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Machine Learning in Manufacturing

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ABSTRACT

Machine learning (ML) is a subset of artificial intelligence that uses algorithms and statistical models to parse data, identify patterns, pinpoint anomalies, and describe next steps, incorporating all it learns from the data to continually improve its output. Machine learning is playing a critical role in the digitalization of manufacturing operations towards Industry 4.0. It is one of the cornerstones for making manufacturing more intelligent, and thereby providing it with the needed capabilities towards greater flexibility and adaptability. In manufacturing, ML enhances efficiency and optimizes operations by using data analysis to improve decision-making in areas like predictive maintenance, quality control, and supply chain management. This paper provides an overview of the applications of machine learning techniques in manufacturing.

KEYWORDS: *machine learning, artificial intelligence, deep learning, manufacturing.*

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INTRODUCTION

Since the evolution of humankind, technology has also undergone evolving at its own pace. Artificial intelligence (AI) and machine learning (ML) are beginning to permeate the manufacturing industry, promising a new level of productivity, agility, and cost control. Applying AI technologies, such as machine learning, computer vision and natural language processing (NLP), improves various aspects of production processes. Machine learning is now one of the main drivers of manufacturing digital transformation, poised to transform the majority of labor- and data-intensive manufacturing processes and improve companies' operational efficiency. It impossible to miss the rapid rise of AI/ML technology in the context of manufacturing. A typical manufacturing plant is shown in Figure 1 [1].

WHAT IS MACHINE LEARNING?

Machine learning is a subfield of artificial intelligence that uses algorithms trained on data sets to create models capable of performing tasks that would otherwise only be possible for humans, such as categorizing images, analyzing data, or predicting price fluctuations. It uses algorithms (essentially lists of rules) trained on data sets to create self-learning models capable of predicting outcomes and classifying information without human intervention. It focuses on algorithms that can "learn" the patterns of training data and, subsequently, make accurate inferences about new data. This pattern recognition ability enables machine learning models to make decisions or predictions without explicit, hard-coded instructions. To ensure such algorithms work effectively, however, they must typically be refined many times until they accumulate a comprehensive list of instructions that allow them to function correctly [2]. A symbol of machine learning is shown in Figure 2 [3].

Generally speaking, a learning problem considers a set of samples of data and then tries to predict properties of unknown data. ML builds heavily on statistics because when we train a machine to learn, we have to give it a statistically significant random sample as training data. Intelligent machines are increasing doing incredible things: Facebook recognizes faces in photos, Siri understands voices, and Google translates websites [4].

Machine learning techniques are transforming many fields including computer science, engineering, mathematics, physics, neuroscience, and cognitive science. We are surrounded by ML-based technologies: search engines learn how to bring us the best results, digital cameras learn to detect faces, credit card transactions are secured by a software that detects frauds, and cars are equipped with accident prevention systems that are built using ML algorithms [5]. In ML, data plays an indispensable role, and the learning algorithm is used to learn from the data. ML algorithms are now easy to use. One can download packages in Python. Programming languages used in ML include C++, Java, Python.

As its name indicates, machine learning works by creating computer-based statistical models that are refined for a given purpose by evaluating training data, rather than by the classical approach where programmers develop a static algorithm that attempts to solve a problem. Because the algorithm adjusts as it evaluates training data, the process of exposure and calculation around new data trains the algorithm to become better at what it does. Algorithms are the computational part of a machine learning project. Once trained, algorithms produce models with a statistical probability of answering a question or achieving a goal. Unlike in expert systems, the logic by which a machine learning model operates is not explicitly programmed; it is learned through experience. Machine learning has come to dominate the field of AI: it provides the backbone of most modern AI systems, from forecasting models to autonomous vehicles to large language models (LLMs) and other generative AI tools. Machine learning has become a household term in recent years as the concept moved from science fiction to a key driver of how businesses and organizations process information [6].

