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THESIS SUMMARY:

Contributions regarding the improvement of quality, efficiency, and effectiveness of series production workflows through the integration of collaborative robots in the automotive industry

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Content of the doctoral thesis

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The summary of the doctoral thesis includes only a short rendering of the most relevant information contained in the thesis. (The author)

Content of the doctoral thesis summary

FOREWORD

The thesis entitled „*Contributions to the Improvement of Quality, Efficiency, and Effectiveness in Series Manufacturing Flows through the Integration of Collaborative Robots in the Automotive Industry*" represents a study dedicated to the quality, efficiency, and effectiveness of series manufacturing processes, with collaborative robots as the main instrument. This topic is highly relevant, considering the increasing implementation of collaborative robots in manufacturing flows within the automotive industry. More and more robot manufacturers are developing innovative models of collaborative robots, providing new solutions that are becoming increasingly prevalent in the market and industrial settings. The adoption of collaborative robots within organizations in the automotive industry is becoming more prominent, driven by the substantial advantages they provide. All intellectual property rights of this doctoral thesis belong equally to both the doctoral supervisor and the doctoral candidate. This aspect is unanimously accepted by both the doctoral supervisor and the doctoral candidate.

The research and the entire scientific endeavour were marked by a productive and beneficial collaboration with the distinguished academic supervisor, Prof. Dr.. Eng. Aurel Mihail ȚÎȚU. I express my deep gratitude for guidance and support, for the precious time devoted, and for the generosity in sharing his extensive knowledge and experience in the field of scientific research. His contributions have had a significant impact on the quality and relevance of the research, serving as a source of inspiration and guidance in this academic and scientific journey.

I extend sincere appreciation to the esteemed professor: Prof. Dr. Eng. Nicolae Ionescu, Prof. Dr. Eng. Cristian Doicin, Prof. Emeritus Dr. Eng. Constantin Oprean, and Prof. Dr. Eng. Mihai Dragomir. I express profound gratitude for their patience, guidance, and experience provided during the conduct and elaboration of scientific research. I particularly appreciate their essential contribution, which played a crucial role in achieving success and developing my skills in the field of scientific research.

I am deeply grateful to my wife, Andra-Ioana, for the constant support provided at every stage of this scientific endeavour, including during travels and any moment dedicated to the completion of scientific research. I also express gratitude to my parents and in-laws for their support. Their trust in my ability to achieve this goal, both personally and professionally, served as a strong anchor in challenging moments of the research process. These external contributions were fundamental to the success of my research.

Eng. Vasile GUSAN

INTRODUCTION

The 21st century marked the debut of the first collaborative robot. Collaborative robots represent highly efficient and versatile equipment, capable of integration into various manufacturing flows by adjusting existing equipment. However, in the automotive industry, it has been observed that not all industrial organizations or technical solution integrators have always succeeded in achieving efficiency, effectiveness, and quality regarding the integration of collaborative robots.

In the context of this aspect, this scientific research aims to establish a standard for collaborative robot programming, with a focus on developing a programming structure and utilizing specialized software languages. The overarching objective of this endeavour is oriented toward ensuring significant improvements in the quality, efficiency, and effectiveness of the automotive industry through the advanced adoption and implementation of collaborative robots. In this perspective, the central objective of the scientific investigation is to highlight the „*personal contributions made to the automotive industry, focusing on the improvement of quality, efficiency, and effectiveness within serial production flows through the implementation of collaborative robots*".

The thesis structure is divided into two specific parts. In the first part, an analysis of the current state of knowledge in the field was conducted. In the opening of the second part, research directions, the main objective, and specific objectives are outlined, highlighting the applied research methodology. This section progresses by presenting detailed contributions and formulating definitive conclusions resulting from this scientific research.

In the first chapter, a detailed analysis of the current state of quality and quality assurance in the automotive industry was conducted. Contemporary trends in quality and associated concepts were explored, focusing on the essential role of quality in attracting customers and generating profit. The implementation of rigorous quality assurance systems in manufacturing processes was investigated, covering various concepts such as technical quality control, total quality philosophy, and zero-defect strategy. The analysis emphasized the benefits of integrating knowledge-based organizations and quality management, highlighting customer satisfaction and continuous process improvement. In this context, special attention was given to efficiency by applying process management and knowledge-based management, highlighting the positive impact of integrating collaborative robots into manufacturing processes. Thus, a strategic perspective focused on customer satisfaction and sustained investment in market research was outlined, recognized as essential elements for the success of organizations in the automotive industry.

Chapter 2 focuses on the manufacturing process in the automotive industry, with particular attention to the automation and interconnectivity of processes. The introduction of collaborative robots is a central element in this transformation, bringing significant benefits in terms of efficiency, product quality, and working conditions. The detailed analysis in this section reveals variable factors influencing the quality of applications with collaborative robots, emphasizing the importance of successful implementation to add value to the production process. Throughout this chapter, it was deemed necessary to identify susceptible parameters that can influence the quality of manufacturing processes.

Next, significant progress in the field of industrial and collaborative robots within the automotive industry was addressed in the context of research evolution. In the analysis in Chapter 3, progress was made by examining robotic solutions with different levels of autonomy, highlighting the benefits of industrial, mobile, and stationary robots. The diversity offered by suppliers of industrial and collaborative robots was also investigated, emphasizing the varied technical properties and functions crucial for improving efficiency and quality in the industrial environment.

In the detailed analysis presented in Chapter 4, the significant influence of the efficiency and effectiveness of manufacturing flows in the automotive industry was highlighted. Special attention was given to the use of collaborative robots, emphasizing their positive impact on economic aspects and productivity. The importance of these robots in reducing production costs, optimizing manufacturing flows, and improving the quality of finished products was emphasized, consolidating the benefits of this technology in the context of the automotive industry.

Based on the aspects addressed in the component chapters of the first part, Chapter 5 was designed to outline clear conclusions regarding the current state of knowledge in the studied field.

In the second part of the thesis, research directions, the main objective, specific objectives, applied research methodology, and original contributions resulting from theoretical research conducted in the first part are presented. This section begins by clearly outlining the research directions, the main objective, and specific objectives, as well as exposing the methods used, a subject addressed in Chapter 6. The argumentation for the necessity of collaborative robot automation was grounded in the acute labour force crisis faced by Romania, the imperative of continuous cost optimization, and the increased requirements to improve the efficiency and effectiveness of manufacturing flows.

Chapter 7 addresses the field of collaborative robot programming, starting by emphasizing the need for efficient standardization. By proposing a programmable structure and providing specific recommendations, this chapter stands out for its innovative approach in a context characterized by standardization gaps. Special attention is given to the importance of configuring basic settings and categories: "BeforeStart," "Robot Program," "SubProgram," and "Thread," elements with a direct impact on the efficiency of the programming process and overall functionality. In addressing human-robot collaboration, the chapter identifies opportunities and manages challenges associated with possible collisions, thus contributing to the development of a safer and more efficient practice in the robotic field. The well-defined structure and focus on standardization represent remarkable contributions to advancing collaborative robot programming.

Although collaborative robot programming is excellently executed, the risk to human safety may persist, especially when collaborative robots operate at high speeds or use hazardous devices. The spatial positioning of collaborative robots is also an essential issue that needs to be clearly defined. This approach led to the development of Chapter 8, with the main objective of highlighting optimal ways of spatially placing collaborative robots and developing an auxiliary safety system. Multiple solutions for suspending collaborative robots were proposed, detailing various methods for optimal spatial positioning within the manufacturing flow. In subsequent stages, various individual devices that can be integrated to form a safety system were presented, specifying how these can be incorporated. Additionally, the functioning principles and programming procedures of devices requiring such interventions were described.

In Chapter 9, multiple original contributions were made regarding the management of collaborative robot integration. A mathematical model for managing implementation costs was developed, and subsequently, a practical application was conducted to demonstrate the validity of this mathematical model. Special attention was given to qualitative validation and preventing potential defects through the implementation of the PFMEA methodology. Mathematical methods for calculating the efficiency and effectiveness of manufacturing flows with collaborative robots were also developed, and these were later applied to demonstrate the validity of the formulated statements.

For the analysis of improving organizational profitability, Chapter 10 was developed. Initially, a detailed process for establishing integration requirements was developed, followed by a comparative cost analysis for various modes of operation with operators, industrial robots, and collaborative robots. Technical and economic recommendations regarding the choice of collaborative robot type were considered opportune. Using the same developed mathematical model, an additional production flow between the operator working mode and the collaborative robot working mode was analyzed. Arguments were formulated to demonstrate how collaborative robots contribute to improving product quality. In this context, the implementation of the „Zero Manufacturing Changeover Times" concept was considered opportune, and the way it integrates with collaborative robots was presented.

Chapter 11 highlights the importance of synergy between the IDEF0 methodology and Lean Manufacturing strategies in the continuous Kaizen improvement process, focusing on collaborative robots in production flows within the automotive industry. Collaborative robots, integrated according to IDEF0, are confirmed as essential entities in final assembly, generating efficiency and significant cost savings. IDEF0 emphasizes the ability of robots to take over repetitive activities, freeing up human resources for tasks with cognitive value. Although IDEF0 considers human resources and collaborative robots as equivalent, the priority given to the cognitive capacity of human operators is highlighted. The IDEF0 model reveals the crucial role of collaborative robots in improving the efficiency and functionality of the production flow. The implementation of Jishuken, developed by Toyota, is the main tool for continuous improvement, eliminating the eight types of losses in production processes. Comparing production flows under Jishuken highlights the advantages of robots in managing deviations and improving quality. By proposing an innovative concept regarding the implementation of Deviation Management in the production sphere, an applicative methodology and a mathematical relationship for evaluating deviations are brought to the forefront. This concept integrates within Lean strategies, where Deviation Management identifies and remedies deviations, optimizing processes after implementing Jishuken and eliminating losses. In a production context with collaborative robots, a significant reduction in deviations is observed, consolidating the importance of the coherent integration of these strategies and methodologies in the evolution of modern industry.

