SILESIAN UNIVERSITY OF TECHNOLOGY PUBLISHING HOUSE

SCIENTIFIC PAPERS OF SILESIAN UNIVERSITY OF TECHNOLOGY 2023
ORGANIZATION AND MANAGEMENT SERIES NO. 184

THE USAGE OF SIX SIGMA IN INDUSTRY 4.0 CONDITIONS

Radosław WOLNIAK[1*], Wies GREBSKI[2]

[1] Silesian University of Technology, Organization and Management Department, Economics and Informatics Institute; rwolniak@polsl.pl, ORCID: 0000-0003-0317-9811
[2] Penn State Hazletonne, Pennsylvania State University; wxg3@psu.edu, ORCID: 0000-0002-4684-7608
* Correspondence author

Purpose: The purpose of this publication is to present the usage of Six Sigma approach in Industry 4.0 conditions.
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 Six Sigma principles with the dynamic landscape of Industry 4.0 offers a promising synergy that brings numerous benefits and challenges. Industry 4.0, characterized by advanced technologies like IoT, big data analytics, AI, and robotics, is reshaping manufacturing and industry. This digital revolution demands adaptability and process optimization for efficiency, quality, and customer satisfaction. Six Sigma, grounded in data-driven process improvement, aligns well with Industry 4.0's goals. Combining these approaches can yield remarkable results, enhancing competitiveness and driving continuous quality and efficiency improvement. Six Sigma's DMAIC methodology, defining, measuring, analyzing, improving, and controlling, offers a structured approach for problem-solving. A hierarchy of roles ensures effective project management and expertise utilization. Real-world applications across various sectors support the integration of Six Sigma and Industry 4.0, aiming to enhance product or service quality, efficiency, and customer satisfaction. The advantages of using Six Sigma in Industry 4.0 conditions are substantial, including improved quality control, enhanced data-driven decision-making, real-time process monitoring, predictive maintenance optimization, process efficiency improvement, and streamlined supply chain management, ultimately leading to higher customer satisfaction, cost reduction, employee skill development, competitive advantage, and improved risk management. However, this integration presents challenges like data overload, complex technology integration, skill gaps, data security, process complexity, change management, implementation costs, and over-reliance on technology. These issues can be addressed through advanced data analytics, well-defined integration strategies, comprehensive training, robust cybersecurity measures, simplification of processes, effective change management, compelling business cases, and maintaining a balanced approach. In a rapidly evolving industrial landscape, integrating Six Sigma with Industry 4.0 offers a promising path for organizations to enhance quality, efficiency, and competitiveness while addressing the challenges of digital transformation.

Keywords: Industry 4.0; Quality 4.0, quality management; quality methods, Six Sigma.

Category of the paper: literature review.

1. Introduction

In today's rapidly evolving industrial landscape, where technology and automation are at the forefront, the application of Six Sigma principles has become more crucial than ever before. Industry 4.0, often referred to as the fourth industrial revolution, is characterized by the integration of advanced technologies such as the Internet of Things (IoT), big data analytics, artificial intelligence, and robotics into manufacturing processes. This digital transformation presents both challenges and opportunities for businesses, making it essential to adapt and optimize processes to ensure efficiency, quality, and customer satisfaction. This text explores the integration of Six Sigma methodologies in Industry 4.0 conditions, highlighting the benefits, challenges, and real-world applications (Wolniak, Sułkowski, 2015, 2016; Wolniak, Grebski, 2018; Wolniak et al., 2019, 2020; Wolniak, Habek, 2015, 2016; Wolniak, Skotnicka, 2011; Wolniak, Jonek-Kowalska, 2021; 2022).

Industry 4.0 aims to create smart, interconnected manufacturing systems that are capable of self-monitoring, self-diagnosing, and self-optimizing. Six Sigma, on the other hand, is a data-driven approach to process improvement that focuses on minimizing defects and variations to achieve higher quality and consistency. Combining these two approaches can yield remarkable results.

The purpose of this publication is to present the usage of Six Sigma approach in Industry 4.0 condition.

2. The basics of Six Sigma approach

Six Sigma, a powerful concept that originated from Motorola in the 1980s and was further popularized by General Electric, has become synonymous with process improvement and excellence in many industries. This two-page text delves into the fundamental principles and methodologies of Six Sigma, highlighting its core components and applications (Bousdekis et al., 2023).

Six Sigma is a systematic and data-driven methodology for process improvement. It aims to minimize defects and variations in any process, product, or service to achieve a level of near-perfection, with an error rate of 3.4 defects per million opportunities. The term "Six Sigma" itself reflects this goal, as it refers to the six standard deviations within the normal distribution curve, with the goal of keeping defects within the range of $\pm 6\sigma$.

Six Sigma employs the DMAIC methodology, which stands for Define, Measure, Analyze, Improve, and Control. This structured approach guides organizations through the process of identifying issues, measuring performance, analyzing root causes, making improvements, and ensuring sustainability (Barsalou, 2023; Maganga, Taifa, 2023):

- Define: This phase involves defining the problem, setting objectives, and understanding customer requirements.
- Measure: Measurement is key to Six Sigma, as it provides data to assess current process performance and establish a baseline.
- Analyze: In this phase, data is analyzed to identify the root causes of defects and inefficiencies.
- Improve: With a deep understanding of the problem, teams work to make necessary improvements and optimize the process.
- Control: Finally, control measures are put in place to ensure that the improvements are sustained over time.

Six Sigma initiatives typically involve a hierarchy of roles, with each person contributing to the project's success (Antony et al., 2023; Escobar et al., 2023; Antony et al., 2023; Salimbeni & Redchuk, 2023):

- Champion: High-level executives who sponsor and support Six Sigma initiatives.
- Master Black Belt: Experts who provide guidance and mentor Green and Black Belts.
- Black Belt: Project leaders who drive improvement projects.
- Green Belt: Team members who support Black Belts in their projects.
- Yellow Belt: Employees with basic Six Sigma knowledge who may participate in projects on a limited scale.

Table 1 contains description of typical applications of Six Sigma.

