SILESIAN UNIVERSITY OF TECHNOLOGY PUBLISHING HOUSE

SCIENTIFIC PAPERS OF SILESIAN UNIVERSITY OF TECHNOLOGY 2023
ORGANIZATION AND MANAGEMENT SERIES NO. 190

# THE USAGE OF STATISTICAL PROCESS CONTROL (SPC) IN INDUSTRY 4.0 CONDITIONS

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**Purpose:** The purpose of this publication is to present the usage of Statistical Process Control (SPC) 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 Statistical Process Control (SPC) with Industry 4.0 signifies a transformative shift in quality management, elevating SPC from a conventional monitoring tool to a proactive force in contemporary manufacturing. Originally employed for ensuring consistent quality through process monitoring, SPC's role has been redefined in the Industry 4.0 era, utilizing data analytics, real-time monitoring, and connectivity to offer a comprehensive understanding of the manufacturing ecosystem. Enabled by the Internet of Things (IoT), SPC gains real-time insights into production processes, crucial for swift anomaly identification and issue resolution. Advanced analytics and artificial intelligence enhance SPC's predictive capabilities, enabling proactive measures to maintain product quality. This publication underscores the significance of SPC in Industry 4.0 conditions, emphasizing its roots in statistical principles, systematic process control, and the distinction between common and special cause variations. The integration of SPC with Industry 4.0 and Quality 4.0 leverages technologies for enhanced quality management, emphasizing real-time data monitoring and collaborative, data-driven approaches. While Table 2 outlines specific aspects of SPC integration, highlighting its versatility, Table 3 enumerates the advantages, emphasizing improved visibility and predictive quality management. However, challenges such as data security concerns and technology integration complexity, outlined in Table 4, necessitate strategic solutions. In conclusion, this integration represents a pivotal advancement, positioning SPC as an indispensable asset for organizations seeking quality excellence, operational efficiency, and resilience in the dynamic landscape of modern manufacturing.
**Originality/Value:** Detailed analysis of all subjects related to the problems connected with the usage of Statistical process Control in Industry 4.0 conditions.

**Keywords:** Industry 4.0; Quality 4.0, quality management; quality methods, SPC, Statistical Process Control.

**Category of the paper:** literature review.

## 1. Introduction

In the traditional manufacturing paradigm, SPC was primarily implemented to monitor and control processes to ensure consistent quality. However, in the era of Industry 4.0, SPC takes on a more dynamic role by harnessing the power of data analytics, real-time monitoring, and connectivity. The advent of the Internet of Things (IoT) allows for the collection of vast amounts of data from sensors and devices throughout the production line.

SPC in Industry 4.0 leverages this data deluge to provide a deeper understanding of the entire manufacturing ecosystem. Real-time analytics enable quick identification of anomalies or deviations in the production process. This agility is crucial in addressing issues promptly, preventing defects, and maintaining overall process stability. Furthermore, the application of advanced analytics and artificial intelligence enhances the predictive capabilities of SPC. By analyzing historical data and identifying patterns, SPC can anticipate potential variations and recommend proactive measures to mitigate risks before they impact product quality. (Barsalou, 2023; Maganga, Taifa, 2023).

The purpose of this publication is to present the usage of Statistical Process Control (SPC) approach in industry 4.0 condition.

## 2. The basics of Statistical Process Control (SPC) approach

Statistical Process Control (SPC) is a powerful method employed in quality management to ensure that manufacturing processes consistently meet specified standards and produce products of high quality. Rooted in statistical principles, SPC involves the systematic monitoring and control of processes to identify and address variations that could lead to defects. The fundamental concept behind SPC is the recognition that any process will exhibit some degree of inherent variability. Instead of attempting to eliminate all variability, SPC focuses on distinguishing between common cause variation, which is inherent to the process and expected, and special cause variation, which arises sporadically and signals potential issues.

Key components of SPC include the collection and analysis of data, typically through the use of control charts. Control charts graphically display process data over time, allowing operators and managers to discern patterns and trends. The central line on the chart represents the process mean, while upper and lower control limits indicate acceptable variation. Points outside these limits suggest the presence of special cause variation, prompting further investigation and corrective action. Continuous monitoring through SPC not only aids in detecting deviations from the norm but also facilitates proactive adjustments to maintain process stability. By understanding the nature and sources of variation, organizations can enhance efficiency, reduce waste, and ultimately deliver consistent, high-quality products (Gajdzik et al., 2023).

