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Review

Revolutionizing Tire Quality Control: AI's Impact on Research, Development, and Real-Life Applications

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Featured Application: The potential application of the work includes conceptual work on the use of artificial intelligence in technical control and maintaining the quality of tires during operation.

Abstract: The tire industry plays a key role in ensuring safe and efficient transportation. With 1.1 billion vehicles worldwide relying on tires for optimum performance, tire quality control is of paramount importance. In recent years, the integration of artificial intelligence (AI) has revolutionized various industries, and the tire industry is no exception. In this article, we take a look at the current state of quality control in the tire industry and the transformative impact of AI on this crucial process. Automatic detection of tire defects remains an important and challenging scientific and technical problem in industrial tire quality control. The integration of artificial intelligence into tire quality control has the potential to transform the tire industry, leading to safer, more reliable, and more sustainable tires. Thanks to continuous progress and a proactive approach to challenges, the tire industry is prepared for a future in which artificial intelligence will play a key role in delivering high-quality tires to consumers around the world.

Keywords: tire; safety; artificial intelligence; machine learning; deep learning; effectiveness

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1. Introduction

The tire industry plays a key role in ensuring safe and efficient transport. With millions of vehicles relying on tires for optimum performance, tire quality control is of paramount importance. In recent years, the integration of artificial intelligence (AI) has revolutionized various industries, and the tire industry is no exception. In this article, we will explore the current state of quality control in the tire industry and the transformative impact of AI on this crucial process.

Tire quality control is an essential aspect of the tire manufacturing process (Figure 1). It involves rigorous inspection and testing to ensure that tires meet stringent standards of safety, performance, and durability. Typically, when considering tire defects, we refer to their size as being between 5 and 20 mm. Quality control not only helps prevent defective tires from reaching consumers but also contributes to the overall reliability and durability of tires. The tire industry is constantly striving to improve its quality control processes to deliver the highest-quality products that meet the evolving needs of consumers.

A detailed review of scientific publications in major databases (Web of Science, Scopus, and DBLP) was carried out using specific keywords. The results obtained were used to develop the next part of this review.

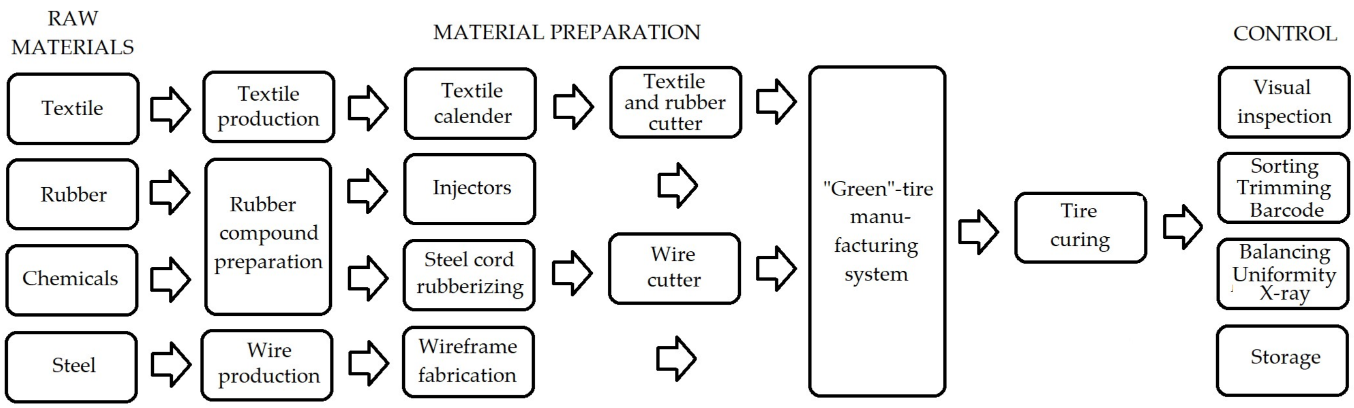

Figure 1. Traditional tire manufacturing process (own figure based on [1–3]).