In the final part, Chapter 12 demonstrates that by increasing the number of collaborative robots, the number of operators is significantly reduced. This aspect is partially true but not entirely, as human resources and collaborative robots are complementary. Additionally, various solutions have been formulated to manage the situation for operators leaving old repetitive jobs, including their relocation.

The mathematical models, programming types, recommendations, ideas, and systems developed and presented in the second part of the thesis represent original contributions, thus demonstrating the achievement of each objective proposed within the doctoral thesis.

PART I. CURRENT STATE OF KNOWLEDGE IN THE FIELD OF ENSURING THE QUALITY OF MANUFACTURING PROCESSES THROUGH THE INTEGRATION OF INDUSTRIAL AND COLLABORATIVE ROBOTS IN THE AUTOMOTIVE INDUSTRY

Chapter 1 CURRENT STATE OF KNOWLEDGE REGARDING QUALITY AND QUALITY ASSURANCE IN THE AUTOMOTIVE INDUSTRY

1.1 The concept of quality. Concepts associated with the concept of quality

QUALITY represents an exceptionally complex concept. Over time, this concept has been defined in various ways, such as:

- conformance to requirements (Crosby, 1979);
- compliance with customer needs (Deming, 1986);
- fitness for use (Juran, 1988);

- a set of characteristics of a material or immaterial entity that includes the ability to meet expressed needs (International Organization for Standardization, 1994);
- the degree to which a set of intrinsic characteristics belonging to an object meets requirements (Oprean, Vanu, & Stan, 2021);
- the totality of features of a product or service that have the capacity to meet specified customer needs (International Organization for Standardization, 2015).

Quality can also be described as the combination of traits that determine or facilitate customer satisfaction, present from product design through the manufacturing process to delivery. Ensuring and maintaining a level of quality is essential and must be considered throughout all stages of the production process.

Given the necessity for continuous assurance of the quality concept in the mass or series industrial environment, the implementation of quality control and quality engineering has become imperative as a means to guarantee quality. (Oprean & Țîțu, 2008)

In accordance with the aforementioned, quality can be defined as:

- the degree to which a set of intrinsic characteristics meets requirements; (ISO 9000:2015, 2024)
- conformity with the specification or the task sheet;
- full compliance with customer requirements;
- the ability to satisfy a need.

Certain keywords such as "need," "requirement," or "necessity" stand out in the definitions of the quality concept. Quality or its absence can only be defined when there is a clearly specified system to which the concept can be referenced. This system is characterized by the needs, requirements, or expressed needs of the market or the customer. The concept of quality would be extremely challenging to define in the absence of these keywords, as a product is considered qualitative, conforming, or compliant only when the expressed conditions have been satisfied. From a practical perspective, an object or entity can be considered to have quality to the extent that it satisfactorily meets the needs and expectations of the customer while simultaneously adhering to specific technical requirements.

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The product or service specification may encompass a variety of requirements that must be fulfilled by the supplier, including technical, aesthetic, economic, social, and usability features. These requirements are crucial to ensure that the final product or service meets the needs and expectations of the customer. By identifying and analyzing these requirements, the supplier can develop an action plan to achieve the ultimate goal, namely customer satisfaction.

The technical characteristics of a product or service can be quantified by defining technical-economic and technical-functional parameters that are essential to guarantee the fulfilment of customer requirements. These parameters may include performance limitations, material specifications, testing parameters, and quality standards, for example. By establishing these technical parameters, it can be ensured that the final product or service meets the needs and expectations of the customer and satisfies their specific requirements. (Oprean & Vanu, 2006)

Aesthetic features are aspects related to the design and visual appearance of a product or service. They may include shape, texture, colour, packaging, and other features that impact the presentation and perception of the product or service. These aesthetic features can significantly influence the attractiveness and acceptability of the product or service in the eyes of the customer or consumer and can contribute to increased sales and customer satisfaction. Therefore, aesthetic features play a crucial role in the design and development of products or services. (Oprean, Vanu, & Stan, 2021)

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Quality assurance is a complex and systematic process aimed at ensuring that products or services provided meet quality standards and specified requirements. One of the main objectives of quality assurance is to ensure that all activities carried out in the manufacturing or service delivery process are planned, implemented, and controlled in a manner that ensures the resulting products or services conform to customer requirements and expectations. This involves the development and implementation of a set of quality policies, procedures, and standards in accordance with recognized international norms and regulations.

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Chapter 2 CURRENT STATE OF KNOWLEDGE IN THE FIELD OF MANUFACTURING PROCESSES IN THE AUTOMOTIVE INDUSTRY THAT INTEGRATES COLLABORATIVE ROBOTS

2.1 Manufacturing process. Manufacturing process in the automotive industry. Manufacturing process in the automotive industry with collaborative robots

Any material entity existing in nature is the result of a process, whether natural or influenced and created by humans. Even if the process is of natural origin, humans have understood that by correctly manipulating parameters, they can replicate or recreate the same result.

Each process can be divided into distinct stages and operates based on specific parameters, such as time, temperature, and environment. One of the processes that can be mentioned among the multitude of others is manufacturing.

The process can be defined, according to (Oprean, Vanu, & Stan, 2021), as a series of correlated or interdependent activities that use inputs to produce a planned outcome.

The manufacturing process can be found under various definitions:

- The manufacturing process can be defined as the set of procedures used in transforming raw materials and semi-finished products into finished goods. (Explanatory Dictionary of the Romanian Language, 2023)
- In scientific terms, the manufacturing process can be defined as a set of planned actions executed by the workers of an organization, with the help of machines and equipment, on raw materials or components, aiming to transform them into finished products or services. (Frățilă, 2019)

In short, the manufacturing process is how raw materials or components are transformed into finished products or parts through the actions performed by the organization's employees and with the help of equipment or machines. This process can be divided into multiple stages, where the product undergoes various technological processes, quality controls, analyses or technical tests, and packaging or wrapping procedures.

Figure 2.1 depicts the manufacturing process diagram of a typical manufacturing process.

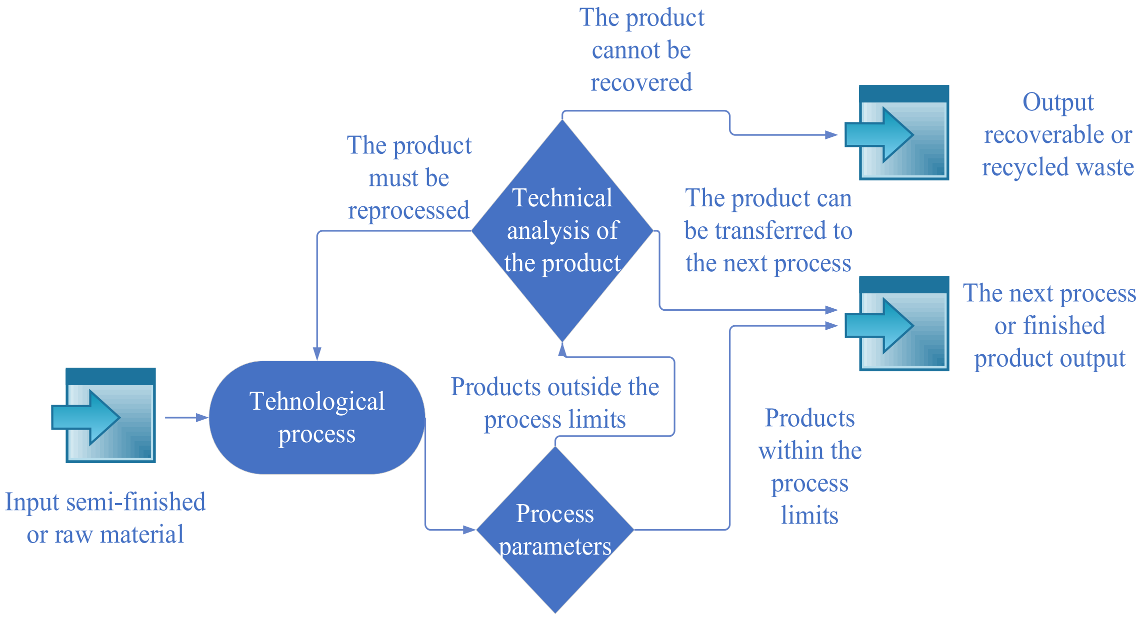

Fig. 2.1 Diagram of a manufacturing process

The technological process is influenced by a series of parameters that must be kept under control and constantly monitored to ensure the quality of the obtained end products.

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The technological process is a set of operations and procedures through which raw materials or semi-finished products are transformed into a finished product of quality. These modifications are critical to ensuring the quality of the final product, and process parameters must be controlled and monitored to ensure they stay within established limits. The changes to which the semi-finished product is subjected can impact:

- Material properties;
- Size;
- Shape (Frățilă, 2019).

In scientific terms, the manufacturing process can be defined as a sequence of complex, integrated, and optimized technological operations used to intervene in the properties, dimensions, and shape of materials to obtain finished products with specific qualities and characteristics. Technological processes are selected and combined rationally, considering production objectives and technical, economic, and environmental factors, to achieve optimal performance in terms of quality, efficiency, and durability of the obtained products.

The automotive industry, also known as the automotive sector, has the main goal of developing, innovating, improving, manufacturing, and distributing vehicles and their components (Omar, 2011).

The manufacturing process in the automotive industry is essential for producing vehicles and their components. The purpose of this process is to obtain finished products, which are then used in the construction or assembly of vehicles. In the automotive industry, various technological processes are used in manufacturing:

- Assembly of the finished product;
- Treatment of the finished product;
- Technological realization of the finished product.