As shown in Figure 3 [7], machine learning can be classified into different types. Different types of machine learning include the following [8]:

- *Supervised Learning*: The program is "trained" on a pre-defined set of "training examples" from a "teacher," which then facilitate its ability to reach an accurate conclusion when given new data. In this case, the data comes with additional attributes that we want to predict. A common case of supervised learning is to use historical data to predict statistically likely future events. Under supervised ML, we have regression ML and classification ML.
- *Unsupervised Learning:* As their name suggests, unsupervised learning algorithms can be broadly understood as somewhat "optimizing themselves." Unsupervised algorithms do not need to be trained with desired outcome data. The program is given a bunch of data and must find patterns and relationships therein. A typical goal of unsupervised learning may be as straightforward as discovering hidden patterns within a dataset. Without being told a "correct" answer, unsupervised learning methods can look at complex data and organize it in potentially meaningful ways. Figure 4 shows a typical artificial neural network [9], which normally consists of an input layer, hidden layer and output layer.
- *Reinforcement Learning:* Reinforcement learning models are trained holistically through trial and error. Reinforcement learning is a method with reward values attached to the different steps that the algorithm must go through. So, the model's goal is to accumulate as many reward points as possible and eventually reach an end goal. Reinforcement learning is an area of machine learning concerned with how software agents ought to take actions in an environment so as to maximize some notion of cumulative reward.
- *Deep Learning:* Deep learning (DL) is a specialized form of machine learning that uses artificial neural networks to mimic the human brain. It is a type of machine learning technique that is modeled on the human brain. It is an advanced technique for handling complex tasks like image and speech recognition. The way in which neural networks are trained can be described as deep learning. It is called deep because the network of neurons is arranged in several hierarchical levels. Deep learning laid the foundation for advances in generative artificial intelligence.

MACHINE LEARNING IN MANUFACTURING

The manufacturing industry has undergone digital transformation, driven by advancements in big data analytics, artificial intelligence, machine learning, and robotics.

The field of manufacturing is witnessing a transformation due to AI/ML's data analysis skills, predictive insights, and capacity to learn continuously on the job. For several industries, the traditional manufacturing processes are time-consuming and uneconomical due to the absence of the right tool to produce the products. In a couple of years, machine learning (ML) algorithms have become more prevalent in manufacturing to develop items and products with reduced labor cost, time, and effort. ML has made the most inroads, as a subset of AI that analyzes data, recognizes patterns, and suggests what might come next. Manufacturers are now embracing machine learning to improve everything from maintenance and quality control in production processes to resilience in supply chain operations. Figure 5 shows how machine learning improves manufacturing [10].

The potential of machine learning (ML) algorithms in manufacturing started to peak in 2014, driven by extensive research on their application for process optimization. In the manufacturing context, machine learning algorithms are applied to process large volumes of data about the production, equipment, and products to help optimize time-consuming aspects of the manufacturing process. ML algorithms learn from production data to identify patterns, predict equipment failures before they happen, automate visual inspections, and forecast demand to reduce costs and downtime, while increasing throughput and quality. As a form of machine learning, deep learning goes beyond ML's basic pattern recognition and prediction capabilities by drawing on neural networks with many more layers of interconnected nodes. This enables deep learning systems to better mimic the human brain. Figure 6 shows steps for implementing ML in manufacturing [11].

APPLICATIONS OF MACHINE LEARNING IN MANUFACTURING

Manufacturers increasingly apply ML for predictive maintenance, quality control, supply chain optimization, production process optimization, and product development. Computer and electronic product manufacturing, chemical manufacturing, and primary metal manufacturing are the top three areas in which machine learning can be applied. New applications of AI/ML continue to emerge at a rapid clip for manufacturing activities. Common application of ML in manufacturing include the following [12,13]:

