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THE USAGE OF ROOT CAUSE ANALYSIS (RCA) IN INDUSTRY 4.0 CONDITIONS

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Purpose: The purpose of this publication is to present the usage of Root Cause Analysis (RCA) 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 Root Cause Analysis (RCA) within Industry 4.0 emerges as a strategic imperative, offering a systematic and holistic approach to problem-solving in the dynamic landscape of advanced technologies and interconnected systems. RCA serves as a powerful tool for dissecting multifaceted issues arising from the convergence of physical and digital systems, crucial in understanding and mitigating problems linked to smart technologies, automation, and data-driven processes. In the context of Industry 4.0's complexities, RCA facilitates a comprehensive examination of events, enabling organizations to identify the fundamental causes of disruptions or inefficiencies. The systematic investigative approach of RCA proves indispensable for navigating the intricate web of factors influencing the performance of smart manufacturing processes, cyber-physical systems, and the Internet of Things (IoT). As industries prioritize real-time data collection and analysis, RCA becomes instrumental in deciphering patterns and correlations within the data deluge, guiding informed decision-making and proactive problem resolution. Overall, RCA's integration into Industry 4.0 signifies a strategic method for fostering resilience, continuous improvement, and sustainable success within this dynamic and technologically-driven landscape.
Originality/Value: Detailed analysis of all subjects related to the problems connected with the usage of Root Cause Analysis in Industry 4.0 conditions.

Keywords: Industry 4.0; Quality 4.0, quality management; quality methods, RCA, Root Cause Analysis.

Category of the paper: literature review.

1. Introduction

Root Cause Analysis in Industry 4.0 conditions involves the application of this systematic investigative approach to understand and mitigate problems arising from the integration of smart technologies, automation, and data-driven processes. With the complexity and interconnectedness inherent in Industry 4.0 systems, the identification of root causes becomes even more challenging yet crucial.

In this context, RCA serves as a powerful tool for dissecting multifaceted issues that may arise in the convergence of physical and digital systems. It enables organizations to delve into the intricate web of factors influencing the performance of smart manufacturing processes, cyber-physical systems, and the Internet of Things (IoT). By identifying the fundamental causes of disruptions or inefficiencies, Industry 4.0 enterprises can develop targeted solutions that address the heart of the problem. Moreover, as Industry 4.0 emphasizes the real-time collection and analysis of vast amounts of data, Root Cause Analysis becomes instrumental in deciphering patterns and correlations within this data deluge. Whether it's a glitch in a production line, a cybersecurity breach, or a malfunction in an IoT device, RCA facilitates a comprehensive examination of events, leading to more informed decision-making and proactive problem resolution (Barsalou, 2023; Maganga, Taifa, 2023).

The purpose of this publication is to present the usage of Root Cause Analysis (RCA) approach in Industry 4.0 condition.

2. The basics of Root Cause Analysis (RCA) approach

Root Cause Analysis (RCA) is a systematic process employed to identify the underlying factors that contribute to an issue or problem within an organization. This analytical approach is crucial for addressing problems at their source rather than merely treating the symptoms. The ultimate goal of Root Cause Analysis is to prevent the recurrence of issues by understanding and addressing the fundamental reasons behind them (Singh et al., 2023).

The RCA methodology involves a thorough investigation into the events and circumstances leading up to a problem. It goes beyond surface-level symptoms and delves into the deeper layers of causation. By examining the entire chain of events, RCA seeks to identify the primary cause or causes responsible for the observed issues. A key aspect of Root Cause Analysis is the recognition that problems are often the result of a combination of factors rather than a single isolated incident. Therefore, it requires a comprehensive examination of various contributing elements, including processes, systems, human factors, and external influences. This holistic approach enables organizations to develop more effective solutions that target the root of the problem (Gajdzik et al., 2023).

The RCA process typically involves the collection and analysis of data, interviews with relevant stakeholders, and a careful examination of documentation. It may also incorporate tools such as Fishbone diagrams, 5 Whys, or Fault Tree Analysis to facilitate a structured and methodical investigation. One of the critical benefits of Root Cause Analysis is its ability to foster a culture of continuous improvement within an organization. By identifying and addressing the root causes of problems, organizations can implement preventive measures and enhance their overall operational efficiency. This proactive approach not only mitigates current issues but also helps prevent similar problems from arising in the future (Yanamandra et al., 2023).

