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Comprehensive Risk Assessment Of Industrial Radiography Process Within Industry 5.0: Towards Continuous Safety Improvement

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Abstract

The radiographic inspection of critical jet engine hardware involves inherent risk factors. Failure to address these risks appropriately can lead to catastrophic operational accidents, including loss of life and aircraft destruction. Recognizing and mitigating these risks is crucial, with the human factor playing a pivotal role in ensuring the success of the inspection process. In the context of Industry 5.0, a groundbreaking paradigm that prioritizes human needs and well-being in technological advancements, our study seeks to illuminate the risks associated with the failure of radiographic inspection of critical hardware. Furthermore, we aim to explore how the Industry 5.0 framework can be effectively leveraged to optimize this inspection process. This research endeavors to generate practical insights into each process variable, offering actionable strategies to prevent failures in both inspection procedures and critical hardware components. Its significance extends to inspectors, manufacturing engineers, safety engineers, and company decision-makers, providing guidance on implementing a risk assessment program rooted in Industry 5.0 principles for process optimization. Distinguishing itself as an innovative endeavor, this study pioneers the application of the Industry 5.0 approach to radiographic inspections. Methodologically, it employs a thorough review of state-of-the-art literature, standards, and regulations to identify risk factors. Subsequently, the study illustrates how Industry 5.0 concepts can be applied to formulate effective responses to these risks. The outcome comprises a comprehensive list of identified risks and practical examples showcasing the application of Industry 5.0 concepts. The ultimate goal is to enhance the overall quality, reliability, and profitability of companies engaged in jet engine hardware maintenance, manufacturing, and other processes employing X-ray and gamma rays. The result can be used as a guideline by jet engine hardware maintenance, manufacturing professionals, and other organizations using X-ray and gamma rays in their processes. Although the primary focus is on the radiographic inspection within a jet engine repair station, the study findings can be generalized to other industries that use industrial radiographic inspection and whose sustainability is affected by inspection failure, resulting in waste, rework, and unnecessary energy consumption. The study provides guidelines to be used by professionals, engineers, inspectors, and decision-makers. The study outlines measures that can significantly improve operational performance, enhance safety standards, reduce costs, minimize waste, and positively impact organizational sustainability. By addressing a critical gap in the literature, our study introduces a pioneering perspective on the transformative potential of Industry 5.0 concepts in radiographic inspections. The guidelines provided can be instrumental for developing risk assessment programs, further contributing to the improvement of organizational quality, safety, and overall financial well-being. This study sets the stage for future academic research, inspiring scholars to delve deeper into refining inspection quality and processes.

Keywords: risk assessment, industrial radiography, analytic hierarchy process, Bayesian Belief Network, Industry 5.0

1. Introduction

Industrial radiography has many process variables that can negatively impact the inspection result (e.g., part exposure parameters such as voltage, amperage, film processing time, and others). If operational risks (that impact the validity and reliability of the result) are not identified and proper responses implemented, catastrophic operational accidents can happen. The accuracy and reliability of the radiographic inspection results could be compromised. This can lead to missed defects, false positive results, and incorrect assessments of material integrity, which might result in operational failures or accidents down the line, with loss of life and equipment destruction. IAEA (2023) states that it is essential to identify and assess operational risks associated with radiographic inspection processes to prevent catastrophic operational accidents. It involves thorough training for personnel, adherence to safety protocols, proper equipment maintenance, regular quality control checks, and clear communication among all involved parties. Effective risk management practices can help ensure the safety of personnel, the public, and the environment during radiographic inspections. NDE (Non-Destructive Examination) is essential in diagnosing the failure's occurrence in parts/products; therefore, high precision and reliability are necessary. Industrial radiography is an NDE process in which many variables can affect the final inspection result. Investigating the risk factors and defining how Industry 5.0 concepts could help process optimization is necessary. This study investigates potential risk factors in the radiographic inspection process based on the most current literature and analyzes the application of new industry 5,0 concepts to address risks. The lack of scientific publications on risk analysis covering this specific process shows that a study on the qualitative failure analysis of the radiographic inspection process and the use of industry 5.0 concepts to implement risk responses has not been carried out yet. The paper answers the following research questions: Research Question 1: What are the risks of failure in the radiographic inspection of critical hardware? Research Question 2: How could industry 5.0 concepts be utilized to optimize the process and ensure effective responses to these risks? The study is structured into five sections: an introduction, a literature review showing state-of-the-art publications on risks in Radiographic Inspection, the use of Technology in Radiographic Inspection, and Industry 5.0 concepts in Industrial Radiographic Inspection. The methodology is presented, the results are discussed, and a conclusion is made.