- *Predictive Maintenance*: Among ML applications in manufacturing, predictive maintenance has so far gained the most traction. In manufacturing, equipment maintenance is a crucial activity, performed by dedicated personnel at regular intervals. Old-school maintenance customarily involves waiting for something to break before fixing it, which can lead to downtime, lost production, safety risks, and damaged customer relations. Today, manufacturing plants and railways are increasingly turning to predictive maintenance. ML algorithms monitor equipment and detect anomalies to predict potential failures, allowing for proactive maintenance and significantly reducing downtime. They uncover deviations from normal product features or functioning. They accelerate the detection of manufacturing errors early, before going to market. Moreover, with their help, you can identify the root causes of errors by analyzing historical data and process parameters, improving production.
- *Generative Design:* Generative AI and machine learning have the capability to create an almost infinite number of design solutions to match any problem/product based on preset factors like size, materials, weight, etc. This allows engineers to find the very best design solution for a product before it goes into production. AI/ML in manufacturing lets you simplify time-consuming engineering design processes. For example, it allows you to develop new product designs considering the material, weight, strength, and cost parameters. The generative AI chatbots that became popular in the past year have ML and neural networks at their core
- *Automation and Robotics:* Robotics is essential to modern manufacturing by automating repetitive tasks, improving efficiency, and reducing labor costs. Automation represents application of AI/ML-empowered advances in the field of manufacturing. Robotic arms, automated storage and retrieval systems, and autonomous guided vehicles are among the robots increasingly used to automate assembly lines and warehouses. Collaborative robots (or cobots) work alongside humans. They can learn different tasks, detect obstacles, and avoid them. Most often, companies use cobots for heavy lifting or on assembly lines. For example, a cobot picks up and holds a heavy part while a worker fastens it. AI/ML advances the field of robotics to the next level of automation to handle product complexity and the growing demand for customization/personalization. Figure 7 shows automation in manufacturing [14].
- *Smart Manufacturing:* The world is entering the fourth industrial revolution, labeled "Industry 4.0." It gives rise to a new sector in manufacturing that uses machine learning technologies — smart manufacturing.
- *Energy Consumption:* Worker robots and other technologies do not have needs like human beings. Therefore, the potential of a "factory without light" is now discussed with optimism. The second application of ML is energy consumption forecasting. This way, you can

ensure that resources are available to meet production needs. AI/ML's application to predictive maintenance, described earlier, can also produce savings in energy consumption.

- *Demand Prediction:* ML in manufacturing industry can detect patterns in the behavior of the target audience and provide valuable information to producers. It includes historical sales and competitors' data, seasonality, prices, promotions, market economics, etc.
- *Inventory Management:* AI optimizes inventory levels by analyzing data to predict stock needs and automate replenishment. By forecasting demand and monitoring inventory in real-time, manufacturers can maintain optimal stock levels, reducing carrying costs and improving cash flow. In addition to predicting demand, the technology tracks stocks and sends out alerts in a timely manner when they need to be replenished. ML is also useful in identifying bottlenecks in supply chains, such as supplier performance, weather, or market trends. Algorithms predict whether an ingredient will be delivered on time and how its delay will affect production.
- *Supply Chain Management:* Manufacturers strive to optimize material flow through their supply chains primarily to reduce transportation, storage, and handling costs. Manual supply chain management can drive any manufacturer crazy, as you deal with many orders, purchases, suppliers, and materials. ML is indispensable here, especially when it comes to defects. ML helps you quickly identify the required items, saving your reputation and money. ML can improve supply chain visibility, forecast demand more accurately, and help reroute logistics to avoid disruptions from external factors like weather. One way AI/ML helps streamline supply chains is route optimization, to find the quickest route for transporting shipping inputs to the factory floor and then delivering final products to customers.

BENEFITS

Manufacturers are increasingly using ML because the technology can learn what to expect and is highly accurate when predicting outcomes. The applications of machine learning in manufacturing promise an extended list of benefits in the domains of cost, productivity, innovation, time-to-market, and efficiency. ML can help respond to extreme weather events, tracking external information feeds, finding alternate transportation routes, and suggesting contingency production schedules to reduce the impact of supply chain disruptions. Benefits include higher productivity, fewer errors, and less waste across the entire manufacturing operation. Other benefits include the following [11-13]:

- *Cost Reduction:* One of the biggest benefits of ML in manufacturing is cost reduction. Manufacturers are feeling cost and compliance pressures today from volatile oil prices, stricter regulations on their use of carbon-based fuels, and the uncertain price tag on renewable energy alternatives. Companies are looking to AI/ML to help lower energy use and costs, including smart building maintenance that eliminates wasted heating and cooling. It is a timeless manufacturing goal: producing more, higher-quality products at minimum cost.
- *Quality Control:* Machine learning is all about data, so understanding some key elements about the quality and type of data needed is very important in ensuring accurate results. Data and algorithms are crucial for the performance of machine learning models. Data availability and data quality are the keys to the performance of machine learning. High-quality data and large data sizes can mostly increase the accuracy of machine learning models. Manual quality control of products is slow, error-prone, and costly because of humans' inherent limitations, inevitable inconsistencies, and the cost of labor. ML can automate visual inspection to identify defects with high accuracy, and analyze data to pinpoint the root causes of quality issues. ML algorithms recognize images and capture the slightest changes in the functioning of your equipment and systems. This allows you to find, classify, and fix defects faster. AI/ML-powered visual inspection systems use cameras with "machine vision" that can analyze images to detect defects on production lines in real time.
- *Predictive analytics:* This uses machine learning, statistical modeling, and data mining techniques to determine future outcomes. In the manufacturing context, predictive analytics are used extensively for equipment diagnostics and failure prediction, quality control automation, and streamlining of material procurement decision-making.
- *Anomaly Detection:* Anomaly detection task is primarily handled with unsupervised learning methods. Similar to the clustering, anomaly detection algorithms group the samples. Pattern recognition and anomaly detection are core capabilities of ML. On the factory floor and in warehouses, this talent comes in handy for predictive maintenance, quality control, surveillance and, more generally, identifying