1.1. The Role of AI in Tire Quality Control

In recent years, AI has emerged as a powerful tool for improving quality control in various industries. The tire industry has recognized the potential of AI in enhancing tire inspections, research and development processes, and real-life tire judgment. By leveraging advanced technologies, machine learning (ML) algorithms, and big data analytics, AI enables tire manufacturers to achieve higher accuracy, efficiency, and reliability in quality control.

AI applications, both traditional and deep learning-based, are already slowly taking a key place in the industry of practical measurement systems, especially based on the paradigms of Industry 4.0 and Industry 5.0. In doing so, they focus on several main groups of issues: measurement and de-noising techniques; applications for recognizing and tracking objects and people; solutions for analyzing and predicting environmental conditions; and above all, recommendation, second opinion, and education systems [1]. This does not bypass the tire manufacturing industry either. An example of this is digital shearography supported by deep learning methods used to assess tire quality with automatic detection of defects, especially those invisible to human eyes, such as air bubbles in shear images. Specifically, it uses sliding-window-based hybrid convolutional neural networks that pre-divide the input shear images into regions to identify bubble defects and then use faster networks to identify bubble defects in the tire shear images themselves, minimizing false alarm rates of up to 18% [2]. The principles of digital shearography are explained in [2–4]. To date, the digital shearography process has relied on detecting bubbles that are not visible to the naked eye, depending on the experience of the field operator's staff, which can be inconsistent. In addition, emerging new defect types may be missed or misdiagnosed by AI. This makes existing models for maintaining tire quality inadequate and requires work to develop and improve them. Among others, a defect (bubble) detection method based on an incremental YOLO architecture was developed for a tire manufacturer in Taiwan. In it, defects are classified into six categories, tire images are pre-processed to improve the visibility of less noticeable defects, and the amount of pre-training model learning data used has been increased. In addition, the incremental YOLO method uses small model training for previously unobserved defects to improve the model detection rate, enabling a detection accuracy of 98% and a sensitivity of 90% [5]. The loss of information about the original depth data can result in reduced error detection in tires. Anomaly detection in a depth image of a tire with a 16-bit size expressed in grayscale is of limited use compared to a three-channel image (colors, better represented shapes, higher brightness). Additionally, for tires, the same defects have different sizes and shapes. Improving the tire defect identification process required a four-step process in the form of image input, highlight image generation, image stacking, and image learning. This deep learning segmentation allows the detection of abnormal defects. Comparison of the pixel area with the actual error in the depth image and the pixel area of the error inferred by the DL network showed a 7–10% improvement in error detection with an 80% reduction in time [6]. This approach is in line with the general trends, as two main directions of transport development have been observed: the development of road infrastructure (more durable materials and improved techniques for laying and repairing pavements) and vehicles (greater steerability, control, and safety). The tire structure and the materials used, the suspension, and the drive system are also subject to continuous improvement, but in conditions of contradictory requirements regarding, for example, driving comfort and vehicle controllability, including on roads with poorer surface quality. A model of vehicle stability was developed that takes into account the condition of tires and suspension as well as the impact of road unevenness [7]. The tests take into account many dimensions: void models of a permeable asphalt mix, silting models, tire drop tests, pavement noise attenuation, and rutting studies. The results showed the critical size of sediment particles (0.3–0.6 mm); differences in the quality of water-permeable pavement layers (increased by 13% for asphalt concrete); reduction of porosity (from 20% to 8%); road noise level (increased by 4 dB) [8]; and controlling the magnetorheological shock absorbers of the semi-active vehicle suspension (also off-road, on various surfaces), taking into account body vibrations and its inclination. The key here is the proper modeling of the vehicle and the characteristics of the surface, as well as the coupling between the vehicle and the road [9]. Low-noise vehicles require the identification of noise sources, including tread noise, according to pattern shape design. Traditional spectrum analysis alone is not enough; it does not take into account the transmission and full noise mechanism of the tire tread. Better results are obtained by combiningthe impulse response of the transfer function with the tread pattern to determine the predicted noise waveform and sound quality index of tire tread noise. This AI-enhanced method can reduce design time and costs for different tire treads [10]. Objective methods of detecting the condition of the road surface, assessing the state of maintenance, and assessing the need for renovation have been developed. This will allow better detection and characterization of the driving environment for autonomous and electric vehicles in the future. The accuracy of surface classification in the urban zone ranges from 72% for endangered lanes to 75% for rehabilitated lanes [11]. Interestingly, it is also implemented for gravel roads (in the amount of loose gravel affectingthe quality and safety of driving) with an exactness of 97.50–97.91%using DL [12]. To assess the completeness and readability of tire markings for smart factories, the image of the marking points needs to be segmented. The k-means clustering algorithm is used for this task with an accuracy of 95–99% [13]. Tire defect detection is also possible with an X-ray image sensor, where this tire structure is represented by a feature distribution—local inverse differential moments—and the defect feature map is constructed by calculating the Hausdorff distance between the feature distributions of the original tire image and each shifted image fragment. Background suppression improves the reliability of the above-mentioned algorithm [14]. An interesting research problem is the consideration of elastic deformations (tire deformation, surface deformation, wheel rim deformation) during the vehicle's motion, which causes a measurement error that is difficult to compensate for. This requires force sensors mounted on the wheel rims. The obtained vehicle load indicators on a real road are (respectively in three dimensions): 88.3%, 91.0%, and 92.05% of vehicle load indicators on a standard road [15].