2. Literature Review

2.1. Risks in the Radiographic Inspection

Previous studies dealing with this specific subject have not covered potential risk factors in this process. The studies of Dobmann (2006), Guo and Yang (2011), Kourkoulis et al. (2006), Franco et al. (2011), Thirugnanam and Anouncia (2014) covered radiographic inspection with no focus on risk assessment. The studies of Nahavandi (2019), Pasman and Yang (2022), Hussain et al. (2022), and Alves et al. (2023) focused on the application of some of the industry 5.0 concepts to radiographic inspection but with no focus on risk assessment. One of the previous works dealing with NDE is the study of Guo and Yang (2011), where the authors analyzed the probability of the detection curve as an essential performance metric for an NDE system. In 2006, Kourkoulis and his team investigated the dependability of NDE findings concerning the inner deterioration of marble samples. Dobmann's research in 2006 brought to light another captivating use of NDE (Non-Destructive Evaluation). He delved into material characterization, explicitly targeting the effects of aging due to thermal embrittlement, fatigue, and neutron degradation. In a parallel endeavor during the same year, Djordjevic harnessed the capabilities of NDE for a distinct purpose. His focus was on prognostic structural characterization, which involved meticulously inspecting materials for signs of damage. To achieve this, he employed a combination of in-situ and hybrid non-contact ultrasonic sensing techniques. Franco et al. (2011) introduced an industrial system combining CT and digital radiography (CT/DR) for non-destructive evaluation (NDE) purposes. Singh (2012) employed the fuzzy Analytic Hierarchy Process (AHP) methodology due to the variability of linguistic interpretations across individuals. Thirugnanam and Anouncia (2014) delved into radiographic inspection processes, pioneering a fresh methodology. Their innovative approach amalgamated fractal-based image analysis to extract intricate details from input images, coupled with a fuzzy-based rule engine. In a study by Metha and Bedi (2016), an investigation was undertaken into applying an adaptive neuro-fuzzy inference system to model and identify cracks and porosity through the liquid penetrant test. Iskandar et al. (2022) explored the theory of risk assessment and management methods. The author used a mathematical model and the introduction of the bowtie risk management method. Akudjedu et al. (2023) studied the advancement of AI technologies and the benefits of AI-enabled radiography workflows and improved efficiencies. As described previously, the studies of Dobmann (2006), Kourkoulis et al. (2006), Guo and Yang (2011), Franco et al. (2011), Thirugnanam and Anouncia (2014), Nahavandi (2019), Iskandar et al. (2022), Pasman and Yang's (2022), Hussain et al. (2022), Akudjedu et al. (2023) and Alves et al. (2023) were relevant and brought new applications and technologies. None of the previously listed studies dealt with a conceptual framework for risk assessment in the industrial radiography process via BBN and AHP with the application of industry 5.0 concepts to improve safety. Risk factors with potential consequences are present during the radiographic examination of vital hardware. Failure to evaluate these risks and establish appropriate countermeasures could lead to severe operational mishaps. Neglecting the identification and mitigation of risks within the radiographic inspection procedure may result in various undesirable outcomes, including jeopardizing the safety of personnel engaged in the inspection activities. Workers may be exposed to dangerous radiation levels without proper risk identification and mitigation, resulting in radiation-related injuries or illnesses, as stated by the ILO (2021) report. If risks are not addressed, the quality of the radiographic inspections may suffer. Undetected risks could lead to inaccuracies in the results, false positives or negatives, or the overlooking of critical defects, all of which can compromise the overall effectiveness of the inspection process.