inefficiencies in the production and handling of goods. AI/ML tools are used to recommend the best course of action based on their reading of patterns and anomalies in the data they are fed.

- *Data Visualization:* While it may seem not mandatory to visualize data for your specific use case, data visualization is a sure way to realize the full potential of machine learning and advanced analytics in general. Easily understandable dashboards can be very useful in unlocking valuable insights about manufacturing processes.
- *Better Efficiency:* Machine learning, paired with high-resolution cameras, can detect anomalies in production with better precision. The same applies to equipment: machine learning can help detect anomalous trends before they become critical and allows them to step in with repair. ML-powered software analyzes massive datasets to gain insights and detect noteworthy patterns. As a result, you produce more with less effort.
- *Worker Safety:* Production injuries include overexertion, falls, and exposure to harmful substances. Musculoskeletal disorders from repetitive motions and heat illnesses also continue to be major problems. Predictive analytics helps to learn historical data and identify patterns related to workplace injuries and incidents. Predictive maintenance helps you identify breakdowns in time and send equipment for repair. This way, you can improve the safety of your work. AI/ML-powered safety systems can predict when and where a safety violation could happen, and remedy the situation before it causes harm.
- *Better Decision-making:* ML elevates manufacturing operations by facilitating quick decision-making based on real-time data to enhance productivity, minimize errors, and reduce waste. ML will help you analyze and process data as soon as it is generated. You can quickly respond to changes, dynamically adjust production schedules, manage inventory, control quality, and reduce risk. Deep learning models can spot hidden trends in past data on supply chains, inventory stocks, and consumer demands.
- *Personalized Manufacturing:* Achieving customer satisfaction today often requires going beyond mass production to what some call "mass customization." AI enables manufacturers to offer mass customization, allowing products to be tailored to individual customer preferences without slowing down production. While product makers can charge more for these customizations, they also face greater complexity and costs during production. AI/ML can assist in taming that complexity and cost. For example, clothing manufacturers use AI algorithms to personalize products, allowing customers to choose designs that meet their specific tastes. This flexibility enhances customer engagement and satisfaction.
- *Sustainability:* Machine learning allows for flexible management of energy and fuel consumption by precisely defining periods of lower activities and implementing frequent and fine adjustments to the volume of fuel used. This way, industrial ML does not just favor cost savings but also considerably reduces waste.

Figure 8 shows some of the benefits of using ML in manufacturing [11].

CHALLENGES

In spite of the enormous number of ML use cases, there is no guidance or standard for developing ML solutions from ideation to deployment. One concern about ML and AI is the lack of transparency in how they produce results. Many expectations have been placed on ML to overcome all types of problems without the need for prior knowledge. Despite numerous ML studies and their promising performance, it remains very difficult for non-experts working in the manufacturing industry to begin developing ML solutions for their specific problems. A major obstacle is the lack of skilled personnel with expertise in data science and ML, coupled with data quality, availability, and interpretability issues as models become more complex. Other challenges include the following [14,15]:

- *Talent Shortage:* There is a scarcity of professionals with expertise in AI, data science, and machine learning. Regardless of the industry, experienced data scientists and machine learning engineers are scarce. This shortage makes it challenging for companies to fully use AI/ML without investing in workforce development. The best solution here is to partner with a full team of specialists comprising data engineers, data scientists, ML engineers, data analytics leads, etc. This way, you can dedicate yourself to business outcomes while leaving all the technicalities to experts.
- *Lack of Data:* While your manufacturing facility constantly produces great amounts of data, properly gathering and structuring it is a whole other story. Investing in establishing proper data governance standards is probably one of the most, if not the most important thing, a modern manufacturing organization can do to secure its

future in an industry that has grown to be so driven by data.