1.2. Objectives and Structure of the Article

The main objective of this article is to provide an overview of the current state of quality control in the tire industry and explore the transformative impact of AI in this field. We will explore the use of AI at different stages of the tire manufacturing process, from research and development to the actual assessment of tires. In addition, we will discuss the benefits, challenges, and future prospects ofAI in tire quality control.

By examining the current status, benefits, challenges, and future prospects of AI in tire quality control, this article aims to shed light on the key role that AI is playing in shaping the tire industry's quality control processes and delivering safer and more reliable tires to consumers around the world.

2. The Current State of Quality Control in the Tire Industry

In the tire industry, ensuring the quality of products is of paramount importance. Manufacturers have traditionally relied on manual inspections and quality control processes to detect any defects or imperfections in tires before they reach the market. However, with advances in technology, the tire industry is using AI to revolutionize its quality control procedures.

Traditionally, tire quality control involved visual inspections and manual measurements. Skilled technicians meticulously examined each tire for abnormalities such as sidewall deformities, tread pattern inconsistencies, or other visual defects. While this method was effective to some extent, it had limitations in terms of speed, accuracy, and consistency.

With the integration of artificial intelligence, tire manufacturers are now able to use automated inspection systems that use ML algorithms to assess tire quality more efficiently and accurately. These AI-based systems use advanced imaging techniques and sophisticated algorithms to detect even the smallest defects that may not be visible to the human eye.

One important aspect of tire quality control is the final production stage, where rigorous checks are carried out to ensure that each tire meets certain standards. According to information provided by https://www.opony.com.pl/ (accessed on 20 June 2023) [16], this final inspection phase involves a comprehensive test of various tire parameters.

At the final stage of production, AI-based systems are used to analyze tire dimensions, tread depth, sidewall structure, and other critical factors. These systems are able to measure various parameters quickly and accurately, enabling manufacturers to identify any deviations from the desired specifications.

What's more, AI algorithms under development can detect surface defects, such as blisters, bubbles, or foreign bodies, which can potentially compromise tire performance and safety. By automating these inspections, tire manufacturers can significantly streamline their quality control processes, reduce human error, and improve overall production efficiency.

Integrating AI into tire quality control not only streamlines the production process but also ensures that customers receive reliable, high-quality products. Using ML algorithms, tire manufacturers can identify potential defects and anomalies with greater precision, minimizing the risk of defective products reaching consumers [16].

3. AI in Research and Development Processes

In the tire industry, research and development (R&D) plays a key role in driving innovation and improving tire performance. AI is changing the way tire manufacturers approach R&D, enabling them to design superior tires, optimize material selection, and improve overall performance. Let's look at some key examples of how AI is revolutionizing tire research and development.