The automotive industry is one of the most crucial sectors in global production, generating significant economic benefits for the world economy. (Nieuwenhuis & Wells, 2015)

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2.2 Collaborative robots integration process

Collaborative robots, known as cobots, are designed to interact directly with human operators. (Peshkin & Colgate, 1999) To achieve efficient and effective integration of collaborative robots, it is crucial to have sufficient resources and adequate documentation on important aspects. The integration itself is a relatively quick and straightforward process.

The integration of collaborative robots into the manufacturing process involves distinct processes that must be followed sequentially to ensure efficient and effective implementation:

- Feasibility study process for integrating collaborative robots;
- Acquisition process;
- Assembly and programming process;
- Validation process for the collaborative robot manufacturing process;
- Launch process into the mass production of the new flow with collaborative robots.

Integrating collaborative robots into a manufacturing process requires initiating a feasibility study process, in which all aspects relevant to their assembly and operation are determined. Among these aspects are the number of gripping devices, the need for scanners or safety barriers, and the communication method between robots and the surrounding environment.

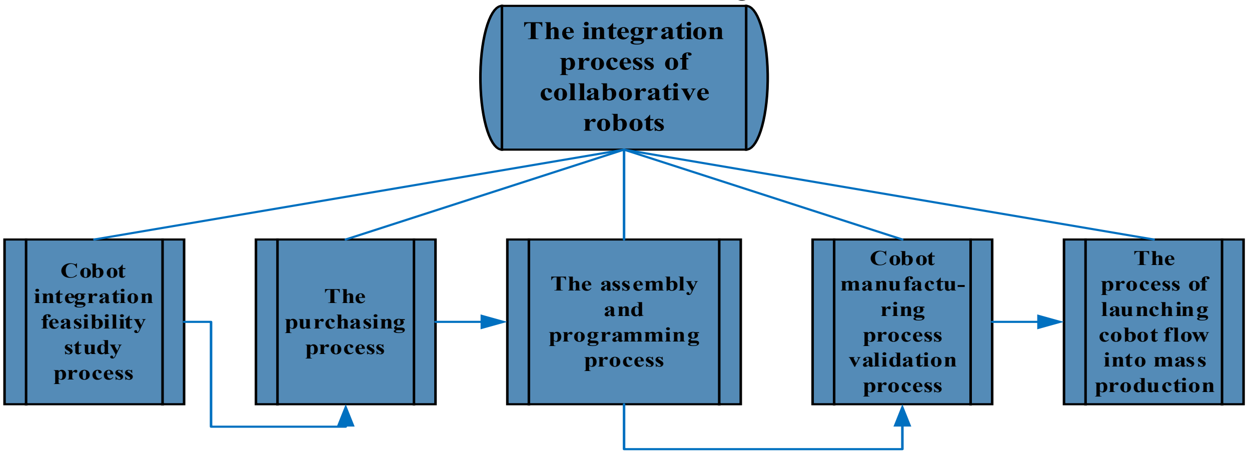

Fig. 2.2 The integration process of collaborative robots
Source: (Țîțu, Gusan, & Dragomir, 2023)

The cycle time and number of robots required for a given application must also be determined. ...

As a first step, the phased assembly process of collaborative robot structures is initiated, followed by the effective implementation of robots, corresponding gripping devices, and, in certain situations, mechanically and electrically secure devices. Subsequently, all devices and equipment associated with collaborative robots are connected to the network, ensuring their efficient communication with the surrounding environment. To facilitate communication, collaborative robots are equipped with various connectivity means, such as electrical inputs-outputs, Modbus industrial protocol, TCP-IP industrial protocol, or Profinet industrial protocol. (Gusan, Țîțu, & Oprean, 2022)

Using a single Ethernet cable for communication between devices can be much more convenient than using a large number of separate wires or cables. This can be concretely exemplified by Figure 2.4. After completing the processes of electrical and mechanical assembly, as well as establishing connections between collaborative robots and the surrounding environment, the programming stage of collaborative robots can be initiated.

To configure an application, it is necessary to follow a set of steps, including:

- Determining and declaring the central point of the tool;
- Declaring the mounting position;
- Naming and declaring electrical inputs and outputs, as well as other signals and variables;

- Saving the basic configurations.

After configuring the basic settings, one can proceed to the actual programming of collaborative robots. The program will be executed sequentially, from start to finish. Each input and output will be queried in the program, and based on these, decisions and logical gates can be constructed using simple if/else if/else instructions. The robot's movements will be defined by establishing coordinates for each point, and for these movements and points, the speeds and deceleration of the robot will be specified in the program. Also, to avoid stopping the robot at each point, it can be programmed to bypass the point according to a radius without stopping. In the end, applications must adhere to the specifications and be developed simply and rapidly. The possibilities for programming and development in this direction are limitless.

The validation process of the collaborative robot manufacturing flow is a set of activities that ensure the certification of functionality and safety of the new production method. This validation procedure is carried out by specialized departments, aiming to recertify the production flow following the implementation of collaborative robots, relocation of equipment, or other relevant modifications. For example, in the automotive industry with a focus on electronics, Electrostatic Discharge (ESD) measurements are performed to obtain ESD certification. This abbreviation stands for Electrostatic Safety Discharge - safe electrostatic discharge. In this case, collaborative robots must be constructed from materials that facilitate electrostatic discharge. Work instructions must be updated to integrate new operating procedures with collaborative robots, facilitating operators' familiarization with them. A revalidation of the production line with collaborative robots will be carried out by a health and safety specialist. During this time, emergency buttons and auxiliary safety elements connected to the collaborative robot will be checked. Ultimately, the Occupational Health and Safety (OHS) auditor will issue an internal certification confirming that the production flow with collaborative robots is safe for regular operation by human operators.

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Chapter 3 CURRENT STATE OF KNOWLEDGE IN THE FIELD OF INDUSTRIAL AND COLLABORATIVE ROBOTS INTEGRATED INTO MANUFACTURING PROCESSES IN THE AUTOMOTIVE INDUSTRY

3.1 Robotics science

The science of robotics represents the discipline concerned with the research, design, production, and technology of robots. Robotics is a science that combines and imposes knowledge in the areas of mechanics, electronics, and programming.

First and foremost, it is important to identify the origin of the science called "Robotics." The term "Robotics" naturally derives from the word "robot." In the past, the word "robot" was only present in science fiction literature. This word was completely absent from the language of engineers and technical personnel until 1920 when the Czech author Karel Capek wrote the work entitled "Rossum's Universal Robots." The play was awarded in Prague in 1921 and was performed in London in 1921 and New York in 1922. The main theme addressed in this work is futuristic workers built by humans. These operators or workers are presented as created by humans to reduce the difficulties of old jobs through their automation. (Kuffers, 2005)

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The idea of robotics is illustrated by replacing human labour with complex automated systems capable of successfully performing tasks imposed by humans without requiring human intervention in real time. (Telea, 2014)

Because the science of robotics encompasses multiple knowledge areas from various engineering fields, such as mechanics, computer science, bioengineering, electrical engineering, and programming, it can be considered an extremely complex science.

The equipment developed in the field of robotics aims to take over various activities from human responsibility or replicate them, thus easing human life. Human life is full of challenges and various repetitive activities, leading to the emergence of various robot models that can differ based on their purpose and use. Mechanically, robots can take various forms, inspired by human biology or other areas. Today, they can be found in numerous forms, designed for various purposes, resembling humans totally or partially: humanoid robots, robotic arms, robotic legs, mobile robots for transportation or cleaning, etc.

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Humans have even drawn inspiration from nature to replicate various activities through the science of robotics. Nowadays, robots can replicate activities such as speaking, thinking, lifting weights, walking, and many more.

Robots can also be classified based on the area of activity for which they were designed, being used in various fields, such as:

- Manufacturing area (activities involving picking and placing, transporting goods and products, handling various tools, etc.);
- Household area (cleaning or serving activities, etc.);
- High-risk areas (inspection of radioactive materials, detection and defusing of explosives, and other similar fields of activity);
- Medical area (replacement of amputated limbs or other organs to support life and assistance in operations requiring high precision are just a few examples of robot applications in the medical field);
- Areas incompatible with human life (exploration and operation in outer space, high-temperature environments, deep-sea environments, oxygen-deprived environments, etc.).

In the past, researchers, engineers, and inventors frequently expressed assumptions that robots would represent the future. There has always been a human desire to create fully autonomous robots, but the research index regarding their functionalities and potential remained low until the 20th century.

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Chapter 4 EFFICIENCY AND EFFECTIVENESS – ESSENTIAL CONDITION FOR IMPROVING THE QUALITY OF THE FINAL PRODUCT IN THE AUTOMOTIVE INDUSTRY

4.1 Efficiency concept approached from the perspective of the doctoral research topic

The concept of efficiency is a complex one and can be approached from both technical and economic perspectives. (Çalmaşur, 2016)

Within academic research in the field of manufacturing, there is a frequent use of the term efficiency in connection with the notion of productivity. Productivity is defined as the production of a greater or at least equal volume of goods using the same or fewer resources. (Pekur, Haapasalo, & Herrala, 2011)

In specialized research, collaborative robots are presented as tools that:

- can improve the production system by supporting workers both physically and cognitively; (Bragança, Costa, Castellucci, & Arezes , 2019)
- can optimize costs by balancing human effort and pursuing ergonomics, ensuring an efficient and productive workflow; (Weckenborg & Spengler, 2019)
- can increase the efficiency, effectiveness, and quality of the production process. (Țîțu & Gusan, 2022)

Collaborative robots enhance efficiency in terms of manufacturing workflows by:

- increasing the number of units produced per hour;

- stabilizing the number of units produced by the manufacturing flow per hour.

Improving the efficiency of the production flow can be achieved by increasing the number of units produced per hour through the optimization of production speed.