2.2. Technology in Radiographic Inspection

Industrial radiographic inspection is a widely used non-destructive testing (NDT) method to examine the internal structures of various materials and components in manufacturing, aerospace, oil and gas, and more, as stated by IAEA (2023). It involves using X-rays, gamma rays, or other radiation sources to penetrate the material and create an image that can reveal defects, flaws, or structural irregularities. Across a spectrum of uses, radiographic examination offers a method for observing and evaluating the intrinsic traits of substances and frameworks non-invasively, thereby establishing itself as a precious asset in upholding safety, excellence, and productivity across diverse industries and scientific pursuits. As regards the field of research, some studies have been focusing on improving the industrial radiography technique using technology. As an example, Pasman and Yang's (2022) study shows that industrial radiographic inspection has been advancing over the years with digitalization; traditional film-based radiography has largely been replaced by digital radiography (DR) and computed tomography (CT) techniques. Digital imaging allows for faster image acquisition, immediate results, accessible storage, and the ability to enhance and analyze images using software tools. Automated radiographic inspection systems have been developed, reducing the need for manual intervention. Aligned with the previous study, Hussain et al. (2022) concluded that advancements in radiographic equipment and techniques have improved resolution and sensitivity, allowing for more minor defects and ensuring higher inspection accuracy. The focus on safety has led to the development of better shielding materials and safety protocols, minimizing radiation exposure to operators and the environment. Artificial intelligence and machine learning algorithms have been applied to radiographic inspection data to automate defect detection, classification, and analysis, further enhancing inspection efficiency and accuracy.

2.3. Industry 5.0 Concepts in Industrial Radiographic Inspection

A specific study on Industry 5.0 concepts in industrial radiographic inspection is, for example, the one conducted by Nahavandi (2019); the author stated that. Industry 5.0, often referred to as "human-robot collaboration," aims to bring together the strengths of both human workers and advanced automation technologies. Industry 5.0 concepts could enhance industrial radiographic inspection by enhanced collaboration; in radiographic inspection, skilled NDT technicians can collaborate with robotic systems to set up inspections, interpret complex results, and make critical decisions based on their expertise. Anticipated benefits encompass heightened precision, instantaneous remote teamwork, competency advancement, optimized resource utilization, tailor-made resolutions, and heightened risk management. This mutually advantageous interaction of humans and technology has the potential to usher in more dependable and streamlined assessment procedures, ultimately favoring sectors dependent on radiographic inspection to uphold quality control and ensure safety. Industry 5.0 encourages a culture of continuous learning and improvement. AI algorithms can learn from past inspection data, identify patterns, and improve defect recognition capabilities over time, resulting in more accurate and efficient inspections. Radiographic inspection systems can adapt to different components, materials, and requirements, ensuring optimal inspection solutions for various industrial applications (Techopedia, 2023). Radiographic inspection using Industry 5.0 would differentiate itself from traditional methods by emphasizing human-machine collaboration, advanced data analytics, remote monitoring, customization, and skill development. These changes would lead to more efficient, accurate, and adaptable radiographic inspections, improving product quality and safety. Another critical study is the one conducted by Alves et al. (2023), which demonstrated that Industry 5.0 emphasizes placing human needs and well-being at the center of technological advancements. With radiographic inspection, this could translate into ergonomic designs for inspection workstations, user-friendly interfaces, and improved safety features. AI-driven radiographic inspection systems can quickly process data, identify defects, and provide instant operator feedback, enabling swift action when required. Industry 5.0 is still an evolving concept, and its implementation and impact on industrial radiographic inspection would depend on various factors, including technological advancements, regulatory considerations, and industry adoption.