- *Cybersecurity:* AI integration increases digital connectivity, opening more potential points for cyberattacks. Manufacturers need advanced cybersecurity measures to protect sensitive systems.
- *Scalability:* This refers to the model's ability to maintain or improve its performance as the data volume increases. It deals with how well the model adapts to increasing dataset sizes and computational demands. In manufacturing, the amount of data generated by sensors, cameras, and other devices can grow exponentially. Scalable ML models can handle this growing data and still deliver accurate predictions and insights. Scalability is essential for large manufacturing plants or those with complex production lines.

FUTURE OF MACHINE LEARNING IN MANUFACTURING

Machine learning (ML) is rapidly transforming manufacturing by analyzing real-time data from shop floor sensors and internal enterprise resource planning systems to optimize production and supply chain operations. AI/ML manufacturing applications continue to attract the attention of investors, entrepreneurs and product developers.

There will be the growing number of autonomous factories that operate with little or no human intervention. Machines and equipment will be able to connect and optimize themselves. Products will become more personalized, considering customers' needs and preferences. At the same time, insights and conclusions from AI/ML will become more understandable for the everyday worker. Manufacturing defects will be reduced to zero with predictive analytics and real-time quality control. The sustainability of production will increase so that ML optimizes energy consumption as much as possible, reduce waste, and minimize environmental impact [12]. ML's future will rely on skilled personnel who can maximize the technology's potential.

CONCLUSION

Machine learning enables computer programs to perform complex tasks such as prediction, diagnosis, planning, and recognition by learning from historical data. It has forever changed the way companies do manufacturing. In today's economy, ML is used for everything from setting consumer credit scores to filtering email spam. Manufacturers use ML-based solutions across the entire production cycle.

Most manufacturers are still piloting and experimenting with AI/ML to identify the technology's potential applications, management requirements, and implications for business.

It is fully recognized that ML is playing an increasingly critical role in the digitization of manufacturing industries towards Industry 4.0, leading to improved quality, productivity, and efficiency. ML is a fairly open tool which can be used to handle a variety of problems in manufacturing. It is necessary to have an understanding of the hidden challenges in ML application in order to provide more realistic and robust outcomes. More information on machine learning in manufacturing is available in the books in [16-24].

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Figure 1 A typical manufacturing plant [1].

Figure 2 A symbol of machine learning [3].

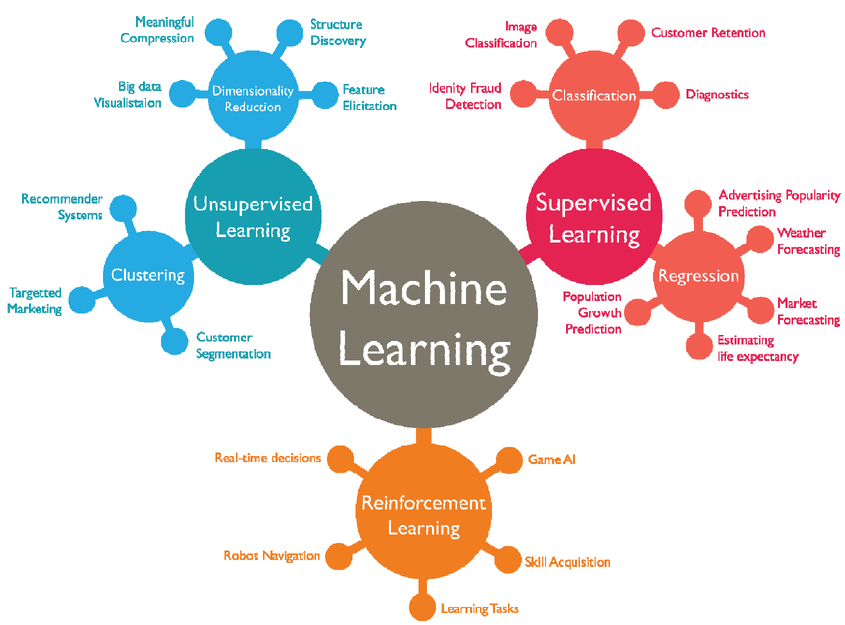

Figure 3 The relationship between some types of machine learning [7].

