errors, missing data	High precision: automated sensor input with no manual handling
Energy Waste Identification	General/High Level: Based on high bills or broad patterns	Specific/Accurate: Identifies waste by machine, line, or time of day
Response Time to Issues	Slow: Reactive (weeks or months)	Fast: Alerts triggered instantly from data thresholds
Use in Reporting	Historical summaries are often delayed	Live dashboards, automated reports, regulatory-ready logs

5. Discussion

The results show SAP Digital Manufacturing with IoT helps cut waste and lower carbon output. Live tracking shows energy use, machine health, and material flow. When problems happen, alerts help teams fix them fast.

This prevents extra scrap, waste, and downtime. Data from IoT sensors allows operators to spot minor problems before they escalate. Managers use reports to make better plans and avoid running machines more than needed. Engineers use the data to fine-tune processes and cut energy use. These actions collectively result in cleaner, more efficient work. Digital work instructions also play a significant role. When workers follow clear, updated steps, they make fewer mistakes. It leads to less rework and a more efficient use of materials. Using 3D models and visuals also helps operators understand tasks more quickly and reduce waste. The study also shows that tracking each part from start to finish supports reuse. Instead of throwing things out, teams can repair them. It keeps waste low and makes better use of raw materials. Tools certainly help in this area for faster processing, but people drive the change. Teams that trust the data and act fast see the most progress. Working together with live info saves time, energy, and materials. It shows that when technology is utilized effectively, it can contribute to the development of cleaner factories.

5.1 Limitations

The study and research have some clear limits. Not all factories can afford IoT sensors or SAP as technology. Smaller plants may lack the necessary funds, personnel, or training to utilize them effectively. That makes it hard to apply the tools in every area. Sensors can also fail or send insufficient data. If they break or lose signal, the results can't be trusted. The study has some clear limits. This affects how well teams can trust and act on the information in the reports. Third, success depends on people. Some workers may ignore alerts or skip digital

steps. If staff doesn't follow the system, results will suffer. Tech alone can't fix problems if people don't use it right.

Also, carbon tracking is just one part of the process. Some energy use originates from external sources, such as transportation or raw material processing. This system doesn't always cover that, which means the complete footprint might be higher than shown.

Finally, the data takes time to study. Teams need skills to understand it. If training is inadequate, workers may not understand the meaning of the numbers or know how to respond effectively. More work is needed to improve sensor accuracy and lower their cost. It may also require some optimization for low-power or battery-free sensors to conserve energy. Cheap, strong sensors could make tracking easier for more factories. In short, the system helps but only if it is used correctly. Costs, human error, and gaps in coverage are key limits to watch.

5.2 Future Research

Future research should show how small and mid-sized factories can hold SAP Digital Manufacturing and various IoT sensors. Many studies focus on large companies, but small plants/businesses also need help in reducing their carbon footprint. It should also study how training affects system use. If workers don't trust or understand the data, they might ignore it. Better ways to teach real-time tools should be explored. Another idea is to link factory carbon data with the whole supply chain. This could reveal the entire supply chain, from raw materials to finished goods. Most systems now stop at the shop floor. New tools could help analyze data and suggest the next steps. They may identify waste before it occurs or reveal useful trends. More case studies from various factories (both local and cross-border) are needed to gain a deeper understanding of the scenarios. They demonstrate what works and what doesn't. Real stories help others fix real problems, not just guess. These steps can lead to cleaner production in more places.

6. Conclusion

This study demonstrates how SAP Digital Manufacturing and IoT tools enable factories to track and reduce their carbon footprint. Real-time data enables teams to identify problems quickly and address them before waste accumulates. It also helps reduce energy use, lower scrap, and utilize raw materials more efficiently.

By linking SAP DM with ERP and warehouse systems, factories can avoid overproduction and excessive storage. Better planning reduces changeovers and conserves energy. Clear work steps and updated guides help workers do the job right the first time. Sensors give strong data on where energy is lost. Alerts help teams act fast. Tracking each part from start to finish also supports reuse instead of waste. These tools make the shop floor brighter and cleaner. They also help meet strict carbon rules. More factories can use these tools to move toward greener goals. Still, tech alone is not enough. Training, teamwork, and clear goals are also necessary. Good results come from people and tools working well together. More sustainable manufacturing methodologies need to be adopted not only by large and medium-sized businesses, but also by everyone, to mitigate environmental hazards in factories. Additionally, not only developed countries but also developing countries should adopt this exact mechanism to save the world and adhere to sustainability regulations.

Sustainable Manufacturing 4.0 is not a far-off idea. With SAP DM and IoT, it's already in reach. The next step is to grow and improve it for more factories.

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