3. Methodology

The research methodology adopted for this study encompassed a mixed-method approach, combining insights from existing literature with a comprehensive case study. The case study employed a variety of data sources, including interviews, document analysis, and direct observations of the underlying process. Considering the work by Reis et al. (2019), qualitative methodology is fitting for this study due to the intricate nature of the subject. The aim here was to uncover patterns and connections between the phenomena being examined without being confined by the strict boundaries characteristic of quantitative methods, as Voss et al. (2002) pointed out. In this context, a mixed-method approach was chosen, involving diverse data collection and analysis techniques. As highlighted by Choi et al. (2016), the utilization of mixed methods contributes to advancing the field of study and lends solidity, rigor, and scientific relevance to research in Operations Management. Following a comprehensive examination of the existing literature, where the underlying concepts were clarified, identified gaps were highlighted, and clear guidelines were established, Reis et al. (2019) commenced the practical investigation. This study, integral to the current research, took the form of a Case Study, leveraging its distinctive capacity to engage with a diverse array of evidence types, including documents, tangible artifacts, interviews, firsthand observations, and participant involvement, as emphasized by Campbell and Yin (2018). The utilization of the case study was embraced due to its valuable role in examining present-day occurrences like 'Open Innovation' and 'Digital Transformation.' This approach delves into real-life situations characterized by vague boundaries and intricate definitions, as elucidated by Campbell and Yin (2018). According to these scholars, the case study becomes apt when a researcher intentionally seeks to delve into authentic contextual circumstances, believing that these circumstances profoundly relate to the subject under scrutiny.

3.1. Data Collection Method

The data gathering approach for the case study embraced a qualitative method, adhering to the triangulation principle supported by eminent researchers such as Eisenhardt (1989), Patton (2014), and Campbell and Yin (2018). The adoption of this principle involved juxtaposing data obtained from diverse sources and through various techniques, enhancing the coherence of results and mitigating inherent constraints associated with each method (Campbell and Yin, 2018). The different sources and methods included: 1. Documents (papers, standards, and regulations) research, 2—analysis of an industrial radiography process, and interviews with experts. The interview was based on a list of risk factors developed from the theoretical framework of the research. The participating subjects were directly involved with the subject's Radiographic Inspection. The objective was to collect relevant perceptions about the risks in the radiographic inspection. The methodology for the development and refinement of the list of risks for the interview and its actual execution was based on Hollway and Jefferson (2000), Gubrium et al. (2012), and Witzel and Reiter (2012). Direct observations range from formal to informal data collection activities (Campbell and Yin, 2018). In this case, a less formal collection, with direct observations, was made during the fieldwork, including interviews.

3.2. Analysis of Results

Content analysis techniques (Neuendorf, 2012) were employed to examine the interviewees' remarks. According to Weber (1990), content analysis, a research approach employing specific procedures, facilitates reliable deductions drawn from textual data. These deductions pertain to the communicator, the message's substance, and the message's intended recipients. In that regard, Neuendorf (2012) also defined content analysis as a methodical and quantitative assessment of message attributes that is both systematic and unbiased. This approach can encompass various applications, such as in-depth scrutiny of in-person human exchanges, computer-assisted scrutiny of lexical patterns, and evaluation of advertising materials and blog content. Aligned with previous arguments, top-notch textual content examinations employed qualitative methodologies, as Weber (1990) indicated. Accordingly, the interview content analysis encompassed quantitative approaches. This involved gauging the occurrence frequency of distinct content traits and discerning the existence or lack thereof of attributes, in line with the insights of Neuendorf (2012). In confronting the results achieved with the systematic literature review, the interviews, documentary analysis, and direct observations, the result of the research was substantiated with the development of the list of risks and list of industry 5.0 concepts application to Radiographic inspection.

4. Results

Pereira (2022) conducted a case study in an RI area of a jet engine overhaul site. The main process steps were defined and documented, as shown in Figure 1, to identify the risk factors involved. The risk factors in each process step were identified by consulting specialists and by research conducted in the most current literature. The risk factors are listed in Tables 1 to 9.

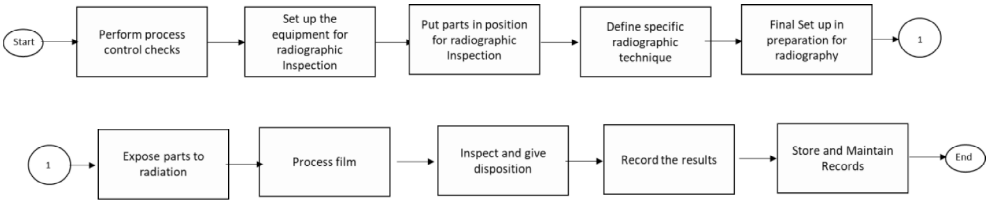

Fig. 1. Main process steps.

