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SMART MANUFACTURING – THE UTILIZATION OF BUSINESS ANALYTICS IN INDUSTRY 4.0 ENVIRONMENTS

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Purpose: The purpose of this publication is to present the applications of usage of business analytics in smart manufacturing.
Design/methodology/approach: Critical literature analysis. Analysis of international literature from main databases and polish literature and legal acts connecting with researched topic.
Findings: The integration of business analytics in smart manufacturing within the framework of Industry 4.0 marks a significant stride in industrial processes, offering manifold advantages alongside notable challenges. Throughout this study, we delve into the expansive realm of business analytics applications, encompassing predictive maintenance, quality control, supply chain optimization, and real-time decision-making. Leveraging business analytics yields palpable benefits in smart manufacturing, exemplified by proactive equipment maintenance, stringent quality standards adherence, and streamlined supply chain operations. Additionally, analytics-driven enhancements in production optimization, energy management, demand forecasting, and asset performance management contribute to heightened productivity, cost reduction, and sustainability improvement. Challenges including data integration complexities, implementation intricacies, security concerns, scalability limitations, model interpretability issues, and skill gaps necessitate concerted efforts for effective resolution. Collaboration among stakeholders—manufacturers, software developers, policymakers, and educational institutions—is imperative. Joint initiatives aimed at bolstering data integration capabilities, providing specialized training, fortifying cybersecurity measures, and fostering a culture of continuous improvement are crucial for successful business analytics deployment.
Originality/Value: Detailed analysis of all subjects related to the problems connected with the usage of business analytics in the case of smart manufacturing.
Keywords: business analytics, Industry 4.0, digitalization, artificial intelligence, real-time monitoring; smart manufacturing.
Category of the paper: literature review.

1. Introduction

Smart manufacturing, under the umbrella of Industry 4.0, epitomizes the fusion of advanced technology with traditional industrial processes. At its core lies the seamless integration of business analytics, empowering manufacturers to harness the full potential of data-driven insights in optimizing operations, enhancing efficiency, and driving innovation.

In the Industry 4.0 landscape, business analytics serves as a cornerstone, revolutionizing the way manufacturers operate. Predictive maintenance stands out as a prime example, leveraging historical data from sensors embedded in machinery to predict and preempt potential failures. By proactively scheduling maintenance tasks, manufacturers minimize downtime, optimize resource allocation, and ultimately reduce operational costs (Zeng et al., 2022; Pech, Vrchota, 2022).

The purpose of this publication is to present the applications of usage of business analytics in smart manufacturing.

2. The selected aspects of business analytics usage in smart manufacturing

Business analytics plays a pivotal role in the realm of smart manufacturing, revolutionizing traditional industrial processes through data-driven insights and decision-making. In this era of interconnected devices and sensor-laden machinery, businesses leverage analytics to unlock a plethora of opportunities across various facets of manufacturing operations. One of the foremost applications of business analytics in smart manufacturing is predictive maintenance. By scrutinizing historical data collected from sensors embedded in machinery and equipment, manufacturers can predict potential failures and schedule maintenance proactively, thereby minimizing downtime and optimizing maintenance costs (Bakir, Dahlan, 2022).

Quality control receives a significant boost through analytics-driven approaches. By analyzing data from different stages of the manufacturing process, anomalies or patterns indicative of defects can be identified promptly. This empowers manufacturers to intervene swiftly, maintaining stringent quality standards and reducing the likelihood of defective products reaching the market. Supply chain optimization benefits immensely from analytics, as businesses analyze data pertaining to inventory levels, demand forecasts, supplier performance, and logistics. Such insights enable streamlined inventory management, efficient resource allocation, and timely delivery of materials, ultimately enhancing supply chain efficiency.

Moreover, analytics optimize production processes by analyzing real-time production data to identify inefficiencies, bottlenecks, or improvement opportunities. This leads to optimized production schedules, streamlined workflows, and maximized resource utilization, driving up production efficiency and cutting costs. Energy management is another area ripe for optimization through business analytics. By monitoring and analyzing energy consumption data, manufacturers can pinpoint energy-intensive processes, detect waste, and optimize energy usage, leading to cost savings and improved sustainability (Ghibakholl et al., 2022).