Table 1.
Examples of applications of Six Sigma

Industry/Sector	Application of Six Sigma	Description
Manufacturing	Defect Reduction	Six Sigma is used to minimize defects and improve product quality in manufacturing processes.
Healthcare	Patient Care Improvement	In healthcare, Six Sigma is applied to enhance patient care, reduce medical errors, and optimize hospital operations.
Financial Services	Process Optimization	In the financial sector, Six Sigma is used to streamline financial processes, minimize errors, and enhance risk management.
Customer Service	Service Quality Enhancement	In customer service, Six Sigma is employed to improve response times, reduce customer complaints, and enhance service quality.
Supply Chain	Inventory Management	Six Sigma helps optimize inventory management, reduce carrying costs, and ensure supply chain efficiency.
Information Technology	Software Development Quality Assurance	Six Sigma is applied to software development processes to improve quality, reduce defects, and enhance reliability.
Aerospace	Safety and Quality Improvement	In the aerospace industry, Six Sigma is used to enhance safety, reduce defects in components, and ensure product quality.

Cont. table 1.

Education	Academic Performance Improvement	In education, Six Sigma can improve academic outcomes by identifying and addressing factors affecting student performance.
Retail	Inventory and Stock Management	Retailers use Six Sigma to optimize inventory and stock management, reducing overstock or out-of-stock issues.
Construction	Project Management Efficiency	In construction, Six Sigma principles are applied to improve project management, reduce delays, and control costs.

Source: (Almeida, Abreu, 2023; Jokovic et al., 2023; Khourshed, Gouhar, 2023; Maganga, Taifa, 2023; Liu et al., 2023; Yanamandra et al., 2023; Escobar et al., 2023; Bousdekis et al., 2023; Antony et al., 2023).

3. How Six Sigma approach can be integrated with Industry 4.0 and Quality 4.0 concept

In Industry 4.0, data is abundant. Machines and sensors generate vast amounts of information. Six Sigma complements this by providing a structured framework for analyzing and utilizing this data. Companies can harness the power of advanced analytics and statistical tools to identify patterns, detect anomalies, and continuously improve processes (Jonek-Kowalska, Wolniak, 2021, 2022, 2023; Rosak-Szyrocka et al., 2023; Gajdzik et al., 2023; Jonek-Kowalska et al., 2022; Kordel, Wolniak, 2021, Orzeł, Wolniak, 2021, 2022; Ponomarenko et al., 2016; Stawiarska et al., 2020, 2021; Stecuła, Wolniak, 2022; Olkiewicz et al., 2021) Data-driven decision-making is a cornerstone of both Six Sigma and Industry 4.0, ensuring that changes are made based on empirical evidence rather than intuition (Sureshchandar, 2023; Saihi et al., 2023).

Industry 4.0 enables real-time monitoring of manufacturing processes, allowing for immediate intervention in case of deviations. Six Sigma principles can help define the critical parameters that should be monitored and set up control charts and alerts to identify issues before they lead to defects. This integration reduces the likelihood of defects and minimizes the cost of poor quality (Almeida, Abreu, 2023).

One of the key advantages of Industry 4.0 is predictive maintenance, which uses sensors and data analytics to predict when equipment is likely to fail (Sułkowski, Wolniak, 2015, 2016, 2018; Wolniak, Skotnicka-Zasadzień, 2008, 2010, 2014, 2018, 2019, 2022; Wolniak, 2011, 2013, 2014, 2016, 2017, 2018, 2019, 2020, 2021, 2022; Gajdzik, Wolniak, 2023; Swarnakar et al., 2023). Six Sigma methodologies can be applied to optimize the predictive maintenance process by fine-tuning algorithms and reducing false alarms. This enhances the overall equipment effectiveness (OEE) and reduces downtime (Alrabadi et al., 2023).

Implementing Industry 4.0 technologies and Six Sigma methodologies requires a skilled workforce. Companies need to invest in training and development to ensure that employees can effectively use the tools and techniques associated with both approaches. Industry 4.0 generates massive amounts of data, which may raise concerns about data security and privacy (Wolniak, 2016; Czerwińska-Lubszczyk et al., 2022; Drozd, Wolniak, 2021; Gajdzik, Wolniak, 2021, 2022; Gębczyńska, Wolniak, 2018, 2023; Grabowska et al., 2019, 2020, 2021). Companies need to implement robust cybersecurity measures to protect sensitive information (Jokovic et al., 2023).

Integrating these two approaches into existing processes can be complex. Companies must develop a clear strategy and roadmap for adoption, ensuring that Six Sigma principles are seamlessly integrated into the new digital infrastructure (Yanamandra et al., 2023).

The integration of Six Sigma with the Quality 4.0 concept represents a powerful symbiosis that leverages data, automation, and structured methodologies to enhance quality, efficiency, and competitiveness in today's industrial landscape (Liu et al., 2023). As organizations navigate the challenges and opportunities presented by the digital transformation, the strategic alignment of Six Sigma with Quality 4.0 emerges as a cornerstone for success, where data-driven decision-making, continuous improvement, proactive quality management, cost reduction, and process optimization become pivotal drivers for achieving and sustaining excellence (Singh et al., 2023). In a world where the quality bar continues to rise, the collaboration between Six Sigma and Quality 4.0 is the answer to achieving near-perfection in product and service quality (Maganga, Taifa, 2023).

Table 2 is listing examples of integration of Six Sigma approach with Industry 4.0. The integration of Six Sigma and Industry 4.0 represents a powerful synergy that leverages data, automation, and structured methodologies to enhance quality, efficiency, and competitiveness in today's rapidly evolving industrial landscape.