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Concurrently, the implementation of collaborative robots also leads to the empowerment of the operator remaining on the manufacturing floor. The operator becomes aware that the production pace is dictated by robots, prompting a better focus on their own tasks, thus becoming the sole variable resource with a significant impact on manufacturing flow productivity.

The variation in a manufacturing flow is amplified with an increasing number of operators present on the manufacturing floor. Each operator introduces variation because:

- they may leave the workstation for breaks;
- can be easily distracted, and there is even the possibility of mutual distractions through socializing, leading to a loss of focus on production activities;
- each individual is different, with varying fatigue resistance, work speed, and attention depending on age or emotional state.

Collaborative robots streamline manufacturing flows from an economic standpoint. They reduce manufacturing costs by decreasing the number of operators, with the investment being recovered in a very short time. By optimizing manufacturing costs, organizations can produce at a significantly lower cost, remaining highly competitive in the market.

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4.2 Effectiveness concept in correlation with the objectives proposed in the context of the doctoral research topic

The definition of effectiveness, according to (eficacitate - definiție și paradigmă | dexonline, 2023), refers to the ability to produce the desired or expected effect positively and qualitatively.

Effectiveness, from a general perspective, pertains to doing the right things, namely selecting and focusing on producing a product or service for which there is genuine demand and identified need. (Sundqvist, Backlund, & Chronéer, 2014)

Starting from the premise that effectiveness involves accomplishing things appropriately, one can consider that the effectiveness of a production flow may also refer to its ability to produce conforming products, meaning adequately meeting customer requirements and expectations. Conforming products are those deemed suitable and in accordance with requirements and specifications, imparting a high degree of quality and potentially leading to their certification as quality products.

Currently, one of the most commonly employed strategies by organizations involves continuous quality improvement and control (Godina, Matias, & Azevedo, 2016).

The quality of the manufacturing process is largely influenced by process parameters, including product handling. Product handling is an essential parameter that cannot be automatically measured as it depends on the operator's effectiveness. Operator effectiveness refers to their ability to perform assigned tasks in accordance with procedures and work instructions.

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Collaborative robots enable the achievement of a higher number of conforming products by ensuring guaranteed repeatability, ranging between ± 0.03 to ± 0.1 mm in the case of Universal Robots' collaborative robots. Repeatability is a specific property of each type of robot and represents its ability to maintain the same coordinates after multiple movements. The collaborative robot can perform precise movements after multiple cycles, serving as a sophisticated tool.

In manufacturing workflows in the automotive industry, approximately 40% of defects are caused by the errors of workers or operators. These errors can be added to another 35% of defects, attributed to other unknown causes, which may, in part, be related to worker errors. Thus, it is estimated that human errors can account for about 75% of the total rejected parts. These errors are caused by:

- Products falling on the floor;
- Mishandled products;
- Non-compliance with work instructions;
- Loading the wrong materials and mixing.

Accumulated fatigue during working hours, operator inattention, lack of knowledge about manufacturing flow operations, lack of interest, emotional state, stress related to meeting production goals, and maintaining efficiency are some of the aspects associated with operational issues. These can also be attributed to various causes.

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By implementing collaborative robots in manufacturing workflows, the complete elimination of the previously mentioned human errors can be achieved. Regarding the impact on production, it has been estimated that 40% of the total manufactured products are rejected due to human errors. Eliminating these rejects would result in a 40% increase in the percentage of conforming final products from the manufacturing flow. Therefore, there is a cause-and-effect relationship between eliminating negative causes and eliminating the associated negative effects that lead to losses due to the lack of quality.

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Chapter 5 CONCLUSIONS REGARDING THE CURRENT STATE OF RESEARCH IN THE FIELD OF QUALITY ASSURANCE FOR MANUFACTURING PROCESSES THROUGH THE INTEGRATION OF INDUSTRIAL AND COLLABORATIVE ROBOTS IN THE AUTOMOTIVE INDUSTRY

Part I addresses the importance of quality in product manufacturing, with a focus on the automotive industry. The IATF 16949:2016 standard imposes essential requirements for certification, attesting to compliance with quality requirements. Quality is defined as meeting the specifications, with the ultimate goal of satisfying customers. Non-conformity arises in the case of quality deficiencies, leading to negative consequences. Concepts associated with quality include quality assurance, the quality management system, quality engineering, quality control, and total quality management. Customer satisfaction is a crucial indicator of quality.

Technical quality control involves assessing the technical characteristics of products to verify compliance with requirements and technical specifications. Total Quality Philosophy and the zero-defect strategy are global approaches to quality improvement, aiming to meet customer needs. In the automotive industry, achieving the "Zero Defects" goal involves implementing the concept of total quality. Quality management involves a quality-focused leadership system that brings benefits and adds value to the organization. The Total Quality Management philosophy plays a crucial role in the pursuit of excellence, with the ultimate priority being customer satisfaction. The close link between quality management, total quality management, and knowledge-based organizations contributes to achieving customer satisfaction efficiently and effectively.

Knowledge-based organizations use digital resources to maintain and distribute knowledge, ensuring continuous employee updating. Integrating this philosophy into quality management contributes to the organization's sustainability, facilitating knowledge distribution, and efficiently identifying root causes in improvement processes. In the automotive industry, adopting collaborative robots through knowledge management optimizes production quality and efficiency. The priority should be meeting customer requirements through needs-centered marketing strategies to gain competitive advantages and long-term stability.

The automotive industry increasingly adopts collaborative robots in manufacturing processes to prevent non-conformities and ensure quality consistency. Their integration optimizes efficiency, reduces human errors, and improves working conditions. Benefits include increased efficiency, cost reduction, and improved quality of end products. The integration process requires meticulous planning, including assessing organizational needs, selecting suitable robots, training personnel, and adapting workflows. Quality assurance in the implementation of collaborative robots is essential for success and efficiency.

The robotics industry is rapidly advancing, offering diverse and autonomous solutions. Investments in research, development, and automation are crucial for optimizing the potential of this industry. Progress in robotics significantly impacts daily life, industry, and medicine. Industrial robots bring substantial benefits, enhancing productivity, quality, and efficiency across various sectors, including the automotive industry. Analyzing the use of robots in production highlights the diversity of solutions and technological advancements, with the potential to streamline processes and adapt to changing market requirements. Progress in autonomous mobile robots can reduce costs and improve efficiency in industry and logistics, providing new opportunities for the benefits robots bring to different sectors.

The integration of collaborative robots in the industrial environment provides optimal solutions for high-risk areas for operators. These robots take on dangerous and repetitive tasks, thereby reducing workplace accidents and enabling operators to focus on valuable activities. The diversity of solutions and innovations in the field of collaborative robots is emphasized, and choosing a suitable robot is essential for maximizing efficiency and productivity while maintaining an optimal balance between performance and costs. The use of these robots contributes to increased efficiency and production stability, reducing costs, and improving the quality of end products. Their integration into serial manufacturing workflows minimizes human errors, ensuring a precise and consistent production process, leading to high-quality end products. Collaborative robots represent the optimal solution for optimizing production costs, improving process efficiency, and certifying product quality in accordance with standards.

PARTEA a II-a CONTRIBUTIONS REGARDING THE RESEARCH AND DEVELOPMENT OF THE EFFICIENCY AND EFFECTIVENESS OF SERIAL MANUFACTURING FLOWS THROUGH THE USE OF COLLABORATIVE ROBOTS TO IMPROVE QUALITY AND PERFORMANCE IN THE AUTOMOTIVE INDUSTRY

Chapter 6 DIRECTIONS, MAIN OBJECTIVE, SPECIFIC OBJECTIVES, AND RESEARCH METHODOLOGY FOR INCREASING THE QUALITY, EFFICIENCY, AND EFFECTIVENESS OF MANUFACTURING PROCESSES THROUGH THE INTEGRATION OF COLLABORATIVE ROBOTS IN THE AUTOMOTIVE INDUSTRY

6.1 Research directions

In modern society, a series of challenges and obstacles are evident. Economic and medical crises, among others, have had a significant impact on humanity.

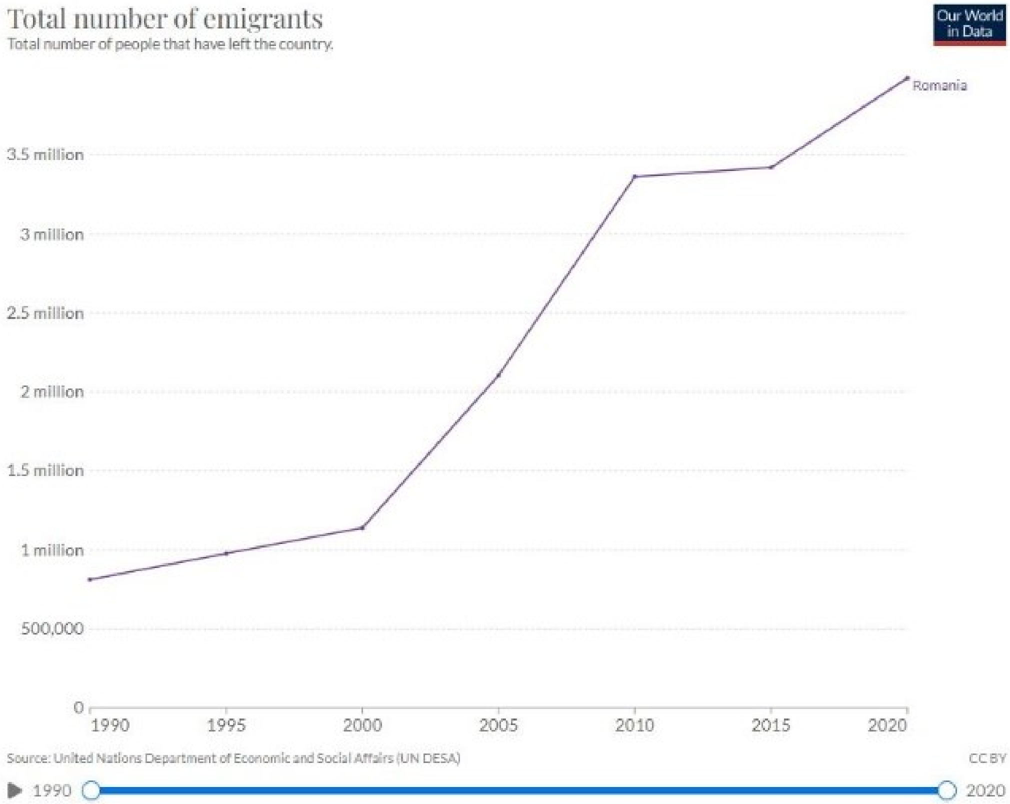

Fig. 6.1 The phenomenon of population emigration from Romania in the period between 1990 and 2020
Source: (Migration - Our World in Data, 2023)

In recent decades, Romania has witnessed an increasing trend of emigration, a situation that has brought new challenges to the industry and society as a whole. From the data presented in Figure 6.1, a significant rise in the number of Romanian citizens choosing to leave the country and settle abroad can be observed, starting from the year 1990.