The integration of RCA into Industry 4.0 practices aligns with the overarching goal of achieving predictive maintenance and minimizing downtime. By understanding the root causes of equipment failures or system malfunctions, organizations can implement predictive analytics and preventive measures, optimizing operational efficiency and reducing the risk of costly disruptions (Jokovic et al., 2023).

In conclusion, the usage of Root Cause Analysis in Industry 4.0 conditions signifies a strategic approach to problem-solving in the face of advanced technologies and interconnected systems. As industries continue to embrace the transformative capabilities of the fourth industrial revolution, the application of RCA becomes indispensable for fostering resilience, continuous improvement, and the sustainable success of organizations operating in this dynamic and technologically-driven landscape.

Table 1 contains description of Root Cause Analysis (RCA) key principles. These principles collectively form the foundation for an effective Root Cause Analysis process, providing a systematic and proactive approach to problem-solving in various industries and contexts.

Table 1.
Key principles of Root Cause Analysis (RCA)

Key principle	Description
Systematic Approach	Root Cause Analysis involves a methodical and structured examination of events, considering the entire system rather than focusing solely on isolated incidents or symptoms.
Holistic Investigation	It emphasizes a comprehensive exploration of various contributing factors, including processes, systems, human elements, and external influences, to identify the primary causes of an issue.
Data-Driven Analysis	Root Cause Analysis relies on the collection and analysis of relevant data to uncover patterns, trends, and correlations that contribute to a deeper understanding of the problem.
Multidisciplinary Perspective	It encourages collaboration and input from diverse stakeholders, incorporating insights from different disciplines to gain a well-rounded understanding of the factors influencing the issue.
Proactive Problem-Solving	The focus is on preventing the recurrence of problems by addressing the root causes rather than merely treating the symptoms, fostering a proactive approach to continuous improvement.
Iterative Process	Root Cause Analysis may involve an iterative process, revisiting and refining the analysis as new information becomes available, ensuring a thorough and evolving understanding of the issue.

Cont. table 1.

Use of Analytical Tools	Various tools, such as Fishbone diagrams, 5 Whys, Fault Tree Analysis, or statistical methods, may be employed to facilitate a structured and effective investigation into the root causes.
Continuous Improvement	It contributes to a culture of continuous improvement by identifying and rectifying the fundamental causes of problems, promoting a learning environment within the organization.

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 Root Cause Analysis (RCA) method can be integrated with Industry 4.0 and Quality 4.0 concept

Root Cause Analysis (RCA) is becoming increasingly integral to the landscape of Industry 4.0, where digitalization and advanced technologies are reshaping industrial processes. In this era of interconnected systems and smart manufacturing, the integration of RCA plays a crucial role in identifying and mitigating issues at their core (Alrabadi et al., 2023).

One key aspect of this integration lies in the digitalization of processes and the use of advanced data analytics. RCA leverages technologies such as the Internet of Things (IoT) sensors and machine learning algorithms to collect and analyze real-time data. This digital approach enables a more comprehensive understanding of complex systems and facilitates the identification of root causes by uncovering patterns and anomalies. Within smart manufacturing systems characteristic of Industry 4.0, RCA addresses issues related to cyber-physical systems and the automation of production processes. As machines become more intelligent and interconnected, RCA provides a systematic approach to dissecting complex problems, ensuring a thorough examination of interconnected elements to pinpoint root causes effectively (Bousdekis et al., 2023).

Moreover, the integration of RCA supports the shift towards predictive maintenance strategies. By analyzing historical data and identifying root causes, organizations can anticipate equipment failures and proactively address issues before they lead to disruptions. This proactive maintenance approach optimizes equipment performance, reduces downtime, and enhances overall operational efficiency.

In the context of the interconnected supply chain in Industry 4.0, RCA extends its application to address disruptions or inefficiencies that may arise from the integration of suppliers, logistics, and production processes. This ensures a holistic examination of the supply chain, identifying root causes that may impact the flow of materials, information, and products across the entire value chain.

Additionally, RCA is crucial in addressing cybersecurity incidents within the digital ecosystems of Industry 4.0. As organizations embrace digitalization, the risk of cyber threats increases. RCA helps in understanding the root causes of cybersecurity breaches, enabling the development of robust measures to safeguard critical assets and maintain the integrity of digital systems (Maganga, Taifa, 2023).