Table 1 list the risk factors present in the first step of the process map from Figure 1, which is the Failure in Process Control Checks.

Table 1. Risks of Failure in Process Control Checks.

Process Steps	Risks	Risk Factors
A - Failure in Process Control Checks	A1 -Verification of instruments and equipment not correctly performed	A11 - Film Viewer not verified
		A12 - Film Wedge not calibrated
		A13 - Densitometer/equipment not calibrated
	A2 - Use of consumables with poor quality	A21 - Film broken, crumpled, scratched, fragile
		A22 - Scratched/stained Screen
		A23 - Film holder damaged
	A3 - Environment and operation conditions not ideal	A31 - Incorrect temperature in film storage room
		A32 - Incorrect moisture in the film storage room
		A33 - Radiography equipment not well maintained

Table 2 lists the risk factors present in the first step of the process map from Figure 1, which is the Initial Set up for Radiographic Inspection.

Table 2. Risks of Failure in Initial Set up for Radiographic Inspection.

Process Steps	Risks	Risk Factors
B - Failure in Initial Set up for Radiographic Inspection	B1 - Error in film handling	B11 - Improper handling during development
		B12 - Exposure during handling before exposition
		B13 - Exposure to radiation during storage
	B2 - Error in the selection of radiographic technique	B21 - IQI selection based on wrong material
		B22 - Wrong film selection
		B23 - Wrong selection of the intensifier screen type
	B3 - Error in the measurement of part thickness	B31 - Wrong instrument used
		B32 - Operator not properly trained
		B33 - Instrument not calibrated

Table 3 lists the risk factors present in the first step of the process map from Figure 1: the failure in positioning Part related to the radiation source.

Table 3. Risks of Failure in the Positioning of Part Related to Radiation Source.

Process Steps	Risks	Risk Factors
C - Failure in the positioning of part related to the radiation source	C1 - Wrong positioning of part	C11 - Wrong source to film distance
		C12 - Improper positioning of IQI
		C13 - Wrong angle of part related to the source
	C2 - Wrong positioning of film in film holder and to the part	C21 - Poor contact between film/intensified screen
		C22 - Film was positioned in the wrong position at the part
		C23 - Incorrect fastening of the film holder to the part

Table 4 list the risk factors present in the first step of the process map from figure 1, which is the failure in the definition of specific radiographic technique.

Table 4. Risks of Failure in the definition of specific radiographic technique.

Process Steps	Risks	Risk Factors
D - Failure in the definition of a specific radiographic technique	D1 - Error in the specification of material	D11 - Wrong part drawing utilized
		D12 - Unprecise information about part material in the drawing
		D13 - Misinterpretation of part drawing
	D2 - Error in the specification of distance from the part concerning the beam	D21 - Wrong part drawing utilized
		D22 - Unprecise information about part dimension in the drawing
		D23 - Misinterpretation of part drawing

Table 5 lists the risk factors present in the first step of the process map from Figure 1: the failure in the final setup in preparation for radiography.

Table 5. Risks of Failure in the final setup in preparation for radiography.

Process Steps	Risks	Risk Factors
E - Failure in the final setup in preparation for radiography	E1 - Use of incorrect technique	E11 - Non-use of procedures/instructions
		E12 - Lack of operator training
		E13 - Misinterpretation of procedures/instructions
	E2 - Wrong setup of exposition parameters in the X-ray equipment	E21 - Use of wrong Amperage
		E22 - Use of wrong voltage
		E23 - Use of wrong exposure time
	E3 - Wrong set up of focus in the X-ray equipment	E31 - Large focus size
		E32 - Small focus size
		E33 - Incorrect use of low-intensity radiation screen

Table 6 lists the risk factors present in the first step of the process map from Figure 1: Failure in Part Exposition.

Table 6. Risks of Failure in Part Exposition.