According to the presented data, in 1990, a total of 811.853 individuals chose to emigrate to other countries, while in 2020, this number increased significantly, reaching 3.99 million citizens who left the country. This sustained growth in emigration has had a major impact on the labour market, leading to a significant decrease in available human resources and an increase in competition among organizations regarding the attraction and retention of employees. Faced with this situation, employers are challenged to attract and retain qualified personnel. Besides financial aspects, they seek to provide attractive benefits to employees for retention. Additionally, they invest in employee development, offering opportunities for specialization, aiming to contribution to the improvement of product quality, efficiency, and effectiveness of manufacturing processes. Thus, in a competitive human resources environment, investment in staff development becomes crucial for the success and growth of organizations. Especially following Romania's accession to the Schengen Agreement, there is the prospect of amplifying this phenomenon. (Tertereanu, Țîțu, Bogorin-Predescu, Gusan, & Bâlc, 2024)

Figure 6.2 illustrates the current number of immigrants in Romania. According to the presented data, in 2020, there were 705,310 international immigrants. This number is exponentially smaller compared to the number of individuals who emigrated from Romania, contributing to a significant reduction in the available workforce in the country.

This discrepancy between the number of immigrants and emigrants underscores that Romania continues to face a significant loss of labour force, and migratory flows do not fully compensate for this situation. Attracting and retaining qualified personnel in the country remains a major challenge to ensure economic development and competitiveness across various sectors. It becomes essential to address this issue meticulously and implement appropriate strategies to counteract the negative consequences of emigration and stimulate the attraction and retention of talent in the country. Investments in human resource development, creating an attractive work environment, and providing opportunities for growth and professional progress can contribute to improving the situation and promoting sustainable development in Romania.

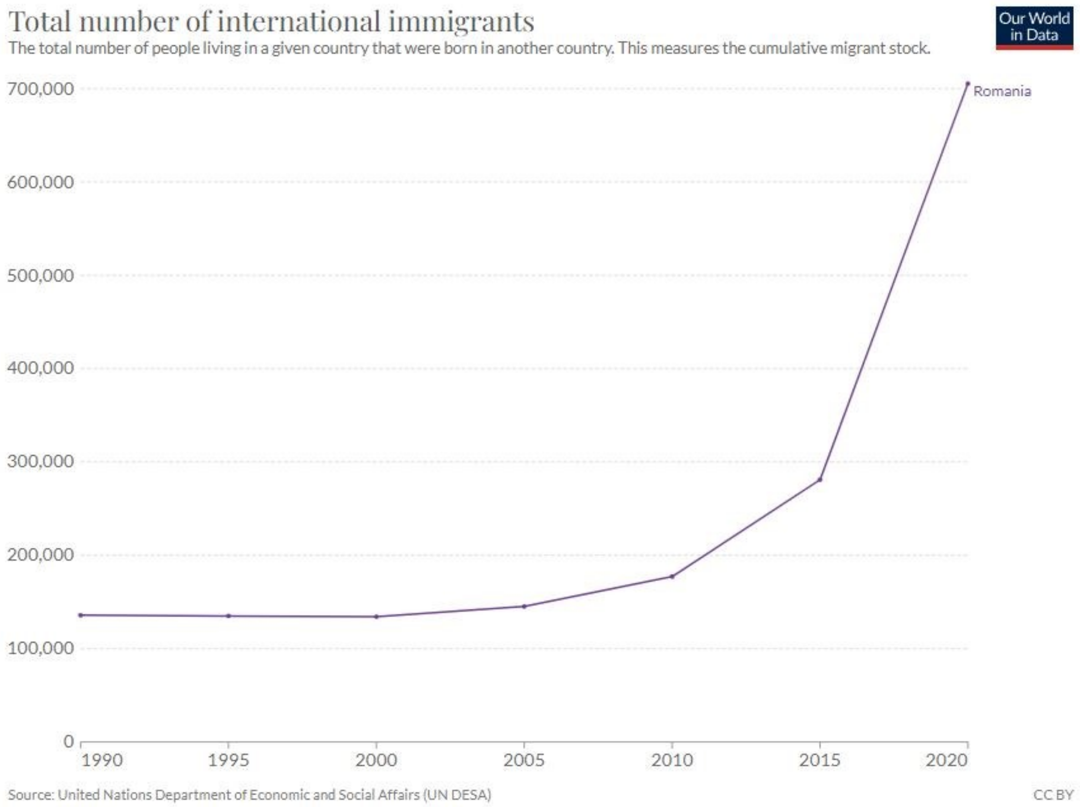

Fig. 6.2 The phenomenon of population immigration from Romania in the period between 1990 and 2020
Source: (Migration - Our World in Data, 2023)

In the context of all these challenges, industrial organizations must ensure profit generation, considering that they are entities oriented toward financial gains. To achieve this objective, efficient strategies for reducing manufacturing costs need to be implemented, and rigorous negotiations with suppliers of raw materials, production equipment, and transportation must take place.

Reducing manufacturing costs involves identifying and implementing solutions that allow process optimization, resource utilization efficiency, waste elimination, and reduction of unnecessary expenses. Negotiations with suppliers of raw materials, equipment, and transportation services represent a crucial aspect in obtaining favourable conditions and competitive costs. These negotiations require negotiation skills and a detailed understanding of the market and the industry's specifics.

The product's execution time is an exceptionally crucial aspect, with a direct impact on the delivery interval. Therefore, organizations direct investments toward production technologies that enable the rapid, automated, and cost-effective production of goods.

An essential criterion in this approach is quality. Quality represents the fundamental basis of the relationship between a client and a supplier and is a key element that opens the door to negotiations for a product or service supplier. Given this importance, quality standards have been developed, and specialized departments for quality management and product or service control have been established. This criterion exerts a considerable influence on the supplier's market durability and credibility in the eyes of current and potential future customers.

Quality must represent a crucial criterion from the product or service development phase. In this regard, analyses such as Design for Manufacturing (DFM) and Design Failure Mode and Effect Analysis (D-FMEA) are conducted both during and after the completion of product design. The purpose of these analyses is to ensure the realization of the product in an efficient technological flow, with high quality, in a short time, and with reduced manufacturing costs. Launching into production without conducting these analyses or tests increases the risk that the project will not be successful and may generate issues in the manufacturing process, leading to high non-conformity costs. In cases where the designed product does not meet certain criteria, and the analyses or tests reveal non-conformities, it is sent back to the design area to undergo the necessary modifications identified following the analyses.

It can be observed that the term quality plays a crucial role in terms of the manufacturing cost of a product. The production cost can be likened to the structure of an iceberg, where in the early phase of a new project, the visible costs, similar to the tip of the iceberg, include launch costs, raw material costs, logistics, and direct production costs. However, the most significant costs are imperceptible, resembling the base of the iceberg hidden underwater, and are represented by costs associated with the lack of quality.

A common scenario illustrates investing in a production machine with lower performance but more economical. Even though the initial cost is low, significant losses will be recorded in the future due to repeated rejects that may occur on this production machine, costs that can be quantified as product non-conformity costs.

In an era where the industry is increasingly moving towards total automation, various devices and automated product quality control processes are developed in parallel. After processing the parts on manufacturing lines, they require mandatory validation of the manufacturing process through specific process parameters, sensors, or inspection cameras.

Moreover, industrial organizations can adopt other strategies to optimize costs, such as implementing advanced technologies, automating production processes, diversifying supply sources, or identifying innovative solutions to streamline the supply and distribution chain.

At the same time, industrial organizations must ensure the acquisition of new profitable projects and the attainment of long-term clients. In the context of negotiation processes, not always does the party proposing the most efficient technical solution win, but rather the one that manages to provide a low cost for a quality considered satisfactory for the client.

All these efforts are necessary for industrial organizations to remain competitive and ensure a balance between profit generation and operational efficiency.

In the automotive sector, a clear trend towards increasingly advanced automation and digitization can be observed. This evolution leads to complete interconnection and communication between equipment, machinery, and robots, regardless of their level of mobility, in various industrial applications. The purpose of this automation is to optimize the efficiency and precision of production processes by eliminating potential errors and the human impact on product quality.

During visits to production areas in the automotive industry, especially in highly automated zones, the presence of collaborative robots, as well as other advanced production technologies, will be noticeable.