Table 2.
Six Sigma integration with Industry 4.0

Aspect	Description
Data-Driven Decision-Making	Industry 4.0 generates vast amounts of data through IoT sensors and automation. Six Sigma provides the structured framework for analyzing this data, making evidence-based decisions, and identifying areas for improvement.
Real-Time Process Monitoring	Industry 4.0 enables real-time monitoring of manufacturing processes, allowing for immediate intervention in case of deviations. Six Sigma principles can be integrated to define critical parameters, set up control charts, and establish alerts for detecting and addressing issues proactively.
Predictive Maintenance	Industry 4.0's predictive maintenance uses sensors and data analytics to predict equipment failures. Six Sigma can optimize this process by fine-tuning algorithms, reducing false alarms, and ensuring maintenance activities are performed efficiently.
Quality Control and Assurance	Industry 4.0 can enhance quality control with automated inspection and data collection. Six Sigma methods can be applied to analyze this data, identify defects, and reduce variations in processes, ultimately improving product or service quality.
Process Optimization	Industry 4.0 automates and optimizes various processes. Six Sigma's DMAIC methodology can be employed to analyze and improve these processes by identifying bottlenecks, reducing waste, and enhancing overall efficiency.
Supply Chain Management	Industry 4.0 technologies provide real-time visibility into supply chain operations. Six Sigma principles can be used to improve supply chain performance, reduce lead times, and ensure on-time delivery of materials and products.
Employee Training and Development	The integration of Six Sigma and Industry 4.0 may necessitate training employees in both areas. Six Sigma training can help ensure that the workforce is equipped to handle the data-driven processes and quality improvements associated with Industry 4.0.

Cont. table 2.

Continuous Improvement Culture	The combination of Six Sigma and Industry 4.0 fosters a culture of continuous improvement, where employees use data and technology to drive ongoing enhancements in processes, products, and services.
Risk Management	Integrating Six Sigma with Industry 4.0 can also support better risk management, as data analytics and process improvements can help identify and mitigate risks more effectively.

Source: (Almeida, Abreu, 2023; Jokovic et al., 2023; Khourshed, Gouhar, 2023; Maganga, Taifa, 2023; Liu et al., 2023; Amat-Lefort et al., 2023; Alrabadi et al., 2023; Singh et al., 2023; Barsalou, 2023; Antony et al., 2023; Saihi et al.2023; Sureshchandar, 2023; Swarnakar et al., 2023; Gimerska et al., 2023; Salimbeni, Redchuk, 2023; Yanamandra et al., 2023; Escobar et al., 2023; Bousdekis et al., 2023; Antony et al., 2023).

Table 3 is describe the advantages of Six Sigma approach usage in industry 4.0. The use of Six Sigma in Industry 4.0 conditions offers numerous advantages, from ensuring product and service quality to optimizing processes and cost-effectiveness, ultimately enhancing an organization's competitiveness and customer satisfaction.

Table 3.
The advantages of Six Sigma integration with Industry 4.0

Advantage	Description
Improved Quality Control	Six Sigma helps ensure the highest product and service quality by reducing defects and variations, which is especially crucial in the precision-driven environment of Industry 4.0.
Enhanced Data-Driven Decision-Making	Industry 4.0 generates vast amounts of data. Six Sigma provides a structured framework for analyzing this data, enabling evidence-based decision-making and continuous improvement.
Real-Time Process Monitoring	Industry 4.0 allows for real-time process monitoring, and Six Sigma principles can be integrated to set up control charts and alerts, proactively identifying and addressing issues as they occur.
Predictive Maintenance Optimization	Six Sigma can fine-tune predictive maintenance algorithms, reducing false alarms and optimizing the process, leading to higher equipment reliability and lower downtime.
Process Efficiency Improvement	The combination of Industry 4.0's automation and Six Sigma's DMAIC methodology enables companies to analyze and optimize processes, reducing waste, improving efficiency, and reducing operational costs.
Supply Chain Optimization	Industry 4.0 technologies provide real-time supply chain visibility. By integrating Six Sigma, organizations can optimize supply chain performance, reduce lead times, and ensure on-time delivery.
Customer Satisfaction	Higher quality and reduced defects, made possible by Six Sigma in Industry 4.0, translate to improved customer satisfaction, which is crucial in competitive markets.
Cost Reduction	Reduced defects and improved efficiency often result in cost savings, making Six Sigma a valuable tool in the cost-conscious landscape of Industry 4.0.
Employee Skill Development	The integration of Six Sigma and Industry 4.0 may require employee training, leading to skill development that benefits both process automation and quality improvement.
Competitive Advantage	Companies that implement Six Sigma in Industry 4.0 conditions gain a competitive edge by delivering high-quality products, optimizing processes, and responding to customer needs quickly and effectively.
Risk Mitigation	By using data analytics and process improvements, Six Sigma helps identify and mitigate risks more effectively in the data-intensive environment of Industry 4.0.

Source: (Almeida, Abreu, 2023; Jokovic et al., 2023; Khourshed, Gouhar, 2023; Maganga, Taifa, 2023; Liu et al., 2023; Amat-Lefort et al., 2023; Alrabadi et al., 2023; Singh et al., 2023; Barsalou, 2023; Antony et al., 2023; Saihi et al.2023; Sureshchandar, 2023; Swarnakar et al., 2023; Gimerska et al., 2023; Salimbeni, Redchuk, 2023; Yanamandra et al., 2023; Escobar et al., 2023; Bousdekis et al., 2023; Antony et al., 2023).

Table 4 is describing the problems of Six Sigma approach usage in industry 4.0 and methods to overcome them. The use of Six Sigma in Industry 4.0 conditions offers numerous advantages, from ensuring product and service quality to optimizing processes and cost-effectiveness, ultimately enhancing an organization's competitiveness and customer satisfaction.