SPC is widely applicable across various industries, including manufacturing, healthcare, and services, providing a robust framework for quality improvement. Embracing Statistical Process Control fosters a culture of continuous improvement, ensuring that processes remain in control and meet or exceed customer expectations. As organizations navigate the complexities of modern production, SPC stands as a valuable tool to optimize processes, enhance product quality, and ultimately drive overall operational excellence (Jokovic et al., 2023).

Collaboration and connectivity are integral aspects of Industry 4.0, and SPC aligns seamlessly with this paradigm. Information sharing across different stages of the supply chain and production network facilitates a holistic approach to quality management. SPC, in conjunction with smart manufacturing systems, fosters a more agile and responsive production environment (Singh et al., 2023).

The usage of Statistical Process Control in Industry 4.0 conditions represents a paradigm shift in quality management. The convergence of data analytics, real-time monitoring, and connectivity amplifies the capabilities of SPC, transforming it from a reactive tool to a proactive force in ensuring the highest levels of quality in the modern manufacturing landscape. As industries continue to evolve in the Industry 4.0 era, SPC stands as an indispensable asset for organizations aspiring to achieve not only quality excellence but also operational efficiency and resilience (Yanamandra et al., 2023).

Table 1 contains description of Statistical Process Control (SPC) key principles. This textual representation provides a description of each key principle of Statistical Process Control without using bullet points.

**Table 1.**
*Key principles of Statistical Process Control (SPC)*

| Key principle | Description |
|---|---|
| **Inherent Process Variation** | Recognizes that every process exhibits natural variation, and distinguishes between common cause (inherent to the process) and special cause (sporadic) variations. |
| **Data Collection and Analysis** | Involves systematic gathering of process data, which is then analyzed statistically to identify trends, patterns, and variations over time. |
| **Control Charts** | Utilizes graphical representations (control charts) to visualize process data, with central lines indicating the mean and control limits showing acceptable variation. |
| **Continuous Monitoring** | Requires ongoing surveillance of the process through the use of control charts, allowing for the timely detection of deviations and potential issues. |
| **Common Cause vs. Special Cause** | Distinguishes between variation inherent to the process (common cause) and unexpected variations (special cause), aiding in targeted problem-solving strategies. |
| **Process Stability** | Aims to maintain the process in a stable state by identifying and eliminating special cause variations, ensuring consistent and predictable outcomes. |
| **Statistical Analysis Tools** | Utilizes statistical methods such as mean, standard deviation, and process capability indices to quantify and analyze process performance. |
| **Proactive Problem Solving** | Encourages a proactive approach to address potential issues before they affect product quality, minimizing defects and optimizing process efficiency. |
| **Feedback and Improvement** | Establishes a feedback loop for continuous improvement by using SPC data to implement corrective actions, enhance processes, and achieve higher quality standards. |

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 Statistical Process Control (SPC) method can be integrated with Industry 4.0 and Quality 4.0 concept

The integration of Statistical Process Control (SPC) with Industry 4.0 and the Quality 4.0 concept represents a synergistic approach that harnesses the power of advanced technologies to enhance quality management in the modern industrial landscape (Maganga, Taifa, 2023).

In the context of Industry 4.0, which emphasizes the seamless integration of digital technologies and data-driven processes, SPC takes on a more dynamic role. The proliferation of sensors and connected devices throughout the manufacturing environment enables real-time data collection. SPC leverages this influx of data to provide a comprehensive and instantaneous view of the production process. By continuously monitoring key variables and utilizing advanced analytics, SPC can quickly identify patterns, trends, and variations, facilitating early detection of potential quality issues. Furthermore, the connectivity aspect of Industry 4.0 aligns seamlessly with the principles of SPC. The exchange of information across different stages of the production chain allows for a holistic and integrated quality management approach. SPC, in this context, becomes a collaborative tool that enables data-driven decision-making not only within the confines of a single facility but across the entire supply chain (Alrabadi et al., 2023).

Quality 4.0, an extension of Industry 4.0 in the realm of quality management, emphasizes the utilization of digital technologies to drive continuous improvement. SPC, with its focus on data analysis and process control, plays a pivotal role in achieving the objectives of Quality 4.0. The integration of SPC with advanced technologies, such as artificial intelligence and machine learning, enhances the predictive capabilities of quality management systems. This proactive approach allows organizations to anticipate potential quality issues, implement preventive measures, and optimize processes for sustained excellence (Bousdekis et al., 2023).

