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Improving the efficiency of the plastic waste processing process using industry 4.0 solutions

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Abstract:

The article focuses on the role of artificial intelligence (AI) in Industry 4.0, with particular emphasis on its application in the plastic waste processing process. In the face of growing challenges related to waste management and environmental protection, digital technologies play a key role in optimizing recycling processes, increasing efficiency and minimizing raw material losses. The article discusses in detail the use of AI in waste sorting automation, where intelligent algorithms using vision systems and spectral sensors allow for precise identification and segregation of different types of plastic. Solutions based on digital twins are also presented, which allow for simulation and optimization of production processes in a virtual environment. The author cites examples of AI implementations in recycling plants, such as AMP Robotics, Recycleye and ZenRobotics, which increased the efficiency of segregation and recovery of secondary raw materials by up to 30-40%. At the same time, the article analyzes the challenges related to the implementation of AI in the industrial sector. Key threats include the risk of cyberattacks, the growing dependence on autonomous systems, and potential social consequences, such as job losses in traditional industrial sectors. The author emphasizes the need to implement appropriate legal regulations, security policies, and educational programs that will allow for the sustainable use of artificial intelligence. In summary, the article presents AI as a key element of the transformation of industry 4.0, which can contribute to significant improvements in plastic waste processing. However, full use of the potential of this technology requires a strategic approach that takes into account both technological, social, and environmental aspects.

Keywords: industry 4.0, waste, plastics, artificial intelligence

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1. Introduction

In the era of the fourth industrial revolution, characterized by the extensive digitalization of production processes, artificial intelligence (AI) has become a key element driving innovation and efficiency. This article aims to explore the dual role of AI in the context of Industry 4.0, focusing both on supporting decision-making processes and automating tasks and on being a catalyst for innovation and business transformation.

AI enables the analysis of huge amounts of data in real time, enabling precise decisions and automating repetitive processes. For example, in predictive maintenance systems, AI algorithms analyze data from machine sensors, predicting failures before they occur, which reduces downtime and repair costs. An example is the use of AI by Siemens in analyzing machine vibrations in factories [1].

AI is driving the development of new business models and technologies. An example is the creation of digital twins, which use data collected by AI to simulate production processes in a virtual environment. This allows companies to optimize their operations and test changes before implementing them in reality. GE Digital uses this technology to simulate and optimize the operation of industrial turbines [2].

AI in industry, as a catalyst for automation and intelligent processes, contributes to increased productivity, optimized supply chain management and product innovation. It transforms traditional factories into intelligent production environments that can independently diagnose problems and adapt to changing conditions in real time. However, for all its advantages, AI carries cybersecurity risks when applied in the case of remote access, using cloud solutions. When AI is used in a closed system, cybersecurity risks can be eliminated. AI also poses a risk related to the ethics of using algorithms and the potential impact on the labor market, which can lead to increased unemployment and social inequality [3].

Analyzing the impact of artificial intelligence (AI) on industry is important for several reasons. First, AI has the potential to radically transform manufacturing processes by automating complex tasks, which can lead to significant increases in efficiency and reduced operating costs. The introduction of AI also enables the creation of smarter manufacturing systems that can predict errors and failures before they occur, minimizing downtime and increasing the overall reliability of operations.

In addition, the development of AI in industry stimulates innovation by enabling mass personalization of products, which would be unattainable with traditional production methods. On the other hand, the increased dependence on automated systems raises questions about data security, privacy and the impact on the labor market, which require thoughtful regulations and management strategies. The ethical and social aspects of the impact of AI cannot be ignored either, such as the potential increase in social inequalities resulting from the automation of work. Therefore, it is extremely important to study and understand these aspects in order to shape the future of industry in a sustainable and responsible way.