The integration of Root Cause Analysis with Industry 4.0 reflects a strategic approach to problem-solving in the context of digital transformation (Jonek Kowalska, Wolniak, 2021, 2022). By leveraging advanced technologies and a systematic analytical approach, RCA becomes an essential tool for organizations aiming to optimize processes, enhance efficiency, and ensure the resilience of interconnected systems in the evolving landscape of Industry 4.0 (Antony et al., 2023; Escobar et al., 2023; Antony et al., 2023; Salimbeni, Redchuk, 2023).

Table 2 is listing examples of integration of Root Cause Analysis (RCA) method with Iindustry 4.0. This table provides a concise overview of how Root Cause Analysis is integrated into various aspects of Industry 4.0, showcasing its relevance in addressing challenges and optimizing processes in the evolving landscape of smart and interconnected industries.

Table 2.
Root Cause Analysis (RCA) integration with industry 4.0

Aspect	Description
Digitalization and Data Analytics	Integration involves leveraging digital technologies like IoT sensors and machine learning for real-time data collection and analysis. This enables a comprehensive understanding of complex systems and facilitates the identification of root causes by uncovering patterns and anomalies.
Smart Manufacturing Systems	RCA is applied within smart manufacturing systems to address issues related to cyber-physical systems and the automation of production processes. It provides a systematic approach to dissecting complex problems in interconnected and intelligent manufacturing environments.
Predictive Maintenance	Integration supports predictive maintenance strategies by analyzing historical data and identifying root causes, allowing organizations to anticipate equipment failures and proactively address issues before disruptions occur. Proactive maintenance optimizes equipment performance and reduces downtime.
Interconnected Supply Chain	RCA extends to the interconnected supply chain, addressing disruptions or inefficiencies arising from the integration of suppliers, logistics, and production processes. It ensures a holistic examination of the supply chain, identifying root causes that may impact the flow of materials, information, and products.
Cybersecurity Incidents	Integration involves applying RCA to investigate and mitigate cybersecurity incidents within digital ecosystems. It addresses the vulnerabilities and root causes of cyber threats, allowing organizations to understand breaches and develop robust measures to safeguard critical assets.
Digital Twin Technology	Integration involves leveraging digital twin technology to create virtual replicas of physical systems. This enables a real-time comparison between the expected and actual performance, aiding in the identification of root causes by simulating and analyzing different scenarios.
Real-Time Monitoring and Control	RCA is integrated with real-time monitoring and control systems to identify deviations from expected performance immediately. This proactive approach ensures quick detection of issues, allowing organizations to analyze root causes promptly and implement corrective measures in real time.

Cont. table 2.

Cross-Functional Collaboration	Integration encourages cross-functional collaboration, involving stakeholders from various departments such as engineering, operations, and IT. This collaboration ensures a holistic analysis, combining diverse perspectives to identify and address root causes comprehensively.
Supply Chain Traceability	RCA extends to supply chain traceability, utilizing technologies like blockchain to track and trace products throughout the supply chain. This aspect ensures transparency and aids in identifying root causes of issues related to quality, delays, or disruptions in the supply chain.
Human-Machine Interaction	Integration considers the human-machine interaction aspects, recognizing that human errors or interactions with automated systems can contribute to issues. RCA in Industry 4.0 includes an analysis of human factors to identify root causes related to training, communication, or decision-making.
Advanced Sensor Integration	RCA leverages the integration of advanced sensors in manufacturing equipment and processes. These sensors provide detailed data on performance, allowing for a more granular analysis of root causes related to equipment malfunctions, wear and tear, or environmental conditions.
Machine Learning and AI Applications	Integration involves the application of machine learning and artificial intelligence algorithms to analyze vast datasets. These technologies enhance the depth of root cause analysis by identifying complex patterns and correlations that may not be immediately apparent through traditional methods.