Process Steps	Risks	Risk Factors
F- Failure in Part Exposition	F1 - Wrong number of expositions	F11 - Radiographic technique not used
		F12 - Incorrect radiographic technique used
		F13 - Misinterpretation o radiographic technique
	F2 - Exposition of part wrong region	F21 - Misinterpretation of radiographic technique
		F22 - Radiographic technique not used as required
		F23 - Incorrect radiographic technique used
	F3 - Lack of control for the backscattering	F31 - Radiographic Technique not followed
		F32 - Misinterpretation of radiographic technique
		F33 - Use of an inadequate intensifying screen

Table 7 lists the risk factors present in the first step of the process map from Figure 1: Failure in Film processing.

Table 7. Risks of Failure in Film Processing.

Process Steps	Risks	Risk Factors
G - Film processing	G1 - Failure in processing parameters	G11 - Developing solutions PH not verified
		G12 - Processing time not observed
		G13 - Solution temperature not observed
	G2 - Developing solutions not correctly prepared	G21 - Tanks not cleaned and not completed with fresh solution
		G22 - Thermometer and accessories not properly cleaned
		G23 - Solution stirring performed with improper devices
	G3 - Failure in film development	G31 - The drying process not uniform
		G32 - Film not moved inside the solution
		G33 - Solution not properly distributed on the film

Table 8 lists the risk factors present in the first step of the process map from Figure 1: Failure in Inspection and Disposition.

Table 8. Risks of Failure in Inspection and Disposition.

Process Steps	Risks	Risk Factors
H - Failure in Inspection and disposition	H1 - Radiography Interpretation error	H11 - Film viewer inspection area dirty
		H12 - Film viewer intensity low
		H13 - Inspection environment inadequate
		H21 - Film wedge out of specification

	H2 - Density in the area of interest out of the specification	H22 - Film wedge not calibrated H23 - Densitometer not calibrated
	H3 - Radiography showing defects	H31 - Stains from poor film development H32 - Marking from poor film handling H33 - Film folding caused by inadequate positioning

Table 9 lists the risk factors present in the first step of the process map from Figure 1, which is the failure in the record of results.

Table 9. Risks of Failure in the record of results.

Process Steps	Risks	Risk Factors
I - Failure in the record of results	I1 - Wrong Records of radiography	I11 - Lack of traceability on radiography I12 - Incorrect traceability identification on Film I13 - Radiography Identification poorly done

Trends and concepts associated with Industry 4.0 focus on integrating digital technologies, automation, and data exchange in manufacturing. These concepts may still apply to radiographic inspection or any quality control process. Industry 5.0 is characterized by integrating advanced technologies like artificial intelligence, big data, and the Internet of Things (IoT) to create intelligent and interconnected systems. These technologies can be applied to radiographic inspection in several ways to prevent risks of failure. Table 10 shows how technologies can be applied to industrial radiography as a response to the risks presented in Tables 1 to 9.

Table 10. Risks of Failure in the record of results

Industry 5.0 concepts	Explanation	Application in Radiographic inspection
Smart Sensors and IoT Integration:	Smart sensors and IoT integration collaborate to efficiently gather, process, and share data from physical devices and environments. Smart sensors, equipped with various sensors and processing capabilities, collect data locally and connect to networks via wired or wireless protocols. Integrated into the IoT ecosystem, these devices transmit data to centralized systems or the cloud, which undergoes analysis using cloud computing resources and advanced analytics, including machine learning.	Use advanced sensors to gather real-time data during radiographic inspections. Implement the Internet of Things (IoT) to connect and communicate data between inspection devices and systems. In real-time inspection, IoT sensors can be attached to equipment to collect data in real-time. This data can be used to perform continuous inspection, which can help to identify and address problems before they become critical. IoT technology can enable remote collaboration between inspectors and experts. This can be helpful for situations where specialized expertise is needed, or equipment is located in a remote or difficult-to-access location.
Big Data Analytics	Big Data Analytics examines and interprets large and complex datasets to uncover hidden patterns, correlations, and insights. It involves using advanced technologies and algorithms to analyze massive volumes of structured and unstructured data, often in real-time, to extract valuable information.	Employ big data analytics to process and analyze large data generated during inspections. Identify patterns, trends, and anomalies that may indicate potential risks of failure.
Artificial Intelligence (AI) and Machine Learning (ML):	Artificial Intelligence (AI) and Machine Learning (ML) represent cutting-edge technologies that aim to mimic and enhance human cognitive abilities in machines. AI is a broader concept that encompasses the development of intelligent agents capable of perceiving their environment, reasoning, and making decisions to achieve specific goals.	Utilize AI and ML algorithms to enhance the accuracy and efficiency of radiographic inspection. Develop predictive maintenance models to anticipate potential equipment failures before they occur. Automated anomaly detection: AI algorithms can analyze radiographic images to identify anomalies and defects that might be missed by human inspectors automatically. This can significantly improve the accuracy and efficiency of inspection, especially for complex or repetitive tasks.
Digital Twins	Digital twins are virtual replicas of physical objects, systems, or processes. These virtual representations are created by integrating data from sensors, IoT devices, and other sources, allowing for a real-time, dynamic reflection of the physical	Digital twins are virtual representations of physical objects that can be used to simulate and test different scenarios. This could be used to develop and test new inspection methods and