The integration of business analytics in smart manufacturing enables real-time decision-making, empowering manufacturers to respond swiftly to changing market conditions, production disruptions, or other operational challenges (Gajdzik, Wolniak, 2022; Gajdzik et al., 2023). This fosters business agility, competitiveness, and sustainable growth in the dynamic landscape of modern manufacturing (Akundi et al., 2022). Asset performance management is also revolutionized through analytics, as businesses monitor and analyze the performance of manufacturing assets in real-time. This involves tracking key performance indicators, identifying patterns of asset failure or degradation, and optimizing maintenance strategies to maximize uptime and extend asset lifespan (Scappini, 2016).

Demand forecasting is enhanced by analytics techniques, which analyze historical sales data and market trends to predict future demand accurately. Manufacturers can then adjust production levels and inventory management strategies accordingly, ensuring optimal response to market dynamics (Cillo et al., 2022).

Table 1 contains descriptions of how business analytics is used in the case of smart manufacturing.

Table 1.
The usage of business analytics in smart manufacturing

Aspect of Smart Manufacturing	Description of Business Analytics Usage
Predictive Maintenance	Business analytics are employed to analyze historical data from machinery and equipment sensors to predict when maintenance is required. This helps in reducing downtime and optimizing maintenance schedules, resulting in cost savings and improved productivity.
Quality Control	Analytics are utilized to monitor and analyze data from various stages of the manufacturing process to identify patterns or anomalies that may indicate potential defects or quality issues. This enables proactive measures to be taken to maintain product quality standards and minimize defects.
Supply Chain Optimization	Business analytics are applied to analyze data related to supply chain processes, including inventory levels, demand forecasting, supplier performance, and logistics. This facilitates optimized inventory management, efficient resource allocation, and timely delivery of materials, ultimately enhancing overall supply chain efficiency.
Production Optimization	Analytics are used to analyze production data in real-time to identify inefficiencies, bottlenecks, or opportunities for improvement in manufacturing processes. This enables manufacturers to optimize production schedules, streamline workflows, and maximize resource utilization, leading to increased production efficiency and reduced costs.
Energy Management	Business analytics are employed to monitor and analyze energy consumption data from manufacturing operations. This helps in identifying energy-intensive processes, detecting energy waste, and optimizing energy usage to reduce costs and improve sustainability.

Cont. table 1.

Demand Forecasting	Analytics techniques are utilized to analyze historical sales data, market trends, and other relevant factors to forecast future demand for products. This enables manufacturers to anticipate market fluctuations, adjust production levels accordingly, and optimize inventory management to meet customer demand while minimizing excess inventory.
Asset Performance Management	Business analytics are used to monitor and analyze the performance of manufacturing assets such as machinery, equipment, and facilities. This includes tracking key performance indicators (KPIs), identifying patterns of asset failure or degradation, and optimizing asset maintenance strategies to maximize uptime and extend asset lifespan.
Real-time Decision Making	Analytics capabilities enable real-time monitoring and analysis of manufacturing operations data, providing decision-makers with actionable insights to make informed decisions quickly. This facilitates agile responses to changing market conditions, production disruptions, or other operational challenges, thereby improving overall business agility and competitiveness.

Source: (Adel, 2022; Akundi et al., 2022; Olsen, 2023; Aslam et al., 2020; Bakir, Dahlan, 2022; Cillo et al., 2022; Ghibakholl et al., 2022; Javaid, Haleem, 2020, Javaid et al., 2020; Cam et al., 2021; Charles et al., 2023; Greasley, 2019; Hurwitz et al., 2015; Nourani, 2021; Peter et al., 2023).

3. Software used in smart manufacturing in Industry 4.0 conditions

Business analytics software is an indispensable tool in the realm of smart manufacturing, facilitating the integration of data-driven insights into various aspects of production processes. This software enables manufacturers to harness the vast amounts of data generated by interconnected devices and sensors, transforming it into actionable intelligence for informed decision-making. One of the key applications of business analytics software in smart manufacturing is predictive maintenance. By analyzing historical data collected from sensors embedded in machinery, this software can predict potential equipment failures before they occur. By identifying patterns and anomalies indicative of impending issues, manufacturers can schedule maintenance proactively, minimizing downtime and optimizing maintenance costs (Adel, 2022).