3.1. Simulation and Modeling

Continental Tires [17] uses advanced simulation techniques to speed up the tire development process. By using AI-based computer simulations, tire engineers can virtually test different tire designs and analyze their performance under different conditions. This allows them to optimize tire parameters such as tread pattern, compound composition, and structural design without the need for extensive physical testing. Artificial intelligence-based simulations significantly increase R&D productivity, enabling faster iterations and more informed decision-making.

3.2. AI in Product Development at Michelin

Michelin [18] uses AI, especially ML, to improve its product development process. Using large data sets and AI algorithms, Michelin can analyze and extract valuable information from a variety of sources, including customer feedback, field tests, and sensor data. This enables it to identify patterns, predict tire behavior, and make data-driven decisions at the research and development stage. AI-based product development helps Michelin optimize tire performance, durability, and safety, resulting in better products for consumers.

3.3. Material Selection and Formulation Optimization

Rubber composition plays a key role in tire performance. AI is transforming the material selection process, enabling tire manufacturers to explore a wide range of possibilities and optimize rubber formulations. Researchers at Lund University [19] have used AI techniques to analyze the interactions between rubber and bearing surfaces. By understanding these interactions at a microscopic level, tire manufacturers can develop rubber compounds with better grip, wear resistance, and rolling resistance, increasing the overall performance of tires.

3.4. Intelligent Tire Design

AI is also revolutionizing tire design processes. Continental tires [20] use AI algorithms to develop innovative tire tread designs that optimize performance characteristics such as grip, noise reduction, and aquaplaning resistance. By simulating and analyzing the tire's interaction with the road, AI-based design methods enable tire manufacturers to create cutting-edge tire designs that deliver improved safety and performance in a variety of road conditions.

Integrating AI into research and development processes enables tire manufacturers to accelerate innovation, optimize designs, and develop superior products. By using AI-based simulations, analyzing huge datasets, and optimizing material selection and design, tire companies can deliver high-performance tires that meet the evolving needs of consumers.

Pirelli's Digital Solutions Centre (DSC) in Bari, Italy, is a joint effort between the public and private sectors (Pirelli R&D with 13 research centers employing more than 2000 people worldwide) and the academic world (including the University of Bari and Bari Polytechnic University) to develop software and algorithms dedicated to advanced planning processes. These include a big data platform for collecting, transforming, and analyzing data from different ecosystems of this multinational company in order to reduce product development times, improve product quality and machine performance, optimize commercial efficiency, and develop new digital services. The aforementioned research will be carried out on the tire's 'digital twin', enabling the design and development of new performance analyses on virtual prototypes [21].

Nexen Tire has developed an artificial intelligence-based tire performance prediction system using machine learning (ML) at the conceptual design stage to provide a faster and more accurate prediction of performance (handling, noise, fuel economy, etc.). During pre-processing of the collected data, it can detect and replace anomalies in the data, and finite element analysis (FEA) is used to predict tire performance with a 3D virtual tire to model tire shapes and material properties. The aforementioned capability effectively increases the number of prototypes and reduces development time [22].

Goodyear's ReCharge concept tire uses AI to monitor and learn from driver behavior. Throughout the life of the tire, it dispenses a synthetic material inspired by the carbon structure of spider silk, changing the composition of the tire and adapting it to the driver's driving behavior. This leads to a stronger surface and longer tire life. Goodyear has applied the digital twin concept to design, prototyping, and testing, resulting in a reduction in product development costs of at least 50% [23].

AI is playing a key role in improving Bridgestone's manufacturing efficiency by enabling intelligent maintenance of smart factory facilities. AI-based data analysis is used to predict potential machine faults and optimize maintenance cycles [24].

4. Real-Life Application: AI in Judgment of Tires during Use

In addition to transforming research and development processes, AI is having a significant impact on tire quality control inreal-world applications. Let's take a look at some notable examples of how ML algorithms are revolutionizing tire assessment in various scenarios.

4.1. RFID Technology and Tire Identification

RFID (Radio-Frequency Identification) technology plays a key role in tire identification and tracking. Michelin [25] uses RFID tags embedded in tires, allowing each tire to be easily and accurately identified throughout its lifetime. By integrating AI-based systems, tire manufacturers and service providers can effectively track tire wear, monitor tireperformance, and ensure proper maintenance and replacement. RFID technology combined with AI improves tire management, reducescosts, and increasessafety.