	counterpart. The concept of digital twins extends beyond static models by incorporating continuous data updates, enabling a deeper understanding and analysis of the real-world entity.	train inspectors in a safe and controlled environment. Create digital twins of the equipment or components undergoing radiographic inspection. Monitor the digital twin in real-time to compare its performance with the physical counterpart and identify discrepancies.
Blockchain for Data Integrity:	Blockchain technology has emerged as a revolutionary solution for ensuring data integrity in various industries. At its core, a blockchain is a decentralized and distributed ledger that records transactions across a network of computers in a secure and tamper-resistant manner. This decentralized nature eliminates the need for a central authority, making it highly resilient to fraud and unauthorized alterations.	Blockchain is a distributed ledger technology that can be used to store and track inspection data securely. This could help to improve the traceability of inspections and prevent fraud. Implement blockchain technology to ensure the integrity and traceability of inspection data. Securely store and timestamp inspection results, creating an immutable record of the inspection process.
Augmented Reality (AR) for Inspection Assistance:	Augmented Reality (AR) for Inspection Assistance is a cutting-edge technology that leverages digital information to enhance and streamline inspection processes across various industries. This innovative application of AR transforms the way inspections are conducted by overlaying computer-generated content onto the real-world environment, providing inspectors with valuable insights and assistance in real time.	Use AR technologies to provide real-time guidance and assistance to inspectors during the radiographic inspection. Overlay relevant information into the inspector's field of view for enhanced decision-making.
Collaborative Robotics (Cobots):	Collaborative Robotics, often referred to as Cobots, plays a significant role in Industry 5.0, representing the next phase of industrial evolution. Collaborative Robotics in Industry 5.0 represents a paradigm shift toward human-robot collaboration, flexibility, safety, and adaptability. Cobots are instrumental in creating more agile and efficient manufacturing processes while enhancing the role of human workers in value-added tasks.	Integrate collaborative robots to work alongside human inspectors, improving efficiency and reducing the risk of errors. Cobots can handle repetitive tasks, allowing human inspectors to focus on complex analyses.
Cybersecurity Measures:	Cybersecurity measures encompass integrated security systems, advanced protection for the Internet of Things (IoT), increased use of AI and machine learning for threat detection, blockchain for enhanced security, adoption of the Zero Trust model, emphasis on supply chain security, compliance with evolving regulations, human element considerations through training, and robust incident response and recovery plans.	Implement robust cybersecurity measures to protect sensitive inspection data from unauthorized access and cyber threats. Regularly update and patch software and firmware to address potential vulnerabilities.
Human-Machine Collaboration:	Human-machine collaboration in Industry 5.0 represents the next phase in the evolution of industrial processes, characterized by a deep integration of humans and advanced technologies. Unlike its predecessors, Industry 4.0, which focused on automation and connectivity, Industry 5.0 emphasizes collaboration between humans and machines. Human-machine collaboration in Industry 5.0 envisions a harmonious partnership between humans and advanced technologies, where both strengths are leveraged to create more efficient, flexible, and ethically sound industrial processes.	Foster collaboration between human inspectors and automated systems to combine both strengths. Provide training for inspectors to work effectively with advanced technologies.
Continuous Improvement through Feedback Loops:	Involves a systematic approach to enhance processes by incorporating feedback mechanisms at various stages. This concept emphasizes ongoing learning, adaptability, and optimization, leveraging real-time data and insights to drive positive change. It fosters a dynamic environment where feedback from different sources, including operators and machines, is actively collected and analyzed.	Establish feedback loops that involve continuous monitoring, analysis, and improvement of the radiographic inspection process. Use insights from inspections to refine and optimize procedures over time.
Big data analytics	Big data analytics refers to examining and uncovering meaningful patterns, trends, and insights from large and complex datasets. "big data" refers to the massive volume, variety, and velocity of data generated in today's digital age. Big data analytics involves using advanced technologies and	Process optimization: By analyzing large datasets of inspection data, it is possible to identify trends and patterns that can help optimize the inspection process. This can include things like optimizing the inspection