From the study of specialized literature, a trend is observed recommending the replacement of human labour with automated systems in situations where automation can bring an increase in the quality and precision of work. (Matúšová, Bučányová, & Hrušková, 2019)

Collaborative robots represent a new stage in the development of industrial robots, where they interact closely with humans and ensure a high level of safety. These robots are equipped with a variety of sensors, including advanced vision systems. (Galin & Meshcheryakov, 2019)

By implementing advanced technologies such as collaborative robots and industrial vision systems, the automotive industry manages to perform complex and repetitive operations with greater speed and precision. These technologies enable safe and efficient interaction between humans and robots within the same production processes. Additionally, the use of sensors and advanced control systems contributes to the continuous monitoring and adjustment of processes, ensuring a high level of quality and reliability in manufacturing. (Bogorin-Predescu, Țîțu, Tertereanu, Bâlc, & Gusan, 2024)

The research was directed towards multiple research directions, as follows:

- Integration of collaborative robots due to their unlimited potential. This direction explores ways to transform manual workflow into automated production workflows with collaborative robots through the reengineering of manufacturing processes.
- Development of programming methodologies for collaborative robots and the implementation of standardization in the structure and terminology for signals, positions, tools, etc., aiming to facilitate program understanding by other programmers, including under significant geographical distances.
- Implementation of the „zero downtime" strategy for manufacturing change in the automotive industry. This concept, personally developed, involves minimizing the time required for adjusting and reconfiguring equipment in mass production processes.
- Study of autonomous manufacturing flows and analysis of existing logistics elements within these flows. This aims at optimizing and efficiently managing material and information flows in production processes to enhance performance and profitability.
- Application of the PFMEA method in a manufacturing flow with collaborative robots. The use of this methodology for developing a specific action plan to prevent and manage potential causes that may generate defects.
- Presentation and composition of functional technical solutions regarding auxiliary safety systems used in the integration of collaborative robots in mass production workflows. This direction focuses on finding technical and methodological solutions to certify and monitor the safety of interactions between robots and humans within manufacturing flows.
- Presentation of concrete methods, supported by scientific data, and the development of mathematical models to determine how collaborative robots enhance the efficiency, effectiveness, and quality of manufacturing flows.
- Definition and detailed analysis of a clear process for outlining requirements for the implementation of collaborative robots in manufacturing workflows.
- Theoretical definition, proposal, and validation of mathematical models for calculating direct and indirect costs, establishing a clear method for calculating the return on investment and the estimated annual electricity costs.

6.2 Main objective and specific objectives proposed in the doctoral research

The overall objective of this scientific research endeavour is to formulate a standard for programming collaborative robots by developing a programming structure and utilizing specialized software languages. The fundamental goal of this approach is to ensure, through programming, the achievement of improvements in terms of quality, efficiency, and effectiveness in the automotive industry, through the advanced adoption and implementation of collaborative robots.

The specific objectives proposed for this research study are as follows:

- Development of a programmable architecture, specific language, and algorithm for collaborative robots, followed by a proposal for standardization of this framework.
- Elaboration of a complementary safety system for critical situations, dedicated to the integration of collaborative robots.
- Definition of requirements and mathematical models useful in the integration of collaborative robots in the automotive industry, application of PFMEA, and establishment of parameters for measuring efficiency and effectiveness.

- Optimization of processes through comparative cost analysis, focusing on quality improvement and integration of zero changeover time strategy into collaborative robot programming.
- Development and application of IDEF0 methodology and Lean Manufacturing in manufacturing processes, emphasizing the use of collaborative robots in the KAIZEN context.
- Development and application of human resource policies for managing excess personnel following the integration of collaborative robots into the automotive industry.

6.3 Research methodology proposed in the doctoral research

The research methodology is conceived and established through mind maps created during the scientific research process. The structure of the research methodology has been designed as a logical sequence of stages necessary to achieve the main objective of the doctoral project and to open up possibilities for further development.

Within this scientific study, the six-step method has been applied, consisting of the following research stages:

- Defining the objective, which involves clearly defining the purpose pursued in the study;
- Analysis of the current stage - a detailed assessment of the current situation to identify existing needs and challenges;
- Hypothesis formulation - stating assumptions and assertions regarding the implementation of collaborative robots;
- Developing mathematical models, technical configurations, and programs - implementing and conducting a controlled activity to obtain relevant data and information regarding the implementation of collaborative robots;
- Results analysis - examining and interpreting the results obtained from scientific research to draw valid conclusions;
- Presenting conclusions - summarizing the results and formulating conclusions based on the analysis and interpretation of the collected data.

Chapter 7 CONTRIBUTIONS IN THE TECHNICAL FIELD REGARDING COLLABORATIVE ROBOTS PROGRAMMING

7.1 Contributions regarding the development and structuring of a proprietary programming model

The increasingly widespread use of collaborative robots is accompanied by a significant challenge related to their programming, especially within small and medium-sized organizations. (Fogli, Gargioni, Guida, & Tampalini, 2022)

Collaborative robots have the advantage of being very easy to program. Following research in the specialized literature and drawing from my own 8 years of experience in the field at Continental Automotive, it has been observed that this ease of programming can be highly risky when implementing an application. The absence of a clear standard regulating collaborative robot programming can lead to low program quality and, consequently, potential collisions between the collaborative robot and its surrounding environment, whether it be another robot or nearby equipment.

The lack of a programming standard also results in a less precise interpretation of the program. This situation can be likened to two individuals living in the same country but speaking different dialects. Although they eventually manage to understand each other, this difference can lead to time loss and a more intensive focus from the interlocutors. Similarly, with collaborative robots, when a project involving such robots is transferred to another organization or production area, the absence of a standard leads to difficulties in understanding the program and requires a detailed study.

Considering these aspects, it was deemed appropriate to propose a proprietary model developed and improved based on the experience gained from implementing multiple applications with collaborative robots. The approach to be presented can be viewed as a „recipe for success", applicable by any integrator or organization to enhance the efficiency, effectiveness, and quality of manufacturing processes through the integration of collaborative robots. In pursuit of this objective, the use of the proposed language developed during this scientific endeavour is suggested.

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Regulating these aspects would facilitate the understanding and easier use of programs by different programmers, thus contributing to more efficient collaboration and knowledge transfer in the field of collaborative robotics. Based on the experience gained from research, it was considered that these aspects should be regulated internationally, ensuring seamless knowledge transfer from one programmer to another. This can begin with the nomenclature of electrical inputs and outputs, Modbus registers, and tools or devices used, allowing another programmer to easily recognize, based on the nomenclature prefix, which command is used in the program. For example:

- **i_**buton_1 represents an **electrical input (input)** activated by a button or another electrical input;
- **o_**electrovalva_1 – an **electrical output (output)** through which the collaborative robot actuates a solenoid valve;
- **ri_**ass_variant – a ModBus **input register** through which the assembly station communicates the type of variant manufactured to the collaborative robot;
- **ro_**clear_zone – a ModBus **output register** through which collaborative robots communicate regarding common work zones;
- **t_**tool_1 – a **tool or device (tool)** numbered 1.

For the continuation of the technical argumentation, it was advocated that this aspect should be carefully regulated and standardized internationally to ensure efficient and consistent programming of collaborative robots. To facilitate easy knowledge transfer between programmers, the adoption of a common language and the use of standardized sequences for programming these robots are proposed. Thus, the following sequences are recommended:

- The „BeforeStart" sequence should be used to return the robot to a safe position at a slow speed, reset variables, reset signals and registers used by it, check the remaining parts in the device, and open/close the necessary devices. This way, the collaborative robot will be able to identify the state of the parts in the device and their correct positioning in the serviced equipment.
- The „Robot Program" sequence should only be used for interpreting signals and registers based on certain conditions set by the programmer. In this sequence, the collaborative robot will call the necessary subprograms based on the signals and conditions met. At the same time, the „Zero Changeover Time" strategy can be implemented, where the collaborative robot will automatically adapt to changes in the registers by surrounding equipment.
- „SubProgram" should be used to program characteristic movements. In the subprogram, in addition to specific movements for a particular application, characteristic signals that need to be checked or triggered and registers that need to be modified will be introduced.

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- The „Thread" should be used to control an external device or to check signals or variables in parallel with the main program.

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Despite considerable freedom in collaborative robot programming, it is considered beneficial to establish standardized structures and names for signals and other aspects. This ensures that the program can be easily understood by other programmers familiar with this standard, even at significant geographical distances. To ensure consistent and efficient programming of these collaborative robots, the language and structure used should be universal.

Chapter 8 CONTRIBUTIONS IN THE TECHNICAL FIELD REGARDING THE IMPLEMENTATION OF AUXILIARY SAFETY SYSTEMS REGARDING THE INTEGRATION OF COLLABORATIVE ROBOTS IN THE AUTOMOTIVE INDUSTRY

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8.2 Existing auxiliary safety systems, integration methods, and operation modes of these systems

8.2.1 Existing auxiliary safety systems used in collaborative robot applications

The interaction between humans and robots can involve significant risks in the absence of proper consideration of the human factor throughout the entire process. (Bragança, Costa, Castellucci, & Arezes , 2019)

Collaborative robots can be integrated into shared spaces with humans. However, this requires operating the collaborative robot at low speeds and with collaborative devices. In situations where the collaborative robot operates at high speeds or uses a hazardous device, sharing the workspace could pose a danger to humans. This situation necessitates that the application as a whole be a collaborative one.

A question may arise regarding the persistence of scientific research efforts in promoting the continuous use of a collaborative robot in this scenario, in contrast to choosing an industrial robot. This option is based on justified premises, such as the lower cost of collaborative robots compared to industrial ones and the lower complexity in terms of integration and maintenance. Additionally, the level of precision between the two types of robots is comparable. Moreover, maintaining an open space brings benefits, including cost reduction by eliminating the need for a protective cell or additional equipment. Minimizing the spatial footprint is a distinctive value, challenging to achieve when integrating collaborative robots within an automated cell. This approach direction brings significant gains to the organization, providing the opportunity to use the remaining space for the implementation of other projects.