This article attempts to analyze aspects of the "AI in Industry 4.0" issue, using the latest research and case studies to provide readers with a balanced view of the potential and challenges associated with implementing AI in industry. Considering both the technological and socio-economic implications of AI, the intention is to present a holistic view of how artificial intelligence (AI) is shaping the future of industrial manufacturing. The AI market in manufacturing is expected to reach $10.51 billion by 2033, with a compound annual growth rate (CAGR) of 42%. Implementing AI in manufacturing processes can bring benefits such as increased operational efficiency, improved product quality, and reduced costs. However, to maximize these benefits and minimize risks, careful planning, ensuring high-quality data, and integrating AI with existing manufacturing systems are necessary [4].

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2. The role of Artificial Intelligence in Industry 4.0

Industry 4.0, also known as the fourth industrial revolution, is characterized by the integration of digital technologies with conventional industrial processes. This revolution marks the transition from traditional production methods to production management systems based on data that is collected and processed by advanced information technologies such as artificial intelligence (AI), the Internet of Things (IoT) and big data analytics.

Artificial intelligence is one of the most important drivers of innovation and automation within Industry 4.0. Thanks to its ability to learn and adapt, AI enables the creation of intelligent systems that can not only perform tasks with greater precision, but also independently identify areas requiring optimization. An example of the use of AI in assembly line automation is the project implemented by BMW at the Dingolfing plant, where AI systems were used to monitor and optimize assembly processes in real time. Algorithms analyze data from sensors located along the production line, enabling dynamic adjustment of operations such as the torque of bolts or quality control of assembled components. As a result, the percentage of defective products was reduced by 25% and downtime was shortened by 15% [5].

A key aspect of using AI in Industry 4.0 is its ability to process and analyze data from a variety of sources to optimize production processes. AI uses data from IoT sensors, production history, end-product quality, and more to provide deep insights into production efficiency. For example, by applying machine learning techniques, companies can predict equipment failures before they actually occur, allowing maintenance to be scheduled at the least intrusive time and minimizing downtime.

AI is also fundamental to the development of autonomous industrial systems that significantly increase efficiency and reduce operating costs. These systems, managed by AI algorithms, are able to make decisions on their own based on the current analysis of operational data. Examples include autonomous industrial robots that can navigate autonomously through company spaces, performing transport or logistics tasks without human intervention [6].

The introduction of AI in Industry 4.0 transforms the traditional approach to manufacturing, making it more flexible, efficient, and innovative. However, implementing these technologies also requires appropriate management strategies, ensuring data security, and considering the ethical aspects of automation. Like any technology, AI offers a wide range of possibilities, but it also comes with new challenges that must be carefully managed in order to realize its full potential [7].

3. The impact of AI on Industry 4.0

The implementation of artificial intelligence (AI) in industry is transforming traditional manufacturing processes by introducing automation that minimizes the need for human intervention. AI enables machines and production systems to perform tasks with higher precision and efficiency, leading to reduced errors and increased efficiency. For example, AI-controlled robots can accurately and quickly assemble complex components that previously required time-consuming human supervision. This allows companies to achieve better production results with lower operating costs.

One of the key aspects of AI's impact on Industry 4.0 is its use in predictive maintenance. AI systems are capable of analyzing sensor data in real time, which makes it possible to predict failures before they actually occur. This allows you to schedule maintenance at the most optimal time without disrupting normal production operations. This effectively reduces downtime and associated costs, while increasing the service life of the machines [8].

The implementation of AI also opens up opportunities for mass personalization of products while maintaining the efficiency and scalability of mass production. AI algorithms can quickly process

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individual customer preferences and adjust products on the fly, without the need for production line downtime. For example, in the apparel industry, AI can analyze real-time data on fashion trends and customer preferences, enabling the production of clothing that better responds to changing consumer tastes.

The use of artificial intelligence (AI) in industry opens up a wide spectrum of opportunities that affect innovation, efficiency and competitive advantages of enterprises. Additional practices that illustrate the diversity of AI applications in industry are:

Quality Control: AI-based vision systems can accurately and quickly inspect products on assembly lines, detecting defects that might escape the human eye. This significantly improves the quality of the final products.