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 Root Cause Analysis (RCA) 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 Root Cause Analysis (RCA) integration with industry 4.0

Advantage	Description
Proactive Issue Resolution	Integration enables organizations to proactively identify and resolve issues at their root causes before they escalate. By leveraging real-time data and advanced analytics, RCA in Industry 4.0 allows for predictive problem-solving, reducing the impact of disruptions and minimizing downtime.
Enhanced Operational Efficiency	The systematic approach of RCA integration optimizes operational efficiency within Industry 4.0. By addressing root causes, organizations can streamline processes, identify bottlenecks, and implement targeted improvements. This leads to increased productivity, reduced waste, and a more efficient utilization of resources.
Cost Reduction through Predictive Maintenance	Integration with predictive maintenance strategies results in cost savings. By identifying and addressing root causes before equipment failures occur, organizations can reduce maintenance costs, minimize unplanned downtime, and extend the lifespan of machinery and assets. This contributes to overall cost efficiency in Industry 4.0 environments.
Improved Quality and Productivity	RCA integration contributes to improved product quality and increased productivity. By identifying and rectifying root causes of quality issues, organizations can enhance the overall product quality. Additionally, addressing efficiency-related root causes leads to increased productivity and throughput in manufacturing processes.
Data-Driven Decision Making	The integration of RCA with Industry 4.0 leverages data-driven decision-making. By analyzing vast amounts of real-time data, organizations gain valuable insights into the factors influencing operations. This informed decision-making enhances overall strategic planning, resource allocation, and continuous improvement initiatives.

Cont. table 3.

Prevention of Recurring Issues	RCA integration helps prevent the recurrence of issues by addressing root causes. Organizations can implement corrective actions based on a thorough understanding of the underlying problems, reducing the likelihood of similar issues arising in the future. This preventive approach contributes to the stability and reliability of processes in Industry 4.0.
Cross-Functional Collaboration	Integration fosters cross-functional collaboration. By involving stakeholders from various departments in the RCA process, organizations benefit from diverse perspectives. This collaboration enhances problem-solving capabilities, encourages knowledge-sharing, and promotes a culture of continuous improvement across different functional areas in the Industry 4.0 environment.
Optimized Supply Chain Performance	RCA integration extends to the supply chain, optimizing its performance. By identifying and addressing root causes of disruptions, delays, or quality issues in the supply chain, organizations can enhance overall supply chain efficiency. This leads to improved on-time delivery, customer satisfaction, and resilience in Industry 4.0's interconnected and dynamic supply chain ecosystems.
Enhanced Cybersecurity Resilience	Integration with RCA strengthens cybersecurity resilience in Industry 4.0. By identifying root causes of cybersecurity incidents, organizations can implement robust measures to safeguard digital systems, protect sensitive data, and mitigate the risks associated with cyber threats. This proactive approach contributes to the overall cybersecurity posture of Industry 4.0 environments.

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 describes the problems of Root Cause Analysis (RCA) 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 Root Cause Analysis (RCA) integration with industry 4.0

Problems	Description of Problem	Overcoming Strategies
Data Overload and Complexity	The integration of RCA with Industry 4.0 often involves dealing with vast amounts of complex and diverse data from interconnected systems, making it challenging to extract meaningful insights.	Implement advanced analytics and machine learning algorithms to automate data analysis. Use data visualization tools to simplify complex data sets. Prioritize relevant data sources and focus on key performance indicators (KPIs). Ensure data quality and accuracy through proper validation and cleansing processes.
Interconnected Systems Challenges	The interconnected nature of Industry 4.0 systems introduces challenges in identifying and isolating root causes due to the intricate relationships between various components and processes.	Develop a comprehensive understanding of system interdependencies through system modeling and digital twin technology. Utilize simulation tools to analyze the impact of changes or disruptions. Foster collaboration between different departments and teams to gain diverse perspectives on interconnected challenges.
Human-Technology Interaction Issues	As Industry 4.0 involves increased human-technology interaction, root causes may stem from factors such as inadequate training, communication gaps, or human errors in interacting with advanced technologies.	Implement comprehensive training programs for personnel interacting with advanced technologies. Emphasize a culture of continuous learning and improvement. Conduct usability studies to identify and address challenges in human-technology interfaces. Establish clear communication channels and protocols for reporting and addressing issues arising from human-technology interactions.

Cont. table 4.