Continental [26] introduced ContiConnect 2.0, an artificial intelligence-based tire management solution. It uses intelligent sensors embedded in tires to collect real-time data on temperature, pressure, and other relevant parameters. AI algorithms analyze this data, enabling fleet operators to monitor tire conditions, detect anomalies, and proactively respond to maintenance needs. This AI-based tire management system improves safety, optimizes tire performance, and reduces downtime, ultimately increasing operational efficiency.

Michelin [27] has developed Michelin Track Connect, an innovative solution based on AI for motorsport enthusiasts. The system uses sensors installed on the tires to collect data on tire pressure, temperature, and lap times during track sessions. AI algorithms analyze this data to provide real-time feedback, helping drivers optimize tire performance and make informed decisions to improve their racing experience. Michelin Track Connect shows how AI can improve tire ratings in high-performance applications.

4.2. Automated Tire Inspection

Proovstation [28] offers an automated tire inspection system that uses AI algorithms to detect tire defects and anomalies in real time. The system uses advanced imaging techniques, including high-resolution cameras and machine vision technology, to capture detailed images of each tire's surface. AI algorithms then analyze these images, enabling fast and accurate detection of defects such as cuts, bulges, or tread wear. Automated tire inspection systems increase the efficiency and reliability of tire quality control processes, reducing human error and ensuring consistent and accurate assessments.

By integrating AI into tire assessments during actual use, manufacturers and users can monitor tire condition, increase performance, and improve safety. These AI-based solutions provide practical information, facilitate predictive maintenance, and enable timely interventions to reduce the potential risk of tire wear or damage.

5. Benefits of AI in Tire Quality Control

Integrating AI into tire quality control processes brings several significant benefits to the industry. Using advanced technologies and ML algorithms, tire manufacturers are improving product reliability, safety, and customer satisfaction (Figure 2).

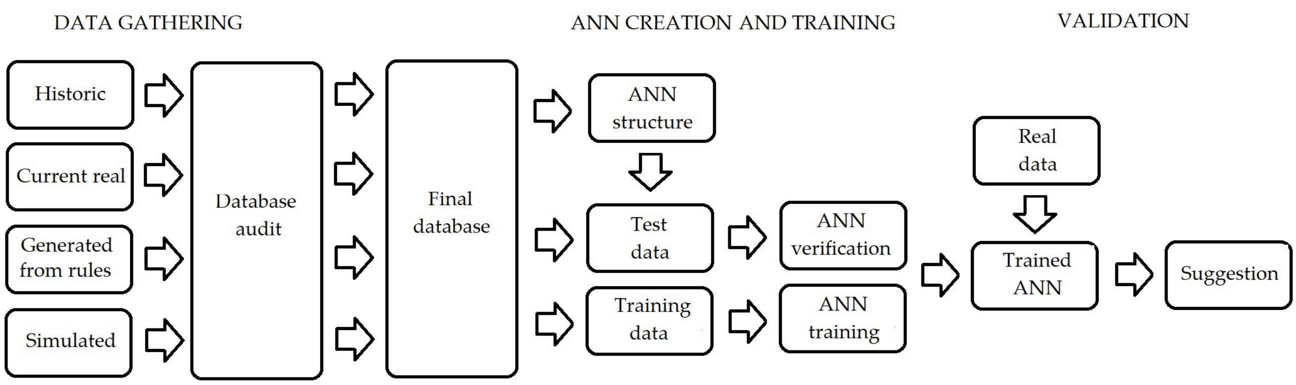

Figure 2. AI system for tire manufacturing purposes (own figure based on [1,6,9–13]).

5.1. Enhanced Accuracy and Efficiency

The implementation of AI-based quality control systems improves the accuracy and efficiency of tire inspections. TireReview [29] highlights how AI technologies enable tire manufacturers to analyze vast amounts of data and identify even the smallest defects or anomalies that may be overlooked by human inspectors. By automating inspections and using AI algorithms, tire quality control processes become more consistent, reliable, and efficient.