Intelligent supply chain management: AI can predict changes in the demand and availability of raw materials, allowing for automatic adjustment of orders and inventory, minimizing the risk of product shortages or overstocks.

Collaborative robotics: Cobots are robots designed to work directly with humans in the workspace. AI helps them interpret and adapt to human actions, which increases safety and efficiency [9].

Energy and resource management: AI can analyze energy consumption patterns and automatically adjust machine and operation settings to maximize energy efficiency and minimize waste.

These practices demonstrate how AI can transform traditional industries, making them more innovative, efficient, and future-proof.

Artificial intelligence is bringing revolutionary changes to the industry, making processes more efficient, cost-optimal and tailored to market needs. Through automation, predictive maintenance, and personalization, AI not only increases productivity, but also allows for more sustainable asset management, which is crucial in the face of growing ecological and economic challenges. With AI, Industry 4.0 is becoming more flexible, resilient and competitive in the global market. An example of the use of AI is AI algorithms that, supported by vision systems, can identify different types of plastics, such as PET, HDPE or PP, based on their visual and chemical characteristics. In addition, these technologies detect contaminants such as food scraps, which increases the efficiency of recycling processes. An example is Tomra's use of AI in advanced optical systems [10, 11].

4. Opportunities thanks to AI in industry

Artificial intelligence (AI) is revolutionizing industry by enabling the creation of new products and services that are more tailored to customer needs and expectations. With AI's ability to analyze big data, companies can now identify unmet market needs and respond quickly by creating innovative solutions. For example, in the automotive sector, AI enables the creation of more individualized car configuration options that suit specific consumer preferences.

AI significantly increases operational efficiency by automating complex manufacturing processes. AI-guided robots can work with greater precision and efficiency, reducing the time it takes to complete a task and the risk of errors. An example is intelligent systems in factories that analyze sensor data in real time to optimize machine parameters, resulting in a significant increase in production efficiency.

In supply chain management, AI plays a key role, enabling more efficient planning and resource management. Predictive algorithms can predict demand for products, optimizing inventory levels and minimizing costs associated with overstocking or out-of-deliveries. In addition, AI can improve

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logistics by automating and optimizing delivery routes, resulting in faster and more cost-effective product delivery.

One of the most important aspects where AI benefits industry is data management. AI technologies such as machine learning are capable of processing and analyzing vast amounts of information much faster than human resources. This allows for deeper analytical insights that can be used to further improve production processes, product quality, and to personalize offers.

According to data published by the European Environment Agency (EEA), the implementation of fully automated lines for the segregation and cleaning of plastic waste (based on AI and IoT sensor systems, m.in) allowed to increase the recovery rate by up to 60% in selected pilot installations [11]. Over the next 5 years, this is expected to contribute to a further increase in plastics recovery by an additional 10-12 percentage points. As a result, less waste ends up in landfills, which translates directly into a smaller environmental footprint [12].

AI is becoming an invaluable tool in Industry 4.0, offering a range of opportunities for innovation, increased efficiency, optimization of operations, and effective data management. Thanks to these advantages, companies are able not only to improve their operational processes, but also to better adapt their products and services to the needs of the market, which in turn leads to increased competitiveness in the global market [13].

5. Risks of AI in industry

The use of artificial intelligence (AI) in industry carries an increased risk of cyberattacks, which can lead to major production disruptions and the loss of sensitive data. Cybercriminals can target AI systems to gain access to industrial networks, manipulate data, or even take control of automated processes. To prevent such threats, it is crucial to implement advanced security solutions, such as encrypted connections, incident detection and response (SIEM) systems, and regular updates to security software and protocols [14].

The introduction of AI into industry can lead to the replacement of workers in many traditional roles, which generates fears of job losses. However, automation with AI can also open up new job opportunities that require new skills. Therefore, it is crucial to invest in retraining and education programs for employees so that they can use new technologies and adapt to the changing labor market.