Table 4.
The problems of Six Sigma integration with Industry 4.0

Problems	Description of Problem	Overcoming Strategies
Data Overload	Industry 4.0 generates vast amounts of data from IoT sensors and automation, leading to information overload. This can overwhelm Six Sigma teams and hinder effective data analysis.	• Implement advanced data analytics and machine learning tools to process, analyze, and prioritize data efficiently. Focus on actionable insights rather than all available data. • Define key performance indicators (KPIs) that are aligned with your objectives and focus on monitoring and analyzing these critical metrics.
Technology Integration	Integrating Six Sigma with Industry 4.0 technologies such as IoT, big data, and AI can be complex, leading to disjointed processes and challenges in achieving synergy.	• Develop a clear strategy and roadmap for technology integration, ensuring alignment with improvement goals and objectives. • Foster open communication and collaboration between Six Sigma teams and IT departments to facilitate seamless technology integration and process improvement.
Skill Gaps	Industry 4.0 requires specialized skills for the operation and maintenance of advanced technologies, which Six Sigma teams may lack. This skills gap can hinder effective implementation.	• Invest in comprehensive training and development programs for employees, aligning them with the specific skill sets needed for Industry 4.0. • Consider cross-training or hiring personnel with the required expertise to bridge the skill gaps within the organization.
Data Security and Privacy	Industry 4.0 data often contains sensitive information, raising concerns about data security and privacy compliance, which is crucial for regulatory and ethical reasons.	• Implement robust cybersecurity measures, including encryption, access controls, and intrusion detection systems, to protect sensitive data. • Ensure compliance with relevant data protection regulations, such as GDPR or HIPAA, to maintain data privacy and avoid legal and reputational risks.
Complexity	The combination of Six Sigma and Industry 4.0 can lead to complex processes and projects that may be challenging to manage effectively.	• Maintain a focus on the core principles of both methodologies and avoid overcomplicating processes. • Ensure that project teams have well-defined objectives, clear scope, and a structured approach to avoid unnecessary complexity.
Change Management	The integration of Six Sigma and Industry 4.0 may lead to resistance from employees who are reluctant to adapt to new technologies and methodologies, potentially slowing down the implementation process.	• Develop a comprehensive change management plan that includes clear and frequent communication with employees. • Provide adequate training and resources to help employees adapt to the new ways of working and understand the benefits of the changes.

Cont. table 4.

Cost of Implementation	Implementing Industry 4.0 technologies and Six Sigma methodologies can be costly, and securing the necessary budget can be challenging.	• Develop a well-defined business case that outlines the expected return on investment (ROI) from quality improvements and efficiency gains. • Prioritize projects that offer the most significant ROI to make a compelling case for funding.
Over-Reliance on Technology	In the pursuit of Industry 4.0, there may be a temptation to rely excessively on technology, potentially neglecting the human element of Six Sigma and its focus on teamwork and problem-solving skills.	• Maintain a balanced approach where technology complements human expertise rather than replacing it. • Continue to emphasize the human factors, such as collaboration, creativity, and critical thinking, which are integral to the success of Six Sigma projects.

Source: (Almeida, Abreu, 2023; Jokovic et al., 2023; Khourshed, Gouhar, 2023; Maganga, Taifa, 2023; Liu et al., 2023; Amat-Lefort et al., 2023; Alrabadi et al., 2023; Singh et al., 2023; Barsalou, 2023; Antony et al., 2023; Saihi et al.2023; Sureshchandar, 2023; Swarnakar et al., 2023; Gimerska et al., 2023; Salimbeni, Redchuk, 2023; Yanamandra et al., 2023; Escobar et al., 2023; Bousdekis et al., 2023; Antony et al., 2023).

4. Conclusion

The integration of Six Sigma principles with the dynamic landscape of Industry 4.0 presents a compelling synergy that offers numerous advantages while also posing certain challenges. Industry 4.0, characterized by the seamless integration of advanced technologies like IoT, big data analytics, AI, and robotics, is transforming the manufacturing and industrial sectors. This digital revolution demands adaptability and optimization of processes to ensure efficiency, quality, and customer satisfaction.

The core principles of Six Sigma, rooted in data-driven process improvement, align well with the goals of Industry 4.0. Combining these two approaches can yield remarkable results, enhancing the overall competitiveness of organizations and driving continuous improvement in quality and efficiency.

Six Sigma's DMAIC methodology, encompassing Define, Measure, Analyze, Improve, and Control, provides a structured approach to problem-solving and process optimization. It guides organizations through the process of identifying issues, measuring performance, analyzing root causes, making improvements, and ensuring sustainability. A hierarchy of roles within Six Sigma initiatives ensures that projects are well-managed and that the right expertise is applied to each task.

The integration of Six Sigma and Industry 4.0 is supported by various real-world applications across diverse sectors, from manufacturing and healthcare to financial services and education, all aimed at enhancing product or service quality, efficiency, and customer satisfaction.

The advantages of employing Six Sigma in Industry 4.0 conditions are numerous. It results in improved quality control, enhanced data-driven decision-making, real-time process monitoring, predictive maintenance optimization, process efficiency improvement, and streamlined supply chain management. These benefits translate to higher customer satisfaction, cost reduction, employee skill development, competitive advantage, and improved risk management.

However, this integration also comes with its set of challenges, such as dealing with data overload, complex technology integration, skill gaps, data security and privacy concerns, process complexity, change management, implementation costs, and the risk of over-reliance on technology. These challenges can be overcome through strategic approaches such as advanced data analytics, well-defined technology integration strategies, comprehensive training programs, robust cybersecurity measures, simplification of complex processes, effective change management, sound business cases for cost justification, and maintaining a balanced approach to technology.

In a rapidly evolving industrial landscape where innovation and adaptation are key, the integration of Six Sigma with Industry 4.0 conditions represents a promising avenue for organizations to achieve higher quality, efficiency, and competitiveness while navigating the challenges posed by the digital transformation.

References

1. Almeida, S., Abreu, L.P.M. (2024). The Quality Manager in the Industry 4.0 Era. *Lecture Notes in Mechanical Engineering*, 468-474.
2. Alrabadi, T.D.S., Talib, Z.M., Abdullah, N.A.B. (2023). The role of quality 4.0 in supporting digital transformation: Evidence from telecommunication industry. *International Journal of Data and Network Science, 7(2),* 717-728.
3. Amat-Lefort, N., Barravecchia, F., Mastrogiacomo, L. (2023). Quality 4.0: big data analytics to explore service quality attributes and their relation to user sentiment in Airbnb reviews. *International Journal of Quality and Reliability Management*, *40(4),* 990-1008.
4. Antony, J., McDermott, O., Sony, M., Cudney, E.A., Doulatabadi, M. (2023). Benefits, challenges, critical success factors and motivations of Quality 4.0–A qualitative global study. *Total Quality Management and Business Excellence*, *34(7-8),* 827-846.
5. Antony, J., Sony, M., McDermott, O., Jayaraman, R., Flynn, D. (2023). An exploration of organizational readiness factors for Quality 4.0: an intercontinental study and future research directions. *International Journal of Quality and Reliability Management*, *40(2),* 582-606.