The integration of Statistical Process Control with Industry 4.0 and the Quality 4.0 concept creates a symbiotic relationship. SPC not only adapts to the digital transformation but also leverages the capabilities of Industry 4.0 technologies to reinforce its role in ensuring product quality. This integration facilitates a more agile, data-driven, and collaborative approach to quality management, aligning with the broader objectives of Industry 4.0 and Quality 4.0 in the pursuit of operational excellence (Antony et al., 2023; Escobar et al., 2023; Antony et al., 2023; Salimbeni, Redchuk, 2023).

Table 2 is listing examples of integration of Statistical Process Control (SPC) method with Iindustry 4.0. This table outlines various aspects of how Statistical Process Control integrates with Industry 4.0, providing a brief description of each aspect.

**Table 2.**
*Statistical Process Control (SPC) integration with industry 4.0*

| Aspect | Description |
|---|---|
| **Real-Time Data Monitoring** | Integration with Industry 4.0 enables SPC to leverage real-time data from sensors and connected devices, allowing immediate monitoring of process variables for timely analysis and intervention. |
| **Data Analytics and Predictive Modeling** | SPC in Industry 4.0 utilizes advanced data analytics and predictive modeling to analyze historical and real-time data, enhancing its ability to identify patterns, trends, and potential variations in the production process. |
| **Connectivity Across the Supply Chain** | SPC becomes a collaborative tool by facilitating the exchange of information across different stages of the supply chain. This connectivity ensures a holistic approach to quality management, aligning with Industry 4.0 principles. |
| **Integration with Smart Manufacturing** | SPC aligns with smart manufacturing systems in Industry 4.0, enabling seamless integration with other digital technologies, automation, and intelligent control systems for a more cohesive and efficient production environment. |
| **Proactive Problem Resolution** | With Industry 4.0 technologies, SPC gains the capability for proactive problem resolution. By leveraging predictive analytics, it can anticipate potential issues and implement corrective actions before they impact product quality. |
| **Utilization of Artificial Intelligence** | Integration with Industry 4.0 allows SPC to harness the power of artificial intelligence for enhanced statistical analysis, decision-making, and process optimization, contributing to the overall efficiency and quality improvement. |
| **IoT-enabled Process Visibility** | SPC leverages the Internet of Things (IoT) to provide comprehensive visibility into the production process. This visibility extends to various manufacturing assets, enabling a deeper understanding of the entire operational ecosystem. |
| **Adaptive Control Strategies** | Industry 4.0 integration enables SPC to implement adaptive control strategies. By dynamically adjusting control parameters based on real-time data, SPC can optimize processes and respond to changing production conditions for continuous improvement. |
| **Cloud-Based Data Storage and Access** | SPC in Industry 4.0 benefits from cloud-based data storage, allowing for centralized and accessible data repositories. This facilitates data sharing, collaboration, and analysis across geographically distributed manufacturing sites. |
| **Cyber-Physical System Integration** | SPC integrates with cyber-physical systems, ensuring synergy between the digital and physical aspects of manufacturing. This integration enhances the coordination and synchronization of processes for improved efficiency and quality. |
| **Automated Quality Control Processes** | Integration with Industry 4.0 enables SPC to implement automated quality control processes. This includes the use of robotics, sensors, and automated inspection systems to enhance the accuracy and speed of quality assessments. |
| **Blockchain for Traceability** | SPC leverages blockchain technology for enhanced traceability of production data. This ensures a transparent and immutable record of quality-related information, supporting compliance and accountability throughout the supply chain. |

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 Statistical Process Control (SPC) approach usage in industry 4.0. This table provides an overview of the various advantages of integrating Root Cause Analysis with Industry 4.0, emphasizing the positive impact on proactive issue resolution, operational efficiency, cost reduction, and overall organizational performance.