The growth of the AI-based industry is associated with an increasing dependence on these systems. Software or hardware failure can lead to a complete production stoppage, highlighting the need for redundancy and contingency planning. Companies need to develop strategies to minimize the risk of failures, including ensuring that they can quickly switch to manual operations if needed.

The implementation of AI comes with serious ethical dilemmas, including privacy issues, bias in algorithms, and accountability for decisions made by machines. It is important to ensure that AI systems are designed and implemented in a transparent manner, taking into account ethical aspects. Companies should also implement control and audit mechanisms that will allow for the evaluation and correction of the performance of algorithms, preventing discrimination and unfair practices.

However, it is important to remember that the implementation of AI-based solutions also comes with challenges. Cybersecurity issues, ethical aspects of automation, and the impact on the labor market require detailed analysis and implementation of appropriate risk management strategies. Therefore, in order to fully exploit the potential of Industry 4.0, it is necessary to combine modern technologies with comprehensive security systems and constant monitoring of processes [15].

While AI offers significant benefits to industry, such as increased efficiency and innovation, it is essential to address the risks associated with it at the same time. Appropriate risk management

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strategies, investments in digital security, employee education programs, and an informed approach to ethical issues are key to the sustainable implementation of AI in industry.

6. The use of AI in industry

The rise of artificial intelligence (AI) is bringing disruptive changes to various industry sectors, enabling companies to achieve higher efficiency, better product quality, and increased innovation. The following are some examples of specific AI applications that illustrate its impact on the industry:

1. Predictive Maintenance – General Electric uses AI algorithms to monitor data from wind turbines, which enables early recognition of potential failures and maintenance planning, thereby minimizing production downtime [16].
2. Optimization of production processes - Siemens uses AI in its electronics factories, where algorithms analyze and automatically adjust machine parameters, which translates into improved efficiency and quality of production.
3. Quality Management - Samsung uses advanced AI vision systems on its TV production lines that efficiently detect defects, ensuring a higher quality standard for products.
4. Intelligent Supply Chain Management – Amazon implements AI to optimize the management of its global supply chain by predicting demand and adjusting inventory placement accordingly, which minimizes delivery times and reduces costs [17].
5. Collaborative robotics (Cobots) - Universal Robots manufactures cobots that collaborate with humans in factories, such as assembling automotive parts, responding and adapting to the actions of human workers in real time.
6. Large-scale product personalization - Nike uses AI to personalize athletic footwear offered over the internet by analyzing user preferences and trends, allowing it to create bespoke products [18].
7. Energy and Resource Management – Tata Steel in Europe has implemented AI systems that optimize energy consumption in production processes by analyzing and adjusting operational parameters in real-time [19].

Each of these examples shows how AI can effectively improve not only efficiency and quality in traditional industries, but also how it contributes to innovation by creating new opportunities for the personalization of products and services. These applications demonstrate the key roles that AI can play in transforming industrial operations around the world.

7. Examples of production processes and case studies

The implementation of Industry 4.0 solutions in the area of plastics waste processing is an increasingly popular topic on a global scale. Companies and research institutions are conducting numerous pilots and commercial projects, using artificial intelligence (AI), robotics or advanced big data analytics to improve segregation and recycling processes. Selected case studies and specific production processes are presented below that show how Industry 4.0 technologies increase the efficiency of plastic waste recovery and treatment.

7.1. Automatic plastic sorting with AI – AMP Robotics

One of the pioneers in the field of plastic sorting automation is AMP Robotics, an American company developing robotic waste recognition and separation systems based on machine learning algorithms.