5.2. Early Detection of Defects

AI algorithms are able to detect potential defects at an early stage, both during production and throughout the life cycle of a tire. Such early detection helps manufacturers solve problems quickly, minimizing the risk of defective products reaching consumers. RubberNews [30] highlights that AI-based systems enable tire manufacturers to proactively identify defects such as tread separation, sidewall irregularities, or uneven wear, reducing the likelihood of tire failure and increasing overall safety.

5.3. Predictive Maintenance

AI technologies enable predictive maintenance strategies in tire management. By continuously monitoring tire parameters such as pressure, temperature, and wear, AI algorithms can predict when maintenance or replacement is required. This proactive approach helps optimize tire life, prevent unexpected failures, and reduce downtime, ultimately improving operational efficiency and reducing costs [30].

5.4. Data-Driven Insights

The implementation of AI in tire quality control generates huge amounts of data that can be analyzed to provide valuable insights. By analyzing this data, tire manufacturers can gain a deeper understanding of tire performance, usage patterns, and customer behavior. This information facilitates product improvements, targeted R&D activities, and the development of customized solutions that meet specific customer needs [30].

5.5. Continuous Improvement and Innovation

Quality control processes based on AI enable continuous improvement and innovation in the tire industry. The ability to collect and analyze data in real time allows tire manufacturers to identify performance trends, customer preferences, and emerging market requirements. With these insights, manufacturers can develop innovative tire designs, optimize materials and formulations, and create products that meet evolving customer expectations.

The integration of AI in tire quality control brings numerous benefits, including increased accuracy, early defect detection, predictive maintenance, data-driven insights, and the opportunity for continuous improvement and innovation. These benefits contribute to the production of high-quality, reliable tires that keep you safe on the road and increase customer satisfaction (Figures 3 and 4) [30].

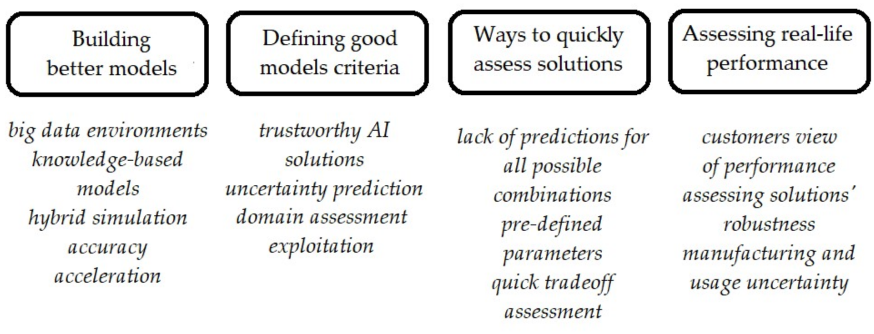

Figure 3. AI-based product development and IT processes in tire industry (own figure based on [18,19]).

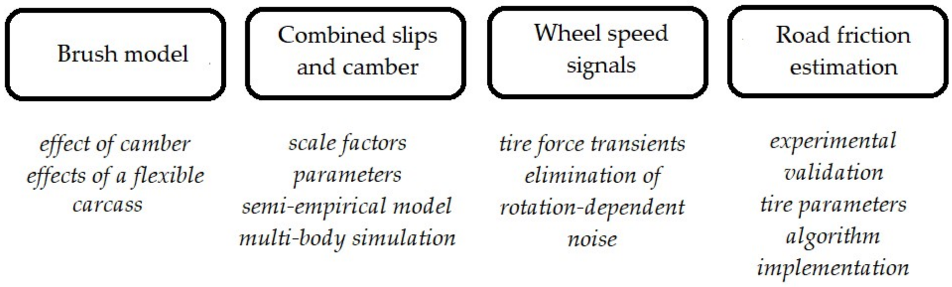

Figure 4. Elements ofAI-based tire assessment during development (own figure based on [18,19]).

6. Challenges and Future Outlook for AI in Tire Quality Control

The implementation of AI in tire quality control processes has shown great potential to improve reliability, safety, and efficiency. However, several challenges need to be addressed, and the future of AI in the tire industry presents exciting opportunities for development. Let's take a look at the challenges and future prospects of AI in tire quality control.