6. Antony, J., Swarnakar, V., Sony, M., McDermott, O., Jayaraman, R. (2023). How do organizational performances vary between early adopters and late adopters of Quality 4.0? An exploratory qualitative study. *TQM Journal*.
7. Barsalou, M. (2023). Root Cause Analysis in Quality 4.0: A Scoping Review of Current State and Perspectives. *TEM Journal, 12(1),* 73-79.
8. Bousdekis, A., Lepenioti, K., Apostolou, D., Mentzas, G. (2023). Data analytics in quality 4.0: literature review and future research directions. *International Journal of Computer Integrated Manufacturing, 36(5),* 678-701.
9. Drozd, R., Wolniak, R. (2021a). Metrisable assessment of the course of stream-systemic processes in vector form in industry 4.0. *Quality and Quantity*, 1-16, DOI: 10.1007/s11135-021-01106-w.
10. Drozd, R., Wolniak, R. (2021b). Systematic assessment of product quality. *Journal of Open Innovation: Technology, Market, and Complexity, 7(4),* 1-12.
11. Escobar, C.A., Macias-Arregoyta, D., Morales-Menendez, R. (2023). The decay of Six Sigma and the rise of Quality 4.0 in manufacturing innovation. *Quality Engineering*.
12. Gajdzik, B., Grebski, M., Grebski, W., Wolniak, R. (2022). *Human factor activity in lean management and quality management.* Toruń: Towarzystwo Naukowe Organizacji i Kierownictwa. Dom Organizatora.
13. Gajdzik, B., Jaciow, M., Wolniak, R., Wolny R., Grebski, W.W. (2023). Energy Behaviors of Prosumers in Example of Polish Households. *Energies, 16(7), 3186*; https://doi.org/10.3390/en16073186.
14. Gajdzik, B., Jaciow, M., Wolniak, R., Wolny, R., Grebski, W. (2023). Assessment of Energy and Heat Consumption Trends and Forecasting in the Small Consumer Sector in Poland Based on Historical Data. *Resources, 12(9),* 111.
15. Gajdzik, B., Wolniak, R. (2021a). Digitalisation and innovation in the steel industry in Poland - selected tools of ICT in an analysis of statistical data and a case study. *Energies, 14(11),* 1-25.
16. Gajdzik, B., Wolniak, R. (2021b). Influence of the COVID-19 crisis on steel production in Poland compared to the financial crisis of 2009 and to boom periods in the market. *Resources, 10(1),* 1-17.
17. Gajdzik, B., Wolniak, R. (2021c). Transitioning of steel producers to the steelworks 4.0 - literature review with case studies. *Energies, 14(14),* 1-22.
18. Gajdzik, B., Wolniak, R. (2022a). Framework for R&D&I Activities in the Steel Industry in Popularizing the Idea of Industry 4.0. *Journal of Open Innovation: Technology, Market, and Complexity, 8(3),* 133.
19. Gajdzik, B., Wolniak, R. (2022b). Influence of Industry 4.0 Projects on Business Operations: literature and empirical pilot studies based on case studies in Poland. *Journal of Open Innovation: Technology, Market, and Complexity, 8(1),* 1-20.

20. Gajdzik, B., Wolniak, R. (2022c). Smart Production Workers in Terms of Creativity and Innovation: The Implication for Open Innovation. *Journal of Open Innovations: Technology, Market and Complexity, 8(1),* 68.
21. Gajdzik, B., Wolniak, R., Grebski, W. (2023a). Process of Transformation to Net Zero Steelmaking: Decarbonisation Scenarios Based on the Analysis of the Polish Steel Industry. *Energies, 16(8), 3384,* https://doi.org/10.3390/en16083384.
22. Gajdzik, B., Wolniak, R., Grebski, W. (2023b). Electricity and heat demand in steel industry technological processes in Industry 4.0 conditions. *Energies, 16(2),* 1-29.
23. Gajdzik, B., Wolniak, R., Grebski, W. (2022). An econometric model of the operation of the steel industry in Poland in the context of process heat and energy consumption. *Energies, 15(21),* 1-26, 7909.
24. Gajdzik, B., Wolniak, R., Nagaj, R., Grebski, W., Romanyshyn, T. (2023). Barriers to Renewable Energy Source (RES) Installations as Determinants of Energy Consumption in EU Countries. *Energies, 16(21),* 7364.
25. Gębczyńska, A., Wolniak, R. (2018). *Process management level in local government.* Philadelphia: CreativeSpace.
26. Gimerská, V., Šoltés, M., Mirdala, R. (2023). Improving Operational Efficiency through Quality 4.0 Tool: Blockchain Implementation and Subsequent Market Reaction. *Quality Innovation Prosperity, 27(2),* 16-32.
27. Grabowska, S., Saniuk, S., Gajdzik, B. (2022). Industry 5.0: improving humanization and sustainability of Industry 4.0. *Scientometrics, 127(6),* 3117-3144, https://doi.org/10.1007/s11192-022-04370-1.
28. Grabowska, S., Grebski, M., Grebski, W., Saniuk, S., Wolniak, R. (2021). *Inżynier w gospodarce 4.0.* Toruń: Towarzystwo Naukowe Organizacji i Kierownictwa – Stowarzyszenie Wyższej Użyteczności "Dom Organizatora".
29. Grabowska, S., Grebski, M., Grebski, W., Wolniak, R. (2019). *Introduction to engineering concepts from a creativity and innovativeness perspective.* New York: KDP Publishing.
30. Grabowska, S., Grebski, M., Grebski, W., Wolniak, R. (2020). *Inżynier – zawód przyszłości. Umiejętności i kompetencje inżynierskie w erze Przemysłu 4.0.* Warszawa: CeDeWu.
31. Hąbek, P., Wolniak, R. (2013). Analysis of approaches to CSR reporting in selected European Union countries. *International Journal of Economics and Research, 4(6),* 79-95.
32. Hąbek, P., Wolniak, R. (2016). Assessing the quality of corporate social responsibility reports: the case of reporting practices in selected European Union member states. *Quality & Quantity, 50(1),* 339-420.
33. Hąbek, P., Wolniak, R. (2016). Factors influencing the development of CSR reporting practices: experts' versus preparers' points of view. *Engineering Economy, 26(5),* 560-570.
34. Hąbek, P., Wolniak, R. (2016). Relationship between management practices and quality of CSR reports. *Procedia – Social and Behavioral Sciences, 220,* 115-123.