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Therefore, research has been initiated in this direction to identify various types of safety auxiliary devices available on the market and evaluate the ways of interconnection between these devices and the collaborative robot, configuring an auxiliary safety system. This system must be designed to prevent any risk of human injury when entering the collaborative robot's workspace. At the same time, the resulting safety auxiliary system must be able to stop the collaborative robot and the associated device in a safe stop state, with collaborative robots resuming their activity from the point where they were stopped upon leaving the workspace. The integration of an emergency stop functionality has also been analyzed if needed.

The proposed auxiliary safety system, through scientific research, has the distinct role of adding a level of safety and protection regarding human-robot interaction in the context of collaborative robot use. This system facilitates direct and appropriate interaction between the operator and the robot, ensuring that the collaborative robot will be systematically stopped in the presence of the operator in proximity.

Fig. 8.4 Safety devices used in the integration of collaborative robots
Source: (Gusan & Țîțu, 2023)

Individual safety devices applied in the development of this safety system include:

- Perimeter scanners;
- Safety barriers;
- Programmable safety controllers (PLCs);
- Safety relays.

Safety systems or components are highlighted by the use of the colour yellow, and this characteristic is illustrated in Figure 8.4.

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Next, both theoretical considerations regarding the operation of safety devices and programming and usage methods will be presented. All presented aspects are supported by practical examples and can be considered successful recipes for any integrator or or

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Chapter 9 CONTRIBUTIONS IN THE MANAGEMENT OF COLLABORATIVE ROBOTS INTEGRATION IN THE AUTOMOTIVE INDUSTRY

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9.2 Cost management of implementation

The formulas and concepts regarding cost structure were developed throughout scientific research and highlighted the expense categories associated with the implementation of collaborative robots. These categories encompass the following aspects:

- Indirect costs: These include expenses related to the acquisition of collaborative robots, support devices, gripping systems, auxiliary safety devices, and other equipment necessary for implementation.

- Direct costs: These represent the expenditures generated by the consumption of electrical energy and the human resources allocated to the integration of collaborative robots into the production environment. For the comprehensive assessment of implementation costs, formula 9.1 has been developed.

$$T_C = C_D + C_I, \tag{9.1}$$

Where:
T_C represents the totality of implementation costs for collaborative robots;
C_I – indirect costs of collaborative robot implementation;
C_D – direct costs of collaborative robot implementation.
...

The direct implementation costs are generated by compensating the human resources involved in the project, as well as the consumption of energy resources. Compensating the human resources involved in the project is determined by the number of work hours allocated to the project. The project involves the use or hiring of multiple professionals contributing to its management. Specific tasks are assigned to each professional, ensuring a clear distribution of responsibilities as follows:

- The project manager develops and coordinates the optimal planning of activities within the project, ensuring careful monitoring of progress about the established schedule and budget;
- The electromechanical technical teams are responsible for assembling mechanical and electrical components. These teams will perform the assembly and fixation of structures, collaborative robots, and their working devices, as well as the installation and securing of electrical and pneumatic connections, as applicable;
- The team specialized in programming collaborative robots and the safety system is responsible for configuring and optimizing their functionality.

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In addition, the investment needs to be recovered in the shortest possible time frame. Collaborative robots are designed to perform repetitive operations. The return on investment in a production flow with collaborative robots can be achieved when they operate continuously over multiple shifts. The weight and complexity of products must fall within the limits of the maximum useful task that the collaborative robot can handle, and this must be adapted to the capabilities of gripping or handling devices. Due to this aspect, it is suggested to implement collaborative robots in large-scale production lines or mass productions, where the product range is limited but the production flow is continuous.

Several companies in the market opt for the implementation of collaborative robots because they provide a way to reduce production costs. By reducing manufacturing expenses, organizations can increase the profit generated from selling each product. This achievement is realized by:

- reducing the number of operators involved in repetitive operations on the production line;
- decreasing the number of defects and unsatisfactory products generated in the manufacturing processes.

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In conclusion, a theoretical perspective has been outlined, and calculation methodologies for direct and indirect costs have been proposed, thus developing an approach for evaluating the return on investment and estimates of annual electricity costs. The importance of budgeting the project in its preliminary phase has also been emphasized and how it must be correlated with the entire range of costs associated with the implementation of collaborative robots.

Chapter 10 CONTRIBUTIONS REGARDING THE IMPROVEMENT OF QUALITY AND IMPLEMENTATION OF THE ZERO CHANGEOVER TIME STRATEGY IN MANUFACTURING

10.1 A comparative analysis of industrial robots versus collaborative robots

Organizations in the industry are constantly seeking ways to produce more efficiently, at lower costs, with higher quality, and in a shorter time frame, aiming to maintain a competitive position in the market. (Galin & Meshcheryakov, 2019)

Due to the need to produce at lower costs, with superior quality, and at a faster pace in the industrial environment, it is important to economically analyze the implementation of collaborative robots compared to industrial robots to determine the profitability of the solutions.

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A study needs to be conducted to bring significant reductions in product manufacturing costs from an economic perspective. The study will be deemed feasible if the investment is amortized within three years.

To perform a feasible comparison, an economic calculation is necessary between the mode of operation with operators and the mode of operation with industrial or collaborative robots. The calculation will be carried out considering that the line was previously serviced by two operators; therefore, the calculations will focus on the operator who will be replaced by the industrial or collaborative robot. Prices will be estimated in Euros.

Economic calculations of how to work with operators include the analysis of the manufacturing costs involved in the production process with operators:

Within this production line, a single operator is required for each shift. Considering that the production line operates in four shifts, it follows that a total of four operators are needed, according to the relationship 10.1.

$$N = O * S = 1 * 4 = 4 \text{ operators,} \qquad (10.1)$$

O represents the number of operators per shift;
S – the number of shifts;
N – the total number of operators.

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An annual salary cost calculation was performed for all operators, according to the relationship 10.3.

$$T_A = T_S * L = 4{,}541.2 * 12 = 54{,}494.4 \text{ de Euro / year,} \qquad (10.3)$$

T_A represents the annual salary received by all operators;
T_S – the total monthly salaries for all shifts;
L – the number of months in a year.

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Economic calculations of the industrial robot way of working that include the analysis of implementation costs and their amortization:

Considering that the industrial robot utilizes electrical energy in its operation, it is imperative to resort to using relation 9.6 to estimate the associated electricity costs over the course of a year. To efficiently implement this relation, it is essential to identify the following data beforehand:

- P_{KWO} represents the price of electrical energy consumption;

- C_{EER} – the estimated electrical energy consumption of the industrial robot per hour;
- N_F – the number of operating hours of the industrial robot per day;
- N_{ZA} – the number of working days per year in which the industrial robot will operate in the manufacturing flow;
- N_R – the number of existing industrial robots in the application.

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For the integration of the industrial robot, a special cell will be constructed, and the estimated price for this (P_c)) is approximately 50,000 euros. This price includes the cost of integrating the industrial robot, automating the cell, packaging, delivery, and installation.

Therefore, considering the mentioned data, the cost of a cell with an industrial robot (C_{cr}) can be calculated according to relation 10.7.

$$C_{cr} = P_{RI} * 1 + P_c * 1 = 53{,}000 + 50{,}000 = 103{,}000 \text{ Euro}, \quad (10.7)$$

The total cost of operating an industrial robot can be determined according to relation 10.8. This is equivalent to the total cost of investment in a cell with an industrial robot (CT_{Iri}). Its calculation will be obtained by summing the cost of ordering the cell with an industrial robot (C_{cr}) and the cost of the robots' electrical energy consumption per year (CRa).

$$CT_{Iri} = C_{cr} + C_{RIA} = 103{,}000 + 5{,}460 = 108{,}460 \text{ Euro}, \quad (10.8)$$

Economic calculations of the collaborative robot way of working that include analysis of implementation costs and their amortization:

First, a calculation was performed to determine the electrical energy consumption of the collaborative robot. To carry out this calculation, an investigation was conducted into:

- P_{KWO} represents the price of electrical energy consumption;
- C_{EER} – estimated electrical energy consumption of the collaborative robot per hour;
- N_F – the number of operating hours of the collaborative robot per day;
- N_{ZA} – the number of working days per year in which the collaborative robot will operate the manufacturing process;
- N_R – the number of existing collaborative robots in the application.

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It can be observed that, in the long run, the best investment is made in the operation mode with collaborative robots. Also, the use of industrial robots represents a viable investment compared to the mode of operation with a human operator.

Starting from the fourth year, annually in the case of the industrial robot operation mode, according to relation 10.14, a total amount can be saved:

$$T_A - C_{RIA} - C_{SMAri} = 54{,}494.4 - 5{,}460 - 2{,}000 = 47{,}034.4 \text{ Euro}, \quad (10.14)$$

In the third year, a total savings of 40,102 euros can be observed through the implementation of an industrial robot, with a total amount of 47,034.4 euros to be saved annually starting from the fourth year until the end of the project's lifecycle.

For the investment in the collaborative robot operating mode, starting from the fourth year, annually, total savings can be achieved, according to relation 10.15, of:

$$T_A - C_{RCA} = 54{,}494.4 - 773.136 = 53{,}721.264 \text{ Euro}, \quad (10.15)$$

In the third year, a total savings of 115,163.6 euros is observed through the implementation of a collaborative robot, with starting from the fourth year, a total amount of 53,721,264 euros to be saved annually until the end of the project's lifecycle. It is noted that the collaborative robot working mode brings significantly greater economic benefit to the organization than the industrial robot working mode. The collaborative robot working mode optimally addresses the organization's costs, reducing expenses and ensuring long-term performance similarity.

Calculations have been made considering the current economic situation, without taking into account inflation or other economically variable parameters over time.