**Table 3.**
*The advantages of Statistical Process Control (SPC) integration with industry 4.0*

| Advantage | Description |
|---|---|
| **Enhanced Real-Time Visibility** | Integration with Industry 4.0 provides SPC with enhanced real-time visibility into the manufacturing process. This allows for immediate identification of deviations and abnormalities, enabling quick responses to maintain quality standards and minimize disruptions. |
| **Predictive Quality Management** | Industry 4.0 integration empowers SPC with advanced analytics and predictive modeling capabilities. SPC can anticipate potential quality issues by analyzing historical and real-time data, facilitating proactive problem resolution and preventing defects before they occur. |
| **Collaborative Supply Chain Quality** | Connectivity across the supply chain in Industry 4.0 enables collaborative quality management. SPC can exchange information seamlessly with suppliers and other stakeholders, fostering a shared commitment to quality standards and facilitating a more integrated and responsive supply chain. |
| **Optimized Smart Manufacturing** | SPC aligns with smart manufacturing systems in Industry 4.0, contributing to optimized and intelligent production processes. The integration enables adaptive control strategies, automation, and synchronization of manufacturing operations, leading to increased efficiency, reduced waste, and enhanced overall productivity. |
| **Proactive Problem Resolution** | The combination of Industry 4.0 technologies and SPC allows for proactive problem resolution. By leveraging real-time data and analytics, SPC can identify and address issues before they escalate, minimizing the occurrence of defects and ensuring a more consistent and reliable production process. |
| **Efficient Utilization of AI** | Integration with Industry 4.0 enables SPC to efficiently utilize artificial intelligence (AI) for enhanced decision-making. AI algorithms can analyze complex data sets, identify patterns, and provide valuable insights for optimizing processes, improving quality, and supporting continuous improvement initiatives. |
| **IoT-Driven Process Optimization** | SPC leverages the Internet of Things (IoT) to drive process optimization. IoT-enabled sensors and devices collect real-time data from various manufacturing assets, allowing SPC to monitor, analyze, and optimize processes for improved efficiency, quality, and overall operational performance. |
| **Cloud-Based Collaboration and Storage** | Industry 4.0 integration facilitates cloud-based collaboration and data storage for SPC. This ensures centralized access to quality-related data, fostering collaboration among teams across different locations. Cloud-based storage also enhances data security, scalability, and accessibility, supporting effective quality management. |
| **Adaptive Control in Dynamic Environments** | SPC integrated with Industry 4.0 is capable of adaptive control in dynamic production environments. By adjusting control parameters based on real-time data, SPC can respond to changing conditions, fluctuations, and variations, ensuring that processes remain within specified control limits for sustained quality and efficiency. |
| **Improved Traceability with Blockchain** | SPC integrated with Industry 4.0 can utilize blockchain for improved traceability. Blockchain technology ensures a secure and transparent record of quality-related information, offering a tamper-proof audit trail. This enhances traceability across the supply chain, supporting compliance, quality assurance, and accountability. |

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 describe the problems of Statistical Process Control (SPC) approach usage in Industry 4.0 and methods to overcome them. Addressing these problems requires a strategic and thoughtful approach, involving a combination of technological solutions, organizational change management, and ongoing adaptation to evolving industry standards and practices.

**Table 4.**

*The problems of Statistical Process Control (SPC) integration with industry 4.0*

| Problems | Description of Problem | Overcoming Strategies |
|---|---|---|
| **Data Security Concerns** | The integration of SPC with Industry 4.0 involves the collection and sharing of sensitive production data, raising concerns about data security, privacy, and the risk of unauthorized access. | Implement robust cybersecurity measures, including encryption, secure data transmission protocols, and access controls. Ensure compliance with relevant data protection regulations. |
| **Complexity in Technology Integration** | The adoption of Industry 4.0 technologies can be complex, involving integration challenges with existing systems, legacy equipment, and diverse technological platforms. | Conduct a thorough technology assessment, invest in compatible and scalable technologies, and engage in phased integration to manage complexity. Collaborate with experienced technology partners for seamless implementation. |
| **High Initial Costs** | The implementation of Industry 4.0 technologies, including sensors, IoT devices, and data analytics platforms, can incur significant upfront costs, posing a financial challenge for some organizations. | Develop a cost-benefit analysis to justify investments. Consider scalable solutions and explore funding options, such as government incentives or partnerships, to alleviate the initial financial burden. |
| **Resistance to Change** | Employees may resist the adoption of new technologies and processes associated with Industry 4.0, leading to challenges in training, acceptance, and a potential slowdown in the integration process. | Implement comprehensive change management strategies, including training programs, communication plans, and fostering a culture of innovation. Involve employees in the decision-making process and highlight the benefits of the changes. |
| **Interoperability Issues** | Incompatibility between different technologies, devices, or systems may result in interoperability issues, hindering the seamless exchange of data and collaboration between various components in the production process. | Prioritize standardization and compatibility when selecting technologies. Utilize open standards and application programming interfaces (APIs) to enable communication between different systems. |
| **Data Overload and Analysis Complexity** | The abundance of real-time data generated by Industry 4.0 technologies can lead to information overload, making it challenging for organizations to extract meaningful insights and perform effective statistical analysis. | Implement advanced analytics tools and artificial intelligence for automated data processing and analysis. Define key performance indicators (KPIs) to focus on relevant data. Train personnel in data interpretation and analysis techniques. |
| **Lack of Skilled Workforce** | The successful integration of Industry 4.0 technologies requires a skilled workforce with expertise in data analytics, cybersecurity, and emerging technologies, which may be lacking in some organizations. | Invest in employee training and development programs to build the necessary skills. Collaborate with educational institutions and industry partners to create a pipeline of skilled professionals. |
| **Overemphasis on Technology, Neglecting People** | Focusing solely on technology implementation without considering the human element can result in dissatisfaction, disengagement, and resistance among employees, leading to suboptimal performance. | Prioritize a human-centric approach by involving employees in the decision-making process, providing adequate training, and fostering a culture that embraces technology while recognizing and valuing the contributions of the workforce. |
| **Integration with Legacy Systems** | Many organizations have existing legacy systems that may not seamlessly integrate with Industry 4.0 technologies, posing challenges in ensuring a smooth transition and coexistence of old and new systems. | Develop a phased integration plan that considers the compatibility of existing systems. Invest in middleware solutions or system upgrades to bridge the gap between legacy systems and Industry 4.0 technologies. |