35. Hys, K., Wolniak, R. (2018). Praktyki przedsiębiorstw przemysłu chemicznego w Polsce w zakresie CSR. *Przemysł Chemiczny*, *9*, 1000-1002.
36. Jokovic, Z., Jankovic, G., Jankovic, S., Supurovic, A., Majstorović, V. (2023). Quality 4.0 in Digital Manufacturing – Example of Good Practice. *Quality Innovation Prosperity, 27(2),* 177-207.
37. Jonek-Kowalska, I., Wolniak, R. (2021a). Economic opportunities for creating smart cities in Poland. Does wealth matter? *Cities*, *114*, 1-6.
38. Jonek-Kowalska, I., Wolniak, R. (2021b). The influence of local economic conditions on start-ups and local open innovation system. *Journal of Open Innovations: Technology, Market and Complexity*, *7(2),* 1-19.
39. Jonek-Kowalska, I., Wolniak, R. (2022). Sharing economies' initiatives in municipal authorities' perspective: research evidence from Poland in the context of smart cities' development. *Sustainability*, *14(4),* 1-23.
40. Jonek-Kowalska, I., Wolniak, R., Marinina, O.A., Ponomarenko, T.V. (2022). *Stakeholders, Sustainable Development Policies and the Coal Mining Industry. Perspectives from Europe and the Commonwealth of Independent States*. London: Routledge.
41. Khourshed, N., Gouhar, N. (2023). Developing a Systematic and Practical Road Map for Implementing Quality 4.0. *Quality Innovation Prosperity, 27(2),* 96-121.
42. Kordel, P., Wolniak, R. (2021). Technology entrepreneurship and the performance of enterprises in the conditions of Covid-19 pandemic: the fuzzy set analysis of waste to energy enterprises in Poland. *Energies*, *14(13),* 1-22.
43. Kwiotkowska, A., Gajdzik, B., Wolniak, R., Vveinhardt, J., Gębczyńska, M. (2021). Leadership competencies in making Industry 4.0 effective: the case of Polish heat and power industry. *Energies*, *14(14),* 1-22.
44. Kwiotkowska, A., Wolniak, R., Gajdzik, B., Gębczyńska, M. (2022). Configurational paths of leadership competency shortages and 4.0 leadership effectiveness: an fs/QCA study. *Sustainability*, *14(5),* 1-21.
45. Liu, H.-C., Liu, R., Gu, X., Yang, M. (2023). From total quality management to Quality 4.0: A systematic literature review and future research agenda. *Frontiers of Engineering Management*, *10(2),* 191-205.
46. Maganga, D.P., Taifa, I.W.R. (2023). Quality 4.0 conceptualisation: an emerging quality management concept for manufacturing industries. *TQM Journal*, *35(2),* 389-413.
47. Maganga, D.P., Taifa, I.W.R. (2023). Quality 4.0 transition framework for Tanzanian manufacturing industries. *TQM Journal*, *35(6),* 1417-1448.
48. Maganga, D.P., Taifa, I.W.R. (2023). The readiness of manufacturing industries to transit to Quality 4.0. *International Journal of Quality and Reliability Management, 40(7),* 1729-1752.

49. Michalak, A., Wolniak, R. (2023). The innovativeness of the country and the renewables and non-renewables in the energy mix on the example of European Union. *Journal of Open Innovation: Technology, Market, and Complexity, 9(2),* https://doi.org/10.1016/j.joitmc.2023.100061.
50. Olkiewicz, M., Olkiewicz, A., Wolniak, R., Wyszomirski, A. (2021). Effects of pro-ecological investments on an example of the heating industry - case study. *Energies, 14(18),* 1-24, 5959.
51. Olsen, C. (2023). Toward a Digital Sustainability Reporting Framework in Organizations in the Industry 5.0 Era: An Accounting Perspective. *Lecture Notes in Networks and Systems*, *557*, 463-473.
52. Orzeł, B., Wolniak, R. (2021). Clusters of elements for quality assurance of health worker protection measures in times of COVID-19 pandemic. *Administrative Science*, *11(2),* 1-14, 46.
53. Orzeł, B., Wolniak, R. (2022). Digitization in the design and construction industry - remote work in the context of sustainability: a study from Poland. *Sustainability*, *14(3),* 1-25.
54. Ponomarenko, T.V., Wolniak, R., Marinina, O.A. (2016). Corporate Social responsibility in coal industry (Practices of Russian and European companies). *Journal of Mining Institute*, *222*, 882-891.
55. Rosak-Szyrocka, J., Żywiołek J., Wolniak, R. (2023). Main reasons for religious tourism - from a quantitative analysis to a model. *International Journal for Quality Research, 1(17),* 109-120.
56. Saihi, A., Awad, M., Ben-Daya, M. (2023). Quality 4.0: leveraging Industry 4.0 technologies to improve quality management practices – a systematic review. *International Journal of Quality and Reliability Management*, *40(2),* 628-650.
57. Salimbeni, S., Redchuk, A. (2023). Quality 4.0 and Smart Product Development. *Lecture Notes in Networks and Systems, 614 LNNS*, 581-592.
58. Singh, J., Ahuja, I.S., Singh, H., Singh, A. (2023). Application of Quality 4.0 (Q4.0) and Industrial Internet of Things (IIoT) in Agricultural Manufacturing Industry. *AgriEngineering*, *5(1),* 537-565.
59. Stawiarska, E., Szwajca, D., Matusek, M., Wolniak, R. (2020). *Wdrażanie rozwiązań przemysłu 4.0 w wybranych funkcjonalnych obszarach zarządzania przedsiębiorstw branży motoryzacyjnej: próba diagnozy.* Warszawa: CeDeWu.
60. Stawiarska, E., Szwajca, D., Matusek, M., Wolniak, R. (2021). Diagnosis of the maturity level of implementing Industry 4.0 solutions in selected functional areas of management of automotive companies in Poland. *Sustainability*, *13(9),* 1-38.
61. Stecuła, K., Wolniak, R. (2022). Advantages and Disadvantages of E-Learning Innovations during COVID-19 Pandemic in Higher Education in Poland. *Journal of Open Innovation: Technology, Market, and Complexity*, *8(3),* 159.