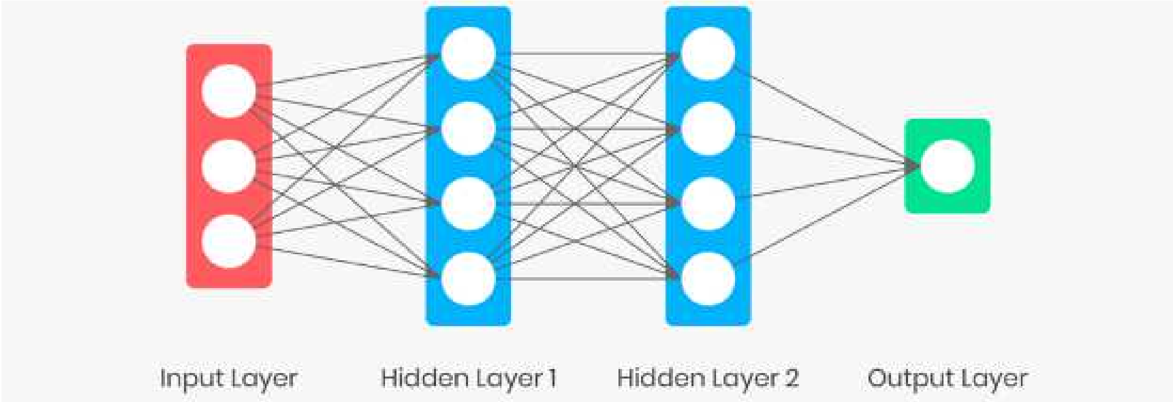

Figure 4 Artificial neural network [9].

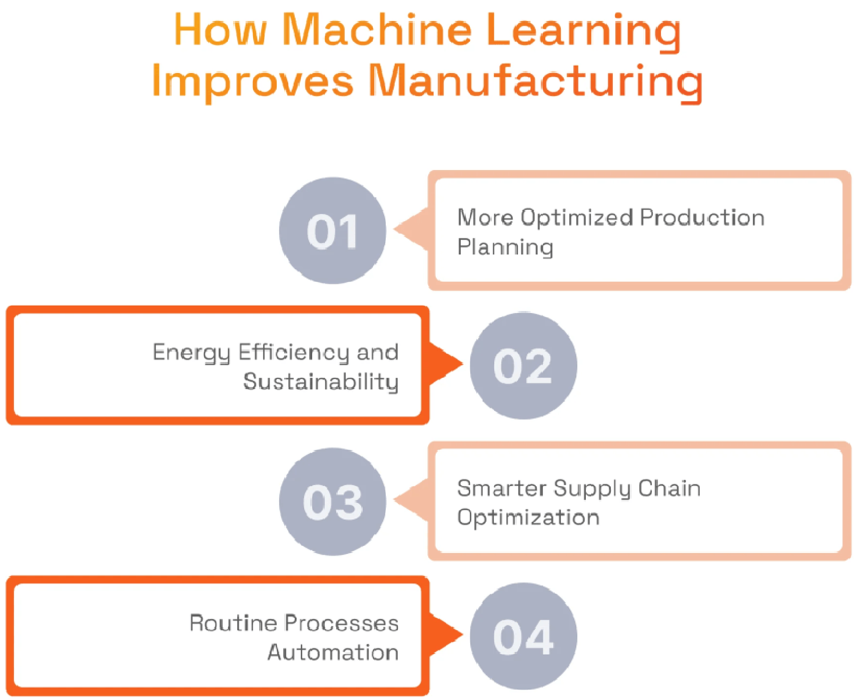

Figure 5 How machine learning improves manufacturing [10].