Integration Costs and Resource Allocation Challenges	Integrating RCA with Industry 4.0 may incur substantial costs, including investments in technology, training, and system integration. Resource allocation challenges may arise due to competing priorities.	Conduct a cost-benefit analysis to justify integration investments. Prioritize critical areas for integration based on their impact on overall operational efficiency. Explore collaboration with technology partners and vendors for cost-effective solutions. Implement a phased approach to integration to manage costs and resource allocation effectively. Consider leveraging open-source solutions and industry best practices for cost-effective integration.
Lack of Standardization and Compatibility	Lack of standardization in data formats, communication protocols, and technology interfaces across Industry 4.0 systems can hinder seamless integration and complicate RCA efforts.	Advocate for industry-wide standardization efforts and adopt common protocols. Ensure compatibility by selecting technologies that adhere to widely accepted standards. Collaborate with industry partners to establish interoperability standards. Work closely with vendors to ensure that solutions are compatible with existing systems and can support the desired level of integration.
Cybersecurity Risks	The integration of RCA with Industry 4.0 introduces cybersecurity risks, as increased connectivity may expose systems to potential vulnerabilities and cyber threats.	Implement robust cybersecurity measures, including encryption, authentication, and access controls. Regularly update and patch software to address known vulnerabilities. Conduct thorough risk assessments and penetration testing. Foster a cybersecurity-aware culture through training and awareness programs. Collaborate with cybersecurity experts and stay informed about emerging threats and best practices in the rapidly evolving landscape of cybersecurity.
Expertise and Skill Gap	Integrating RCA with Industry 4.0 may face challenges due to a lack of expertise and a skill gap among personnel in handling advanced technologies and data analytics.	Invest in training programs to upskill existing personnel. Recruit or collaborate with experts in data analytics, machine learning, and Industry 4.0 technologies. Foster a culture of continuous learning and knowledge-sharing within the organization. Consider partnerships with educational institutions or external consultants to bring in specialized expertise.
Resistance to Change	Employees may resist the changes introduced by RCA integration, such as new technologies, altered workflows, or a shift in organizational culture.	Develop a comprehensive change management plan to communicate the benefits of RCA integration. Involve employees in the decision-making process to address concerns and garner support. Provide training and support during the transition period. Highlight success stories and quick wins to demonstrate the positive impact of RCA integration. Foster a culture that values innovation, adaptability, and continuous improvement.
Data Privacy and Compliance Concerns	The integration of RCA with Industry 4.0 involves handling sensitive data, raising concerns about data privacy and compliance with regulations such as GDPR.	Implement robust data privacy policies and compliance measures. Conduct regular audits to ensure adherence to data protection regulations. Employ encryption and anonymization techniques to protect sensitive information. Collaborate with legal and compliance experts to stay updated on relevant regulations. Educate personnel about data privacy best practices and compliance requirements. Consider adopting privacy-enhancing technologies to minimize the risk of data breaches.

Cont. table 4.

Complex Supply Chain Dynamics	Root causes of issues within the supply chain can be complex, involving multiple stakeholders, global logistics, and dynamic market conditions.	Employ advanced supply chain analytics to gain visibility into complex dynamics. Collaborate closely with suppliers and partners to share information and address challenges collectively. Utilize blockchain or other traceability technologies to enhance transparency and trace root causes through the supply chain. Develop contingency plans for supply chain disruptions and build resilience through diversified sourcing and flexible logistics strategies.
Legacy System Integration Challenges	Legacy systems in Industry 4.0 environments may pose challenges in integrating with modern RCA technologies, leading to compatibility issues and data silos.	Develop a phased approach to legacy system integration, starting with essential components. Explore middleware solutions that facilitate communication between legacy and modern systems. Prioritize updates or replacements for legacy systems that pose significant integration challenges. Leverage APIs and standard data formats to improve compatibility between legacy and new systems. Engage with vendors that specialize in retrofitting or upgrading legacy systems for Industry 4.0 compatibility.
Overemphasis on Technology Solutions	There might be an overemphasis on adopting new technologies without addressing underlying organizational or process-related issues that contribute to root causes.	Conduct thorough organizational assessments to identify systemic issues beyond technological considerations. Implement a holistic approach that includes organizational restructuring, process optimization, and cultural change alongside technology adoption. Prioritize addressing fundamental issues in workflows, communication, and collaboration to ensure the effectiveness of RCA integration beyond technology alone.
Limited Scalability and Flexibility	RCA solutions may face limitations in scalability and adaptability to evolving Industry 4.0 requirements, hindering their effectiveness in dynamic environments.	Choose RCA solutions that are scalable and adaptable to changing business needs. Regularly review and update RCA processes to align with evolving technologies and industry standards. Implement modular and flexible solutions that can be easily integrated with new technologies and accommodate future expansions. Stay informed about emerging technologies and trends to proactively address scalability challenges.