62. Stecuła, K., Wolniak, R. (2022). Influence of COVID-19 Pandemic on Dissemination of Innovative E-Learning Tools in Higher Education in Poland. *Journal of Open Innovations: Technology, Market and Complexity, 8(1),* 89.
63. Sureshchandar, G.S. (2023). Quality 4.0 – a measurement model using the confirmatory factor analysis (CFA) approach. *International Journal of Quality and Reliability Management*, 40(1), 280-303.
64. Wang, Y., Mo, D.Y., Ma, H.L. (2023). Perception of time in the online product customization process. *Industrial Management and Data Systems, 123(2),* pp. 369-385.
65. Wolniak, R., Skotnicka-Zasadzień, B. (2014). The use of value stream mapping to introduction of organizational innovation in industry. *Metalurgija*, *53(4)*, 709-713.
66. Wolniak, R. (2011). *Parametryzacja kryteriów oceny poziomu dojrzałości systemu zarządzania jakością.* Gliwice: Wydawnictwo Politechniki Śląskiej.
67. Wolniak, R. (2013). Projakościowa typologia kultur organizacyjnych. *Przegląd Organizacji*, *3,* 13-17.
68. Wolniak, R. (2014). Korzyści doskonalenia systemów zarządzania jakością opartych o wymagania normy ISO 9001:2009. *Problemy Jakości*, *3,* 20-25.
69. Wolniak, R. (2016a). Kulturowe aspekty zarządzania jakością. *Etyka biznesu i zrównoważony rozwój. Interdyscyplinarne studia teoretyczno-empiryczne*, *1,* 109-122.
70. Wolniak, R. (2016b). *Metoda QFD w zarządzaniu jakością. Teoria i praktyka*. Gliwice: Wydawnictwo Politechniki Śląskiej.
71. Wolniak, R. (2016c). Relations between corporate social responsibility reporting and the concept of greenwashing. *Zeszyty Naukowe Politechniki Śląskiej. Seria Organizacji i Zarządzanie, 87,* 443-453.
72. Wolniak, R. (2016d). The role of QFD method in creating innovation. *Systemy Wspomagania Inżynierii Produkcji, 3*, 127-134.
73. Wolniak, R. (2017a). Analiza relacji pomiędzy wskaźnikiem innowacyjności a nasyceniem kraju certyfikatami ISO 9001, ISO 14001 oraz ISO/TS 16949. *Kwartalnik Organizacja i Kierowanie, 2*, 139-150.
74. Wolniak, R. (2017b). Analiza wskaźników nasycenia certyfikatami ISO 9001, ISO 14001 oraz ISO/TS 16949 oraz zależności pomiędzy nimi. *Zeszyty Naukowe Politechniki Śląskiej. Seria Organizacji i Zarządzanie*, *108*, 421-430.
75. Wolniak, R. (2017c). The Corporate Social Responsibility practices in mining sector in Spain and in Poland – similarities and differences. *Zeszyty Naukowe Politechniki Śląskiej. Seria Organizacji i Zarządzanie*, *111*, 111-120.
76. Wolniak, R. (2017d). The Design Thinking method and its stages. *Systemy Wspomagania Inżynierii Produkcji, 6,* 247-255.
77. Wolniak, R. (2017e). The use of constraint theory to improve organization of work. 4th International Multidisciplinary Scientific Conference on Social Sciences and Arts. SGEM 2017, 24-30 August 2017, Albena, Bulgaria. Conference proceedings. Book 1,

Modern science. Vol. 5, Business and management. Sofia: STEF92 Technology, 1093-1100.
78. Wolniak, R. (2018a). Functioning of social welfare on the example of the city of Łazy. *Zeszyty Naukowe Wyższej Szkoły, Humanitas. Zarządzanie, 3,* 159-176.
79. Wolniak, R. (2018b). Methods of recruitment and selection of employees on the example of the automotive industry. *Zeszyty Naukowe Politechniki Śląskiej. Seria Organizacja i Zarządzanie*, *128*, 475-483.
80. Wolniak, R. (2019a). Context of the organization in ISO 9001:2015. *Silesian University of Technology Scientific Papers. Organization and Management Series*, *133*, 121-136.
81. Wolniak, R. (2019b). Downtime in the automotive industry production process - cause analysis. *Quality, Innovation, Prosperity, 2,* 101-118.
82. Wolniak, R. (2021). Performance evaluation in ISO 9001:2015. *Silesian University of Technology Scientific Papers. Organization and Management Series*, *151*, 725-734.
83. Wolniak, R. (2022). Engineering ethics – main principles. *Silesian University of Technology Scientific Papers. Organization and Management Series*, *155*, 579-594.
84. Wolniak, R. (2023a). Analiza danych w czasie rzeczywistym. *Zarządzanie i Jakość*, *2(5),* 291-312.
85. Wolniak, R. (2023b). Analysis of the Bicycle Roads System as an Element of a Smart Mobility on the Example of Poland Provinces. *Smart Cities, 6(1),* 368-391; https://doi.org/10.3390/smartcities6010018.
86. Wolniak, R. (2023c). Design thinking and its use to boast innovativeness. *Silesian University of Technology Scientific Papers. Organization and Management Series*, *170,* 647-662.
87. Wolniak, R. Sułkowski, M. (2015). Rozpowszechnienie stosowania Systemów Zarządzania Jakością w Europie na świecie – lata 2010-2012. *Problemy Jakości*, *5,* 29-34.
88. Wolniak, R., Grebski, W. (2023a). Comparison of traditional and sustainable business practices. *Silesian University of Technology Scientific Papers. Organization and Management Series, 177*, 671-688.
89. Wolniak, R., Grebski, W. (2023b). Smart biking and traditional biking. *Silesian University of Technology Scientific Papers. Organization and Management Series, 178,* 717-734.
90. Wolniak, R., Grebski, W. (2023c). Smart mobility in smart city – Singapore and Tokyo comparison. *Silesian University of Technology Scientific Papers. Organization and Management Series*, *176*, 751-770.
91. Wolniak, R., Grebski, W. (2023d). The basis of prospective analytics in business. *Silesian University of Technology Scientific Papers. Organization and Management Series*, *176,* 771-789.
92. Wolniak, R., Grebski, W. (2023e). The five stages of business analytics. *Silesian University of Technology Scientific Papers. Organization and Management Series, 178,* 735-752.