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 Statistical Process Control (SPC) with Industry 4.0 marks a paradigm shift in quality management, transforming SPC from a traditional monitoring tool into a dynamic and proactive force in the modern manufacturing landscape. In the traditional manufacturing paradigm, SPC was employed to ensure consistent quality through process monitoring and control. However, the advent of Industry 4.0 has redefined SPC's role, leveraging data analytics, real-time monitoring, and connectivity to provide a deeper understanding of the entire manufacturing ecosystem.

In Industry 4.0, the Internet of Things (IoT) facilitates the collection of vast amounts of data from sensors and devices, enabling SPC to gain real-time insights into the production process. This agility is crucial for quick identification of anomalies, deviation detection, and prompt issue resolution. Advanced analytics and artificial intelligence further enhance SPC's predictive capabilities, allowing organizations to anticipate potential variations and take proactive measures to ensure product quality.

This publication aims to present the usage of the Statistical Process Control (SPC) approach in Industry 4.0 conditions. SPC, deeply rooted in statistical principles, systematically monitors and controls processes, distinguishing between common cause and special cause variations. The principles of SPC, as outlined in Table 1, form a robust framework applicable across diverse industries, fostering a culture of continuous improvement and quality excellence.

The integration of SPC with Industry 4.0 and the Quality 4.0 concept signifies a synergistic approach that harnesses advanced technologies for enhanced quality management. SPC, in the context of Industry 4.0, benefits from real-time data monitoring, data analytics, and connectivity, fostering a collaborative and data-driven approach to quality management. Quality 4.0 emphasizes the use of digital technologies for continuous improvement, and SPC plays a pivotal role by enhancing predictive capabilities and facilitating proactive issue resolution.

Table 2 outlines specific aspects of SPC integration with Industry 4.0, showcasing its versatility across real-time data monitoring, predictive modeling, connectivity across the supply chain, and utilization of artificial intelligence, among others. These aspects collectively contribute to a more agile, efficient, and collaborative production environment. The advantages of SPC integration with Industry 4.0, detailed in Table 3, highlight the positive impact on real-time visibility, predictive quality management, collaborative supply chain quality, and overall process optimization. These advantages underscore the transformative potential of this integration for organizations aspiring to achieve operational excellence and sustained quality. However, challenges exist in the integration process, as outlined in Table 4. Issues such as data security concerns, technology integration complexity, and resistance to change require strategic approaches, including robust cybersecurity measures, comprehensive change management.

The integration of Statistical Process Control with Industry 4.0 represents a pivotal advancement in quality management. As industries evolve in the Industry 4.0 era, SPC stands as an indispensable asset for organizations striving not only for quality excellence but also operational efficiency and resilience. By addressing challenges and capitalizing on the advantages, organizations can unlock the full potential of this integration, ensuring a future-ready approach to quality management in the dynamic landscape of modern manufacturing.

## 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. 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*.
10. 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.

11. 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.
12. 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.
13. Jonek-Kowalska, I., Wolniak, R. (2021). Economic opportunities for creating smart cities in Poland. Does wealth matter? *Cities, 114,* 1-6.
14. 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.
15. Khourshed, N., Gouhar, N. (2023). Developing a Systematic and Practical Road Map for Implementing Quality 4.0. *Quality Innovation Prosperity, 27(2),* 96–121.
16. 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.
17. 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
18. 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.
19. 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.
20. 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.
21. Salimbeni, S., Redchuk, A. (2023). Quality 4.0 and Smart Product Development. *Lecture Notes in Networks and Systems, 614.* LNNS, 581–592.
22. 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.
23. 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.
24. 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.
25. 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.