Quality control is another critical area where business analytics software shines. Manufacturers utilize this software to monitor and analyze data from different stages of the production process, identifying anomalies or patterns that may indicate defects (Wolniak, Grebski, 2018; Wolniak et al., 2019, 2020; Wolniak, Habek, 2015, 2016; Wolniak, Skotnicka, 2011; Wolniak, Jonek-Kowalska, 2021; 2022). With this insight, they can intervene swiftly to maintain stringent quality standards, thereby safeguarding brand reputation and customer satisfaction. Supply chain analytics software plays a pivotal role in optimizing supply chain processes. By analyzing data related to inventory management, demand forecasting, supplier performance, and logistics, manufacturers gain insights into streamlined operations, efficient resource allocation, and timely delivery of materials. This enables them to optimize inventory levels, minimize stockouts, and enhance overall supply chain efficiency (Nourani, 2021).

Furthermore, production optimization software enables manufacturers to maximize efficiency and productivity across their production processes. By analyzing real-time production data, this software identifies inefficiencies, bottlenecks, or improvement opportunities. With this insight, manufacturers can optimize production schedules, streamline workflows, and maximize resource utilization, ultimately driving down costs and increasing profitability (Jonek-Kowalska, Wolniak, 2021, 2022, 2023; Rosak-Szyrocka et al., 2023; Gajdzik et al., 2023; Jonek-Kowalska et al., 2022; Kordel, Wolniak, 2021, Orzeł, Ponomarenko et al., 2016; Stawiarska et al., 2020, 2021; Stecuła, Wolniak, 2022; Olkiewicz et al., 2021). Energy management software is also instrumental in smart manufacturing, helping manufacturers monitor and analyze energy consumption data from their operations. By identifying energy-intensive processes, detecting waste, and optimizing energy usage, this software enables manufacturers to reduce operating costs and minimize their environmental footprint (Du et al., 2023; Fjellström, Osarenkhoe, 2023; Castro et al., 2014; Wang et al., 2023).

Demand forecasting software is essential for manufacturers to anticipate market trends and adjust production levels accordingly. By analyzing historical sales data, market trends, and other relevant factors, this software predicts future demand for products. With this insight, manufacturers can optimize inventory management strategies, minimize stockouts, and maximize customer satisfaction (Sułkowski, Wolniak, 2015, 2016, 2018; Wolniak, Skotnicka-Zasadzień, 2008, 2010, 2014, 2018, 2019, 2022; Gajdzik, Wolniak, 2023; Swarnakar et al., 2023). Asset performance management software enables manufacturers to monitor and analyze the performance of their manufacturing assets in real-time. By tracking key performance indicators and identifying patterns of asset failure or degradation, this software optimizes maintenance strategies to maximize asset uptime and extend asset lifespan. Lastly, real-time decision-making software empowers manufacturers to respond swiftly to changing market conditions, production disruptions, or operational challenges. By monitoring and analyzing manufacturing operations data in real-time, this software provides actionable insights and decision support tools, enabling manufacturers to make informed decisions and maintain agility in the face of uncertainty.

Table 2 highlighting examples of software and applications used in global supply chain coordination, along with descriptions of their usage.