93. Wolniak, R., Grebski, W. (2023f). The implementation of Industry 4.0 concept in Smart City. *Silesian University of Technology Scientific Papers. Organization and Management Series*, *178*, 753-770.
94. Wolniak, R., Grebski, M.E. (2018a). Innovativeness and creativity as factors in workforce development – perspective of psychology. *Zeszyty Naukowe Politechniki Ślaskiej. Seria Organizacja i Zarządzanie*, *116*, 203-214.
95. Wolniak, R., Grebski, M.E. (2018b). Innovativeness and creativity as nature and nurture. *Zeszyty Naukowe Politechniki Ślaskiej. Seria Organizacja i* Zarządzanie, *116*, 215-226.
96. Wolniak, R., Grebski, M.E. (2018c). Innovativeness and Creativity of the Workforce as Factors Stimulating Economic Growth in Modern Economies. *Zeszyty Naukowe Politechniki Ślaskiej. Seria Organizacja i Zarządzanie*, *116*, 227-240.
97. Wolniak, R., Grebski, M.E., Skotnicka-Zasadzień, B. (2019). Comparative analysis of the level of satisfaction with the services received at the business incubators (Hazleton, PA, USA and Gliwice, Poland). *Sustainability*, *10,* 1-22.
98. Wolniak, R., Hąbek, P. (2015). Quality management and corporate social responsibility. *Systemy Wspomagania w Inżynierii Produkcji*, *1,* 139-149.
99. Wolniak, R., Hąbek, P. (2016). Quality assessment of CSR reports – factor analysis. *Procedia – Social and Behavioral Sciences, 220,* 541-547.
100. Wolniak, R., Jonek-Kowalska, I. (2021a). The level of the quality of life in the city and its monitoring. *Innovation (Abingdon*), *34(3),* 376-398.
101. Wolniak, R., Jonek-Kowalska, I. (2021c). The quality of service to residents by public administration on the example of municipal offices in Poland. *Administration Management Public*, *37,* 132-150.
102. Wolniak, R., Jonek-Kowalska, I. (2022). The creative services sector in Polish cities. *Journal of Open Innovation: Technology, Market, and Complexity*, *8(1),* 1-23.
103. Wolniak, R., Saniuk, S., Grabowska, S., Gajdzik, B. (2020). Identification of energy efficiency trends in the context of the development of industry 4.0 using the Polish steel sector as an example. *Energies*, *13(11),* 1-16.
104. Wolniak, R., Skotnicka, B. (2011). *Metody i narzędzia zarządzania jakością – Teoria i praktyka, cz. 1.* Gliwice: Wydawnictwo Naukowe Politechniki Śląskiej.
105. Wolniak, R., Skotnicka-Zasadzień, B. (2008). *Wybrane metody badania satysfakcji klienta i oceny dostawców w organizacjach.* Gliwice: Wydawnictwo Politechniki Śląskiej.
106. Wolniak, R., Skotnicka-Zasadzień, B. (2010). *Zarządzanie jakością dla inżynierów.* Gliwice: Wydawnictwo Politechniki Śląskiej.
107. Wolniak, R., Skotnicka-Zasadzień, B. (2018). Developing a model of factors influencing the quality of service for disabled customers in the condition s of sustainable development, illustrated by an example of the Silesian Voivodeship public administration. *Sustainability*, *7, 1*-17.

108. Wolniak, R., Skotnicka-Zasadzień, B. (2022). Development of photovoltaic energy in EU countries as an alternative to fossil fuels. *Energies*, *15(2),* 1-23.
109. Wolniak, R., Skotnicka-Zasadzień, B. (2023). Development of Wind Energy in EU Countries as an Alternative Resource to Fossil Fuels in the Years 2016-2022. *Resources, 12(8),* 96.
110. Wolniak, R., Skotnicka-Zasadzień, B., Zasadzień, M. (2019). Problems of the functioning of e-administration in the Silesian region of Poland from the perspective of a person with disabilities. *Transylvanian Review of Public Administration*, *57E,* 137-155.
111. Wolniak, R., Sułkowski, M. (2015). Motywy wdrażanie certyfikowanych Systemów Zarządzania Jakością. *Problemy Jakości, 9,* 4-9.
112. Wolniak, R., Sułkowski, M. (2016). The reasons for the implementation of quality management systems in organizations. *Zeszyty Naukowe Politechniki Śląskiej. Seria Organizacji i Zarządzanie*, *92*, 443-455.
113. Wolniak, R., Wyszomirski, A., Olkiewicz, M., Olkiewicz, A. (2021). Environmental corporate social responsibility activities in heating industry - case study. *Energies*, *14(7),* 1-19, 1930.
114. Yanamandra, R., Abidi, N., Srivastava, R., Kukunuru, S., Alzoubi, H.M. (2023). *Approaching Quality 4.0: The Digital Process Management as a Competitive Advantage*. 2nd International Conference on Business Analytics for Technology and Security, ICBATS 2023.