Plastic waste is placed on a sorting conveyor belt, where high-resolution cameras and spectral sensors are mounted. The AI system (trained neural networks) recognizes the type of plastic (e.g. PET, HDPE, PP) based on the shape, color and surface characteristics in a fraction of a second. Robotic arms catch the right parts and redirect them to the right containers. Data on the composition of the waste is collected and used for continuous improvement of algorithms and reporting on the effectiveness of the process. This solution achieves up to twice the separation accuracy compared to classic optical methods. According to information published by AMP Robotics, their customers are seeing a 30-40% increase in sorting efficiency and a significant reduction in misclassification [20].

7.2. Robotic sorting of hard-to-recover plastics – STADLER

STADLER specialises in the design and construction of waste sorting plants for municipal companies. As part of one of the projects in Switzerland, a robotic line for the selection of plastics with non-standard shapes (e.g. large containers, crates) was integrated.

Using 3D scanners in combination with AI to identify objects with complex geometries. The SI system categorizes waste according to the type of plastic and the approximate weight. Robots with vacuum or jaw grippers transfer the appropriate components to dedicated tanks. As a result, fractions that were previously difficult to sort out efficiently are processed, and the recycling rate of these plastics has increased by up to 25% [21].

7.3. Real-time monitoring of the quality of PET granules – Nextek

Nextek is a UK-based consulting company that specialises in optimising plastics recycling processes.

One project implemented a spectral camera system and AI to monitor the quality of PET granules as early as the extrusion stage.

Process description:

The granules are fed from the extruder to a short belt, where a camera is mounted to detect possible discoloration or inhomogeneity.

The AI module calculates the degree of contamination or color deviations in real time.

If the established standards are exceeded, the system automatically corrects the production parameters (e.g. temperature, screw speed) and signals the need for additional cleaning of the load.

Thanks to this solution, the quality of the obtained regranulate is more uniform, which translates into higher value and the possibility of using it in more demanding products

7.4. Recycling plant digital twin – Circularise

Dutch startup Circularise, in collaboration with several European recycling plants, has created a project for digital twins of plastic processing plants.

The goal of the implementation is to map the main processes and material flow in a virtual environment, simulate changes in throughput, processing time and utility consumption depending on the modifications made (e.g. adding a new cleaning module), and optimize energy consumption and analyze potential bottlenecks in production.

Research presented by Circularise shows that this approach can reduce raw material waste by 10-12%, reduce repair downtime and implement organizational changes in the plant faster [22].

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7.5. Black Plastic Recognition & Separation System – Recycleye

Recycleye is a British company specializing in solutions based on machine learning and vision systems for automatic waste segregation. One of the more difficult challenges in the recycling industry is the detection and separation of black plastics, which are often invisible to traditional optical sensors due to their absorption of light.

The implemented technology consists of:

1. Infrared spectral scanning, supported by AI, can distinguish black plastics from other components.
2. Robots equipped with vacuum (or finger grippers) capture the detected material and redirect it to the appropriate recycling streams.
3. The collected data is collected in the cloud and used for continuous improvement of recognition algorithms.

According to information published by Recycleye, at one of the British plants, the implementation of an AI system for the separation of black plastics increased the level of recovery of this fraction by up to 20% in a few months [23].

7.6. Application of collaborative robotics for separation of multi-material waste – Machinex SamurAI

Machinex is a Canadian company that has developed a series of robotic sorting stations called SamurAI™. The solution combines collaborative robots (cobots) with real-time image analysis and machine learning algorithms.

The scheme of operation consists in a sorting line, HD cameras and sensors are installed to recognize various types of plastics, including multi-material packaging (e.g. laminates). SamurAI™ robots that can perform up to several dozen selective grips per minute, precisely distributing waste. The self-learning system continuously improves the accuracy of recognizing unusual shapes or contaminated elements (e.g. foil with food residues).

According to a case study presented by Machinex at the RWM (Recycling & Waste Management) conference in Birmingham (2021), sorting efficiency there increased by 25% and the percentage of waste misclassification decreased by almost 30% [24].

7.7. Robots that Selectively Collect Waste from Conveyor Belts – ZenRobotics

ZenRobotics is a Finnish company known for the development of intelligent robots for the waste management industry. Although it originally specialized in construction waste, it is now successfully introducing solutions to plastics sorting plants.