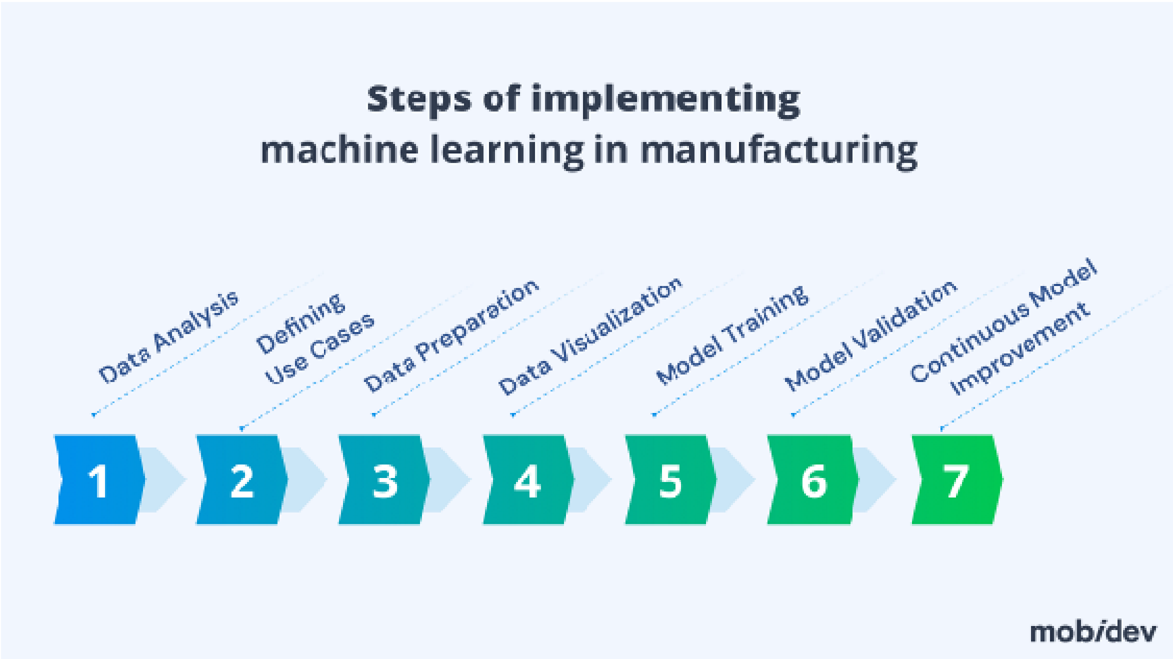

Figure 6 Steps for implementing ML in manufacturing [11].

Figure 7 Automation in manufacturing [14].

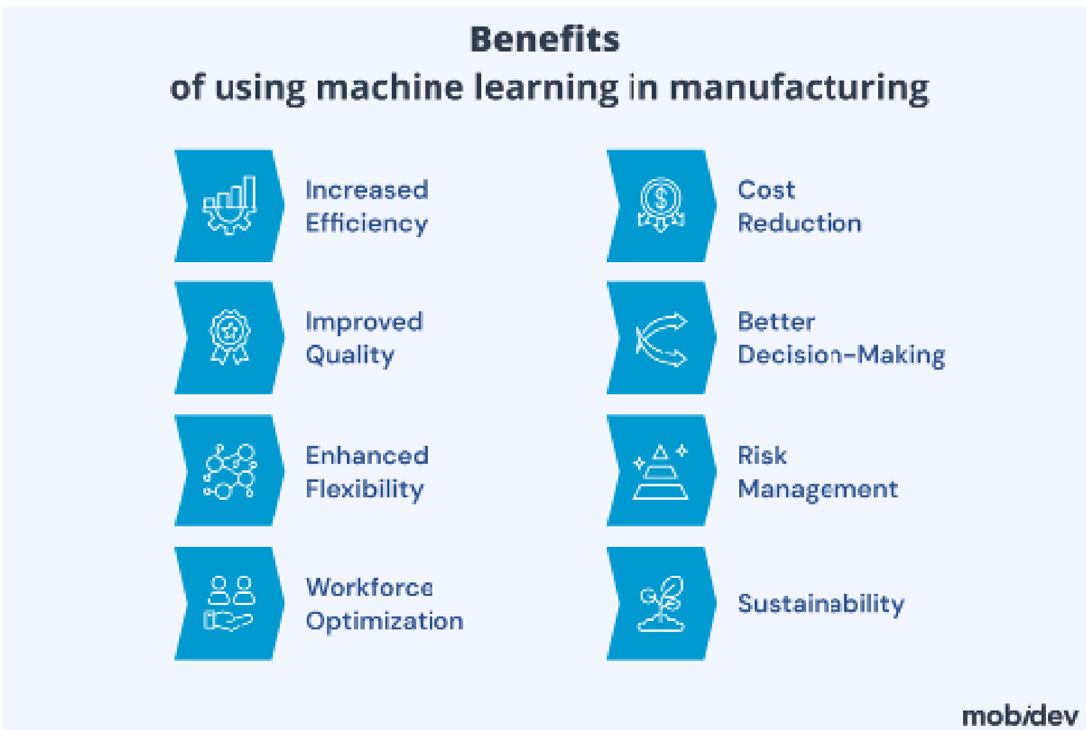

Figure 8 Some benefits of using ML in manufacturing [11].