Table 2.
The usage of business analytics software in smart manufacturing

Software/ Application	Description	Key Features
Predictive Maintenance	Predictive maintenance software analyzes historical data from machinery sensors to predict potential equipment failures. By identifying patterns and anomalies, it enables proactive maintenance scheduling, minimizing downtime and optimizing maintenance costs.	• Data analysis for predictive modelling • Real-time monitoring of equipment health • Automated maintenance scheduling
Quality Control	Quality control software monitors and analyzes data from various stages of the manufacturing process to ensure product quality. It detects anomalies or patterns indicating defects, allowing for swift intervention to maintain stringent quality standards.	• Statistical process control (SPC) • Defect detection and classification • Automated inspection and quality assurance
Supply Chain Analytics	Supply chain analytics software optimizes supply chain processes by analyzing data related to inventory management, demand forecasting, supplier performance, and logistics. It provides insights for streamlined operations, efficient resource allocation, and timely delivery of materials.	• Inventory optimization • Demand forecasting • Supplier performance analysis • Logistics optimization
Production Optimization	Production optimization software analyzes real-time production data to identify inefficiencies, bottlenecks, or improvement opportunities. It enables manufacturers to optimize production schedules, streamline workflows, and maximize resource utilization.	• Real-time production monitoring • Workflow optimization • Resource utilization analysis • Production scheduling optimization
Energy Management	Energy management software monitors and analyzes energy consumption data from manufacturing operations. It identifies energy-intensive processes, detects waste, and optimizes energy usage to reduce costs and improve sustainability.	• Energy consumption tracking • Identification of energy waste • Energy usage optimization • Renewable energy integration
Demand Forecasting	Demand forecasting software analyzes historical sales data, market trends, and other factors to predict future demand for products. It enables manufacturers to adjust production levels and inventory management strategies accordingly.	• Sales data analysis • Market trend analysis • Demand prediction modelling • Inventory management optimization
Asset Performance Management	Asset performance management software monitors and analyzes the performance of manufacturing assets such as machinery, equipment, and facilities. It tracks key performance indicators (KPIs) and identifies patterns of asset failure or degradation, optimizing maintenance strategies to maximize uptime and extend asset lifespan.	• Real-time monitoring of asset performance • KPI tracking • Predictive analytics for maintenance • Asset lifecycle management
Real-time Decision Making	Real-time decision-making software provides actionable insights by monitoring and analyzing manufacturing operations data in real-time. It enables decision-makers to respond swiftly to changing market conditions, production disruptions, or operational challenges.	• Real-time data monitoring • Predictive analytics -

Source: (Adel, 2022; Akundi et al., 2022; Olsen, 2023; Aslam et al., 2020; Bakir, Dahlan, 2022; Cillo et al., 2022; Ghibakholl et al., 2022; Javaid, Haleem, 2020, Javaid et al., 2020; Cam et al., 2021; Charles et al., 2023; Greasley, 2019; Hurwitz et al., 2015; Nourani, 2021; Peter et al., 2023).

4. Advantages and problems of business analytics usage in smart manufacturing

Business analytics in smart manufacturing offer a myriad of advantages, revolutionizing traditional industrial processes and driving efficiency, productivity, and competitiveness to new heights. One key advantage lies in predictive maintenance, where analytics analyze historical data from machinery sensors to forecast potential equipment failures. This proactive approach minimizes downtime, optimizes maintenance schedules, and reduces maintenance costs significantly. Moreover, analytics-driven quality control ensures adherence to stringent standards by monitoring and analyzing data from various production stages. By swiftly identifying defects or anomalies, manufacturers can intervene promptly, safeguarding brand reputation and enhancing customer satisfaction (Charles et al., 2023).

Supply chain optimization is another crucial benefit of business analytics. By analyzing data related to inventory management, demand forecasting, supplier performance, and logistics, manufacturers streamline operations, allocate resources efficiently, and ensure timely delivery of materials. This enhances supply chain efficiency, minimizes lead times, and boosts overall operational performance. In terms of production efficiency, analytics optimize processes by analyzing real-time production data, identifying inefficiencies, bottlenecks, or improvement opportunities. This leads to optimized production schedules, streamlined workflows, and maximized resource utilization, resulting in increased efficiency and reduced costs.

Energy management is also significantly enhanced through analytics, enabling manufacturers to monitor and analyze energy consumption data. By identifying energy-intensive processes and detecting waste, analytics facilitate optimized energy usage, leading to reduced operating costs and improved sustainability. Furthermore, analytics enable accurate demand forecasting by analyzing historical sales data, market trends, and other relevant factors. Manufacturers can adjust production levels and inventory management strategies accordingly, minimizing stockouts, reducing excess inventory, and maximizing customer satisfaction (Nourani, 2021).