Key features of the solution include the integration of cameras and vision sensors with deep learning algorithms, robots capable of differentiating the shapes of PET bottles, LDPE films and other plastics on a single belt, and automatic adjustment of the speed and direction of arm movement to the density and speed of waste flow.

In practice, the use of ZenRobotics to sort plastic films and bottles has allowed one recycling plant in Spain to increase yields by 15-20% while reducing human labor costs in the most monotonous and physically demanding areas [25].

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Conclusions from case studies:

- Increased efficiency: In each of these cases, the use of AI, robotics or digital twins leads to increased efficiency of waste treatment processes and higher quality of the raw material obtained.
- Cost reduction: Automation and data analytics reduce downtime, material waste, and energy input.
- Improving the quality of the final product: Uniform granulate, better sorted secondary raw material or ongoing defect control are key to achieving marketable plastics.
- Flexibility and scalability: Industry 4.0 technologies facilitate the rapid adaptation of the plant to the changing waste stream and the increasing quality requirements of customers.
- Added value: These projects often strengthen the company's image as an innovative and environmentally friendly entity, which can be a competitive advantage.

The presented case studies confirm that the key success factors are the skillful use of data (IoT sensors, vision systems), the implementation of AI algorithms in real time, and a gradual, well-planned transition to automated digitally managed processes. This makes the plastic waste processing industry more efficient, flexible and environmentally sustainable, in line with the global trend of finding innovative ways to manage the growing amount of plastic waste.

8. Vision of the future and an integrated approach

With the Fourth Industrial Revolution in mind, the importance of artificial intelligence (AI) in industry is becoming increasingly clear. Today's use of AI not only results in increased efficiency, innovation, and product personalization, but also raises questions about digital security, changes in the labor market, dependence on technology, and ethical issues. From General Electric to Nike, AI can be a key enabler of transforming traditional manufacturing processes and opening the door to a new era of smart industrial systems.

However, the use of AI brings both promising opportunities and significant challenges. The need to balance technological potential with its social and ethical implications requires thoughtful strategies that support sustainable development and innovation, while minimizing risks to security, privacy, and social justice. This requires not only continuous dialogue between all stakeholders, including engineers, entrepreneurs, workers, legislators and society, but also dynamic adaptation of laws and policies in response to evolving technologies [26].

An integrated approach that includes both technological development and social engagement will be key to realizing the full potential of AI in Industry 4.0. This is necessary not only to achieve economic success, but also to ensure that this progress goes hand in hand with ethics and responsibility. Ultimately, the future of Industry 4.0 will only be as bright as our ability to manage the complex tools we create in a way that promotes the well-being of all.

A doctoral dissertation from Bialystok University of Technology from 2021 analyzes the level of readiness of companies in the machinery industry to implement Industry 4.0 tools. The research showed that only 10% of the surveyed companies have sufficient knowledge about Industry 4.0 and its tools, which indicates the need to intensify education and training activities in this area. In addition, these companies have noticed the benefits of implementing modern technologies, such as increased efficiency of production processes and better resource management [27].

The presented analysis clearly shows that artificial intelligence is no longer just a tool of the future – it is a technology that is already shaping the industrial reality on a global scale. By taking a proactive and informed approach to integrating AI into industry, we can not only maximize its benefits, but also

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effectively manage the challenges it brings. It can be concluded that this path opens up broad prospects for future research, policy development and technological innovations that will shape the world in the coming decades.

The implementation of Industry 4.0 solutions in the plastic waste treatment sector brings a number of benefits, including increased sorting accuracy, reduction of operating costs, greater efficiency of raw material recovery and real energy savings. At the same time, automation and digitization of processes have a positive impact on work safety and the development of staff competences. These results show that investment in modern technologies can be a key factor in the development of competitive, sustainable and profitable business models in the plastics recycling industry.

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