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 Root Cause Analysis (RCA) in Industry 4.0 conditions represents a strategic and indispensable approach to problem-solving within the dynamic landscape of advanced technologies and interconnected systems. Root Cause Analysis serves as a powerful tool, allowing organizations to dissect multifaceted issues that may arise in the convergence of physical and digital systems. Its systematic investigative approach is crucial for understanding and mitigating problems stemming from the integration of smart technologies, automation, and data-driven processes.

The complexities and interconnectedness inherent in Industry 4.0 systems elevate the significance of Root Cause Analysis. In this context, RCA enables organizations to navigate the intricate web of factors influencing the performance of smart manufacturing processes, cyber-physical systems, and the Internet of Things (IoT). By identifying the fundamental causes of disruptions or inefficiencies, Industry 4.0 enterprises can develop targeted solutions that address the heart of the problem. Moreover, as Industry 4.0 emphasizes real-time data collection and analysis, Root Cause Analysis becomes instrumental in deciphering patterns and correlations within the data deluge. Whether addressing glitches in production lines, cybersecurity breaches, or malfunctions in IoT devices, RCA facilitates a comprehensive examination of events, leading to more informed decision-making and proactive problem resolution.

The purpose of this publication is to underscore the usage of the Root Cause Analysis approach in Industry 4.0 conditions, highlighting its role as a strategic method for problem-solving. The fundamentals of Root Cause Analysis involve a systematic and holistic investigation into the underlying factors contributing to an issue. This method aims not only to address surface-level symptoms but to prevent the recurrence of problems by understanding and rectifying their fundamental reasons. The integration of RCA into Industry 4.0 practices aligns with the overarching goal of achieving predictive maintenance and minimizing downtime. By understanding the root causes of equipment failures or system malfunctions, organizations can implement predictive analytics and preventive measures, optimizing operational efficiency and reducing the risk of costly disruptions.

In the landscape of Industry 4.0, RCA is increasingly integral, leveraging digitalization and advanced technologies to reshape industrial processes. The integration of RCA plays a crucial role in identifying and mitigating issues at their core, using technologies like IoT sensors, machine learning, and digital twin technology. This integration extends to various aspects of Industry 4.0, including smart manufacturing systems, predictive maintenance, interconnected supply chains, and addressing cybersecurity incidents. Table 1 outlines the key principles of Root Cause Analysis, forming the foundation for an effective problem-solving process. These principles include a systematic approach, holistic investigation, data-driven analysis, multidisciplinary perspective, proactive problem-solving, iterative process, use of analytical tools, and a focus on continuous improvement.

Table 2 provides examples of how Root Cause Analysis is integrated into Industry 4.0, illustrating its relevance in addressing challenges and optimizing processes. This integration encompasses digitalization and data analytics, smart manufacturing systems, predictive maintenance, interconnected supply chains, cybersecurity incidents, digital twin technology, real-time monitoring, cross-functional collaboration, supply chain traceability, human-machine interaction, advanced sensor integration, and machine learning applications. Table 3 enumerates the advantages of Root Cause Analysis integration with Industry 4.0, emphasizing proactive issue resolution, enhanced operational efficiency, cost reduction through predictive maintenance, improved quality and productivity, data-driven decision-making, prevention of recurring issues, cross-functional collaboration, optimized supply chain performance, and enhanced cybersecurity resilience.

Table 4 delves into the challenges associated with Root Cause Analysis integration with Industry 4.0, offering a comprehensive view of the problems and suggested overcoming strategies. These challenges include data overload and complexity, interconnected systems challenges, human-technology interaction issues, integration costs and resource allocation challenges, lack of standardization and compatibility, cybersecurity risks, expertise and skill gap, resistance to change, data privacy and compliance concerns, complex supply chain dynamics, legacy system integration challenges, overemphasis on technology solutions, and limited scalability and flexibility.

The usage of Root Cause Analysis in Industry 4.0 conditions signifies a strategic approach to problem-solving in the face of advanced technologies and interconnected systems. As industries continue to embrace the transformative capabilities of the fourth industrial revolution, the application of RCA becomes indispensable for fostering resilience, continuous improvement, and the sustainable success of organizations operating in this dynamic and technologically-driven landscape.

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 2023.