Chapter 11 INTEGRATION OF THE IDEF0 METHODOLOGY AND IMPLEMENTATION OF LEAN MANUFACTURING STRATEGIES IN THE CONTEXT OF KAIZEN ON MANUFACTURING PROCESSES USING COLLABORATIVE ROBOTS

11.1 Manufacturing processes in the automotive industry. Process map proposed for this industry

The IDEF0 methodology was applied to develop a schematic representation of the production flow in the automotive industry. The process was decomposed from a general level down to a detailed third level. It is important to note that in the automotive industry, production processes are particularly complex. This method will be illustrated through a specific example in the field of electronic component manufacturing in the automotive industry.

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In the automotive sector, the organization operates by the laws, regulations, and standards in force, both at the national level in the country where it is headquartered and internationally. Organizations in the automotive industry must obtain relevant certifications, attesting to customers that their operations and activities comply with standard requirements. These certifications are an important way for organizations in the automotive sector to demonstrate their commitment to quality and compliance.

The primary goal of organizations in the automotive industry is to produce and supply products for vehicles, culminating in delivering them to customers. This represents the main output of these organizations, and their success is largely measured by the ability to successfully produce and market high-quality automotive components and products.

The leadership of the organization is a key element that directs and ensures that the organization understands and implements customer requirements by the legal framework, regulations, and standards in force, with the aim of manufacturing products of the highest quality and delivering them to customers on time.

All these ICOMs represent the pillars that allow the smooth operation of the automotive organization. It is observed that the finished product constitutes the output of the process, while market or customer requirements represent the entry point. This highlights the fact that any organization in the automotive industry is subordinate to customer requirements. These requirements are essential in the development of products intended for marketing and delivery to the end consumer. Therefore, it can be concluded that the success of the organization in the automotive industry is directly linked to its ability to manufacture high-quality products.

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To gain a detailed understanding of how this organization operates, a decomposition of the A0 diagram of the automotive organization was performed. The A0 decomposition, according to illustration 11.2, was carried out with a focus on key processes existing in an automotive organization. This analysis led to the identification of the following categories of key processes:

- Management processes: These processes represent the actions through which the organization is led and controlled as a whole. They include planning, coordination, and decision-making activities that ensure the direction and objectives of the organization.
- Operational processes: These are key processes that add value to the organization through activities such as selling, purchasing, and producing products or services. They are essential for the day-to-day functioning of the organization and for delivering products or services to customers.
- Support processes: These processes provide support to the organization's operations and facilitate the efficient functioning of operational and management processes. They may include activities such as accounting, data analysis, human resource management, and financial resource management.

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Taking these aspects into consideration, collaborative robots can be seen as a resource element involved in the final assembly stage of the product. Collaborative robots represent a system that interacts synergistically with the human workforce but, at the same time, competes with it due to reduced costs and other benefits.

Chapter 12 CONTRIBUTIONS REGARDING HUMAN RESOURCE POLICIES AND STRATEGIES IN THE CONTEXT OF COLLABORATIVE ROBOT INTEGRATION: MANAGING AND RESOLVING WORKFORCE SURPLUS

12.1 Human resources and collaborative robots

In the context of human resources and collaboration with robots, there is a close cooperation. Although collaborative robots can be seen as potential replacements for humans and may lead to job reductions, they can truly function collaboratively only in the presence and collaboration with human resources. To achieve effective collaboration, humans need to be an integral part of the workflow of collaborative robots.

Certainly, as exemplified in the previously presented applications through the implementation of IDEF0, which achieves the equivalence of the two resources or mechanisms, it can be observed that collaborative robots can take on certain responsibilities within the production flow. An observation arises that the implementation of collaborative robots leads to a reduction to some extent in the number of operators. This observation is partially true, but the jobs that collaborative robots can take over are mainly characterized by repetitive activities, meaning they can be automated. These positions are undoubtedly suitable to be taken over by collaborative robots as they are inherently linked to the processes of robotization. On the other hand, jobs involving decision-making and human interaction cannot be replaced by collaborative robots and will continue to be occupied only by human operators.

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If a check were to be made, it would be observed that indeed, the number of high-quality products increases within a collaborative production flow. This improvement occurs because when the activity performed is not tedious or repetitive, monotony does not set in, and the operator's attention remains more focused.

It has been concluded that integrating collaborative robots into the work environment represents a significant advancement in the automation of production processes and related fields. This collaboration between human resources and intelligent machines offers significant opportunities for increasing efficiency and productivity while contributing to reducing health and safety risks in the workplace and improving working conditions. Overall, this evolution in industrial automation and other fields demonstrates that technology and human resources can collaborate to achieve higher levels of performance and innovation. It is crucial to continue researching and implementing collaborative robots to fully exploit the potential of this intelligent collaboration between humans and machines in a constantly changing world.

Chapter 13 FINAL CONCLUSIONS AND KEY CONTRIBUTIONS REGARDING THE IMPROVEMENT OF QUALITY, EFFICIENCY, AND EFFECTIVENESS THROUGH THE IMPLEMENTATION OF COLLABORATIVE ROBOTS IN SERIAL MANUFACTURING FLOWS IN THE AUTOMOTIVE INDUSTRY

General conclusions

The fundamental purpose of this scientific research is to formulate a standard for collaborative robot programming by developing a programming structure and utilizing specialized software languages. The primary objective of this approach is to ensure, through programming, the achievement of improvements in terms of quality, efficiency, and effectiveness in the automotive industry, through the advanced adoption and implementation of collaborative robots.

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Original contributions

The innovations brought about through the scientific endeavour, a significant portion of which has been disseminated throughout the research program via scientific publications, include:

- Emphasizing the need for clear standardization in structuring programs for collaborative robots. In this regard, a programmable structure has been developed, providing specific recommendations targeting both program structure and language used. Special emphasis has been placed on universality and coherence in language and structure to facilitate collaboration among programmers globally.
- Articulating the configuration of basic settings, recognizing their fundamental role in ensuring proper initiation and appropriate behaviour of collaborative robots. This solid initiation serves as the foundation upon which their subsequent functionality is successfully built.
- • Advocating for the efficient use of „BeforeStart", „Robot Program", „SubProgram", and „Thread". Each category has been meticulously detailed, providing essential guidance for optimizing the programming process and the overall functionality of collaborative robots.
- Addressing the contribution to human-robot collaboration, identifying opportunities for human intervention while being aware of challenges associated with potential collisions during collaborative robot operations.
- Contributing to the development of methods for optimal positioning of collaborative robots in production, highlighting the importance of 3D simulations, and presenting a cost-effective alternative for simulating their mobility.
- Highlighting various safety and security solutions integrated into an original system, detailing the programming process and implementation of devices from recognized suppliers such as SICK AG and PILZ GmbH & Co. KG.
- The contributions extend to the development of a safety system personally tested at Continental Automotive, presented both theoretically and practically integrated into specific projects with collaborative robots. This comprehensive approach not only provides practical solutions but also a "recipe for success" for integrators and organizations, ensuring efficiency and sustainability.

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- Quantifying efficiency and effectiveness through a mathematical approach, providing a clear perspective on managing these aspects in organizations. In the presented scenario, the successful implementation of collaborative robots in a manufacturing workflow has generated significant improvements, including a productivity increase of approximately 24% and a 98.9% reduction in production costs.

- The analyses and conclusions support the idea that operating with collaborative robots is about 2% more effective than operating with human operators in the analyzed production workflow context. These findings underscore the importance of collaborative robot technology in the manufacturing environment and reflect expertise in managing the efficiency and effectiveness of implementation.
- A detailed analysis of three distinct types of production workflows - with human operators, with industrial robots, and with collaborative robots - reveals a significant economic benefit of the collaborative robot approach. The estimated total savings are 115,163.6 euros in the third year of implementation, with a consistent annual savings of 53,721.264 euros starting from the fourth year, highlighting the efficiency and sustainability of this method.
- Analysis of robot selection methods, defining clear criteria such as payload, speed, acceleration, and the number of axes. These play a crucial role, in ensuring the maximization of reliability and productivity at minimal costs.
- From a quality perspective, it has been demonstrated that collaborative robots are essential tools, precisely managing the production flow and eliminating human fluctuations and errors. These robots significantly contribute to optimizing manufacturing processes, reducing costs, and improving efficiency.
- The integration of the innovative concept of programming, „Zero Manufacturing Changeover Times", has been successfully developed and applied to multiple collaborative robot applications implemented in the workplace. It illustrates how the concept can be integrated into a collaborative robot program. This approach allows a smooth transition between various production configurations without human intervention, with the potential for expansion and implementation in a variety of applications.
- Identifying collaborative robots as a crucial resource in final assembly, through the application of the IDEF0 methodology and defining the process map in the automotive industry. In the IDEF0 context, where collaborative robots and human operators are identified as comparable resources or mechanisms, it is suggested to primarily leverage the cognitive abilities of human operators and delegate repetitive tasks to collaborative robots.
- Analysis and comparative evaluation of results through the Jishuken methodology of two production workflows, one based solely on human resources and the other collaborative in nature, involving both human operators and collaborative robots.

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Further research directions

- The first subsequent research direction could involve expanding and refining the mathematical models associated with the efficiency and effectiveness of collaborative robots, with a focus on specific considerations of the industrial domain. This represents an essential direction for further research. This continuation might entail adapting the models to variables specific to particular industries or processes, contributing to a more accurate assessment of the benefits brought about by the implementation of collaborative robots.

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- A crucial research direction in the evolution of collaborative robots focuses on cybersecurity, aiming to develop innovative technologies that prevent and protect these intelligent agents against cyber threats and potential attacks.
- A promising research direction aims to enhance the social abilities of collaborative robots to facilitate more natural collaboration with human operators. This perspective may involve developing aspects such as facial expressions, gestures, and other modes of communication.

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Anexe 1-6

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