6.1. Challenges in AI Implementation

The implementation of AI in tire quality control presents some challenges. One of the main challenges is data availability and quality. Accurate and comprehensive data sets are crucial for the successful training of AI algorithms. Ensuring data quality, availability, and compatibility between different systems and manufacturers is critical to the success of AI implementation. In addition, overcoming resistance to change and integrating AI technology into existing manufacturing processes can be a major challenge.

6.2. Complexity and Interpretability

AI algorithms, particularly deep learning models, can be very complex and difficult to interpret. The decision-making process of the models may not always be transparent, making it difficult to understand the factors influencing the assessment of tire quality. Ensuring that AI models can be interpreted and explained is key to building confidence in the technology and addressing concerns about bias or incorrect assessments.

6.3. Continual Learning and Adaptation

Tire quality control processes require constant learning and adaptation to keep pace with changing tire designs, materials, and performance requirements. AI algorithms need to be regularly updated and trained on new data to provide accurate and up-to-date tire quality assessments. Implementing systems that facilitate continuous learning and adaptation is critical to long-term success.

6.4. Ethical Considerations and Safety

As AI continues to evolve in the tire industry, ethical and security issues must remain paramount. Ensuring data privacy and security, addressing issues of bias and fairness, and maintaining transparency in AI decision-making are essential to building trust among consumers and regulators. In addition, establishing industry standards and regulations for the implementation of AI in tire quality control will help maintain safety and reliability standards.

The future of AI in tire quality control is extremely promising. Advances in data collection and processing, the interpretability of AI models, and continuous learning mechanisms will address current challenges and drive further improvements. By embracing new technologies and prioritizing ethical considerations, the tire industry can unlock the full potential of AI and deliver safer, more reliable, and more sustainable tires to meet changing consumer needs.

In summary, AI offers exciting opportunities for the tire industry, and overcoming the challenges of data, complexity, continuous learning, and ethics will pave the way to a future where AI-based tire quality control becomes the norm [31,32].

7. Discussion

Our study has proven that automatic tire defect detection is difficult but possible. Like other industries, the tire industry is gearing up for a future in which artificial intelligence will play a key role in delivering quality tires to consumers around the world. This is based on both past research and expectations of new technology development in the tire industry.

The AI methods described in the paper can help in the development of AI-based semi-automated tire quality control and reduce the labor costs associated with technical inspection and defect removal at the earliest possible stages of production, in line with the Industry 4.0 paradigm. Research using DL to detect errors, product defects, and diseases in in-depth images is used in various fields such as manufacturing, industry, and medicine [33–37].

The integration of AI into tire quality control processes has brought significant advances to the tire industry. In this article, we have analyzed the current state of quality control in the tire industry, the use of AI in research and development processes, and real-world applications of ML in tire assessment. We also discussed the benefits, challenges, and future prospects of AI in tire quality control.

In conclusion, the integration of AI in tire quality control processes has revolutionized the tire industry. Using AI technologies, tire manufacturers have improved inspection accuracy and efficiency, improved tire design and performance, and optimized maintenance strategies. The benefits of using AI in tire quality control include improved reliability, early fault detection, predictive maintenance, and data-driven decision-making.

However, challenges remain, including data quality, the interpretability of AI models, and ethical issues. Addressing these challenges will be critical to the successful implementation and widespread adoption of AI in the tire industry. Furthermore, the future of AI in tire quality control is extremely promising, thanks to advances in sustainable manufacturing, advanced materials, and sensor technologies.

As tire manufacturers embrace AI and continue to innovate, the tire industry will have safer, more reliable, and more sustainable tires. By prioritizing data integrity, interpretability, and ethical considerations, tire manufacturers can build trust with consumers and regulators by ensuring that AI-based tire quality control processes meet the highest safety and quality standards.