Asset performance management benefits from analytics as well, with real-time monitoring and analysis of asset performance data. By tracking key performance indicators and identifying patterns of asset failure or degradation, analytics optimize maintenance strategies, maximize asset uptime, and extend asset lifespan, ultimately maximizing return on investment. Lastly, real-time decision-making is facilitated by analytics, providing actionable insights into manufacturing operations data. This enables swift responses to changing market conditions, production disruptions, or operational challenges, fostering agility in decision-making, optimal resource allocation, and maintaining competitiveness in dynamic environments (Greasley, 2019).

Table 3 contains the advantages of using business analytics in smart manufacturing within Industry 4.0 conditions, along with descriptions for each advantage. This table showcases how business analytics in smart manufacturing offer various advantages across different facets of operations, ultimately driving efficiency, reducing costs, and enhancing competitiveness.

Table 3.
The advantages of using business analytics in smart manufacturing

Advantage	Description
Predictive Maintenance	Business analytics enable predictive maintenance by analyzing historical data from machinery sensors, predicting potential equipment failures before they occur. This proactive approach minimizes downtime, optimizes maintenance schedules, and reduces maintenance costs.
Quality Control	Analytics-driven quality control monitors and analyzes data from various production stages to identify defects or anomalies. Swift intervention based on these insights ensures adherence to stringent quality standards, safeguarding brand reputation, and enhancing customer satisfaction.
Supply Chain Optimization	Business analytics optimize supply chain processes by analyzing data related to inventory management, demand forecasting, supplier performance, and logistics. This leads to streamlined operations, efficient resource allocation, and timely delivery of materials, ultimately enhancing supply chain efficiency.
Production Efficiency	Analytics optimize production processes by analyzing real-time production data, identifying inefficiencies, bottlenecks, or improvement opportunities. This leads to optimized production schedules, streamlined workflows, and maximized resource utilization, resulting in increased production efficiency and reduced costs.
Energy Management	Analytics help monitor and analyze energy consumption data from manufacturing operations, identifying energy-intensive processes and detecting waste. This leads to optimized energy usage, reduced operating costs, and improved sustainability through the integration of energy-saving measures.
Demand Forecasting	Business analytics analyze historical sales data, market trends, and other factors to predict future product demand accurately. This enables manufacturers to adjust production levels and inventory management strategies accordingly, minimizing stockouts, reducing excess inventory, and maximizing customer satisfaction.
Asset Performance Management	Analytics monitor and analyze the performance of manufacturing assets in real-time, tracking key performance indicators and identifying patterns of asset failure or degradation. This leads to optimized maintenance strategies, maximized asset uptime, and extended asset lifespan, ultimately maximizing return on investment.
Real-time Decision Making	Analytics provide real-time monitoring and analysis of manufacturing operations data, enabling swift responses to changing market conditions, production disruptions, or operational challenges. This fosters agility in decision-making, ensuring optimal resource allocation and maintaining competitiveness in dynamic environments.

Source: (Adel, 2022; Akundi et al., 2022; Olsen, 2023; Aslam et al., 2020; Bakir, Dahlan, 2022; Cillo et al., 2022; Ghibakholl et al., 2022; Javaid, Haleem, 2020, Javaid et al., 2020; Cam et al., 2021; Charles et al., 2023; Greasley, 2019; Hurwitz et al., 2015; Nourani, 2021; Peter et al., 2023).

Table 4 contains the problems of using business analytics in smart manufacturing within Industry 4.0 conditions, along with descriptions for each advantage. These problems underscore the importance of addressing data quality, integration, skill development, and change management to successfully harness the benefits of business analytics in global supply chain coordination.