techniques to collect, store, process, and analyze this vast amount of data to extract valuable information.	parameters, improving the training of inspectors, and developing new inspection methods.
	Risk assessment: Big data analytics can be used to develop more accurate risk assessments for equipment and components. This information can be used to prioritize inspection tasks and allocate resources more effectively.

5. Discussion of results and conclusion

The study systematically outlines the risks associated with the potential failure in the radiographic inspection of critical hardware and identifies how the Industry 5.0 framework could be utilized to optimize the process. By following the steps defined in the methodology, the study assessed the risk factors in the IR process, which were drawn from the available literature. The risk factors are listed in Tables 1 to 9. Table 10 shows how technologies can be applied to industrial radiography as a response to the risks presented in Tables 1 to 9. The information can help industry professionals obtain better results, higher quality, and safer products. Each step of the radiographic inspection process was analyzed for risks qualitatively. The conclusion is that the integration of Industry 5.0 concepts into industrial radiography yields substantial benefits and advancements for the field. Embracing these concepts marks a paradigm shift towards innovative, interconnected, and data-driven processes, ultimately fostering enhanced efficiency, safety, and quality in inspection procedures. In addressing the initial research question posed at the outset of this paper, we outlined the potential risks associated with the radiographic inspection of critical hardware. Subsequently, in response to the second research question, we identified specific Industry 5.0 concepts that can be leveraged to optimize the inspection process and formulate effective responses to mitigate these risks. Drawing insights from a case study conducted in real-world scenarios, as detailed by Pereira (2022), our conclusion underscores the effectiveness of the proposed method. It emerges as an invaluable resource for safety engineers and decision-makers within companies, augmenting their knowledge and aiding in the identification of critical risks in Radiographic Inspection. This, in turn, facilitates the implementation of strategic actions to prevent critical parts failure, thereby enhancing safety and reliability throughout the inspection process, while concurrently optimizing energy consumption. As highlighted in the introduction section, previous studies on this specific subject have overlooked potential risk factors and the application of Industry 5.0 concepts in this context. The radiographic inspection process was mapped out and assessed based on the most current literature on the subject and the opinion of IR inspection operators and engineers. So, it completes a gap in the literature, has practical application, and can help industry professionals obtain better results in industrial radiography, leading to manufacturing products with higher quality, safety, reliability, and less energy consumption. The study, offering comprehensive guidelines for professionals, engineers, inspectors, and decision-makers, holds the potential to significantly impact the quality, reliability, and profitability of companies. Moreover, it catalyzes optimizing operational performance and safety measures, bringing about noteworthy improvements, cost reductions, waste avoidance, and positively influencing organizational sustainability. By advocating for the implementation of risk assessment in radiographic inspection through the lens of Industry 5.0 concepts, our research encourages the utilization of cutting-edge technologies and methodologies. This, in turn, empowers professionals in radiographic inspection to refine their risk assessment processes, optimize operational performance, and prioritize safety. The integration of Industry 5.0 concepts emerges as a transformative force, contributing holistically to the overall quality, profitability, and sustainability of industrial processes.

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