7.1. Limitations of the Review

A limitation of the current research is that it is difficult to check the composition of the tire on the surface. In addition, the properties of a tire depend on many factors, including its concept, and require separate models for each tire type and size. An additional issue is the modeling of tire wear and changing its characteristics when the weather or car load changes and the type of road surface changes. Potential tire repair may also result in changes in its interaction with the suspension and road surface.

All of the above factors combine to make the technical inspection of both new and used tires a major computational challenge, both at the model formulation stage as well as its fine-tuning, practical application, and analysis of the results. Different computational models can be difficult to compare, although tire defect detection should be standardized.

7.2. Directions for Further Studies

The future of the tire industry awaits significant advances through the integration of AI and other new technologies. Sustainable and circular tire manufacturing processes, as highlighted in ToptireReview [31], will become increasingly important to minimize environmental impact. The use of advanced materials, such as nanomaterials and graphene, will increase the performance and durability of tires [32]. In addition, the use of sensor technology, Internet of Things (IoT) connectivity, and advanced analytics will enable real-time monitoring of tire conditions, usage patterns, and predictive maintenance. These technological advances will further streamline tire quality control processes and improve overall performance and safety.

The main research directions in the area of AI-assisted tire defect detection relate primarily to:

- Adaptation of defect detection processes for different types of tires (summer, winter, all-season, studded, etc.) [38];
- Simple "early warning" solutions built into the tire or rim, such as changing the color of the tire or its parts depending on the degree of wear, pressure changes, etc. [38];
- Predictive maintenance related to the natural wear of tires (including mileage in thousands of kilometers), aging, and the impact of climatic factors and agents spilled/poured on roads, revealing defects [39];
- Integration of technical control processes at various stages of production under the Industry 4.0 paradigm [40];
- Monitoring the tire life cycle, including its suitability for safe use, based on observations (analysis of video images of the tire at rest and during operation) and data from sensors mounted in the rims [41];
- Construction of larger quality control systems, e.g., for autonomous cars or self-charging road lanes for electric cars [41];
- Future-proof alternatives, e.g., tires with variable tread or pre-programmed properties that change over time [37,42–44].

Sustainable development is also important, as is the search for economical production technologies (lower energy consumption, less waste, recycling), slower-wearing tires, and quieter tires with widths and treads better adapted to the properties of new surfaces and drives (e.g., lower rolling resistance and fasterelectric cars) [45–47]. The reduction in CO_2 emissions can also be linked to the less frequent use of the tire retreading process. This requires an automatic or semi-automatic assessment of the technical condition of the tire casing, whether used on motor vehicles or slow-moving machines, in order to objectively determine the suitability of the casing for the retreading process. A separate issue is the monitoring of the life cycle of tires, not only within the production process but from the material and its quality and origin (e.g., recycled), through the entire production process, analysis in use, obsolescence, and re-cycling. Creating such a closed loop requires the development of effective methods for labeling and unambiguous identification of materials and intermediates (including, for example, electronic sensors) used in tire production.

Even as a game changer, AI solutions don't have to make big changes to processes straight away—to start with, it's enough to start with more efficient, faster analysis of the datasets that companies already hold. This will not only allow for more efficient management of resources and processes, but also catch errors or mechanisms previously difficult to catch with traditional methods. The next stages of AI implementation typically involve better sensing of production lines and warehouses (both material and finished goods warehouses) and exploiting the capabilities of the secure Industrial Internet of Things (IIoT). Leveraging AI or IIoT does not always mean moving to cloud resources, although in some cases this would be easier and cheaper with faster integration of Enterpise Resource Planning (ERP) systems or enterprise-class cyber security and data analytics processes within Infrastructure as a Service (IaaS), Platform as a Service (PaaS), or Software as a Service (SaaS).

In terms of AI solutions, the key is to use solutions that are as simple as possible, usually based on data (ML): traditional neural networks and DL. Building larger AI systems is one of the next steps.

8. Conclusions

Automatic detection of tire defects remains an important and challenging scientific and technical problem as part of industrial tire quality control. The integration of AI in tire quality control has the potential to transform the tire industry, leading to safer, more reliable, and more sustainable tires. With continued progress and a proactive approach to challenges, the tire industry is poised for a future in which AI plays a key role in delivering quality tires to consumers around the world.

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