Table 4.
The problems of using business analytics in smart manufacturing

Problem	Description
Data Integration Challenges	Smart manufacturing involves the collection of vast amounts of data from various sources, leading to challenges in integrating disparate data types and formats. Inconsistent data quality, compatibility issues, and data silos hinder the seamless aggregation and analysis of data, impeding the effectiveness of business analytics initiatives.
Complexity of Analytics Implementation	Implementing business analytics solutions in smart manufacturing environments requires specialized expertise in data analytics, machine learning, and software development. The complexity of integrating analytics platforms with existing systems, configuring algorithms, and interpreting results poses challenges, requiring significant time, resources, and investment.
Security and Privacy Concerns	The interconnected nature of smart manufacturing systems increases susceptibility to cybersecurity threats and data breaches. Concerns regarding data security, privacy, and intellectual property protection arise due to the transmission and storage of sensitive information across networks, necessitating robust cybersecurity measures and compliance with regulatory requirements.
Scalability and Performance Limitations	Scaling business analytics solutions to accommodate the growing volume and velocity of data in smart manufacturing environments poses challenges. Performance bottlenecks, latency issues, and resource constraints may arise, impacting the real-time processing and analysis of data and limiting the scalability and responsiveness of analytics systems.
Interpretability and Explainability of Models	The adoption of machine learning and artificial intelligence (AI) models in business analytics introduces challenges related to model interpretability and explainability. Complex algorithms may produce results that are difficult to interpret or lack transparency, hindering stakeholders' ability to understand the rationale behind decisions and undermining trust in analytics outcomes.
Maintenance and Upkeep of Analytics Systems	Business analytics systems require regular maintenance, updates, and optimization to ensure their effectiveness and reliability. Challenges related to system downtime, software updates, and compatibility issues may disrupt operations, necessitating continuous monitoring, support, and investment in maintenance activities to mitigate risks and ensure system stability.
Skill Gaps and Training Needs	The successful implementation and utilization of business analytics in smart manufacturing require a skilled workforce proficient in data analysis, statistics, and software development. Skill gaps and training needs may arise, hindering the adoption and effectiveness of analytics initiatives and necessitating investment in training programs to upskill existing personnel.
Return on Investment (ROI) Uncertainty	Despite the potential benefits of business analytics in smart manufacturing, uncertainties regarding return on investment (ROI) may pose challenges for stakeholders. Determining the tangible ROI of analytics initiatives, quantifying the value of insights generated, and justifying investments in analytics infrastructure and talent acquisition require careful evaluation and strategic planning.

Source: (Adel, 2022; Akundi et al., 2022; Olsen, 2023; Aslam et al., 2020; Bakir, Dahlan, 2022; Cillo et al., 2022; Ghibakholl et al., 2022; Javaid, Haleem, 2020, Javaid et al., 2020; Cam et al., 2021; Charles et al., 2023; Greasley, 2019; Hurwitz et al., 2015; Nourani, 2021; Peter et al., 2023).

5. Conclusion

The integration of business analytics in smart manufacturing within the framework of Industry 4.0 represents a significant advancement in industrial processes, offering a multitude of benefits while also presenting certain challenges. Throughout this paper, we have explored the diverse applications of business analytics, ranging from predictive maintenance and quality control to supply chain optimization and real-time decision-making.

The advantages of leveraging business analytics in smart manufacturing are evident, with predictive maintenance enabling proactive equipment upkeep, quality control ensuring stringent adherence to standards, and supply chain optimization streamlining operations for enhanced efficiency. Moreover, analytics-driven production optimization, energy management, demand forecasting, and asset performance management contribute to increased productivity, reduced costs, and improved sustainability.

However, the implementation of business analytics in smart manufacturing is not without its hurdles. Challenges such as data integration complexities, analytics implementation intricacies, security and privacy concerns, scalability limitations, interpretability of models, maintenance requirements, skill gaps, and uncertainties regarding return on investment need to be addressed effectively. Addressing these challenges requires a concerted effort from stakeholders, including manufacturers, software developers, policymakers, and educational institutions. Collaborative initiatives aimed at enhancing data integration capabilities, providing specialized training programs, bolstering cybersecurity measures, and fostering a culture of continuous improvement are essential for the successful deployment and utilization of business analytics in smart manufacturing.

Despite the challenges, the potential benefits of business analytics in smart manufacturing are undeniable. By harnessing the power of data-driven insights and decision-making, manufacturers can achieve unprecedented levels of efficiency, productivity, and competitiveness in the dynamic landscape of modern industry. As technology continues to evolve and new advancements emerge, the integration of business analytics will undoubtedly play a pivotal role in shaping the future of manufacturing, driving innovation, and fostering sustainable growth.

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