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Human-Robot interaction dynamics in industry 5.0: maximizing performance and ensuring safety

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ABSTRACT:

As industry 5.0 begins to take shape and the focus is shifting from full automation to a move balanced partnership between people and smart machines. This thesis explores how humans and robots can work together effectively, and area known as human and robot collaboration (HRC). The goal is to boost productivity while keeping the work environment safe for everyone involved. Robots are built to work side by side with human operators. But for them to be truly effective it’s not just about technology. It’s also about building trust with workers and designing systems that are comfortable and intuitive to use.

This study uses a mixed method approach that blends theoretical modelling, digital twin simulations, hands-on experiments of robotic air bag. It builds on established frameworks like the 5C model of human-robot collaboration and the safety – performance trade-off to explore how people and collaborative robots (cobots) can work together safely in real settings.

A key part of the research involved developing and testing a robotic airbag designed to protect workers during accidental collisions with cobots. Both simulations and real impact tests confirmed that the airbag effectively reduced force, allowing robots to operate at high-robot collaboration isn’t just about having advanced technology it also depends heavily on building trust, ensuring comfort, and designing systems that are easy to use. In short, prioritizing human-centred design and smart safety measures is crucial for creating workplaces that are both safe and efficient.

The study concludes by presenting a practical framework for introducing collaborative robots (cobots) into industrial environments one that strikes a balance between safety, performance, and human-centred values. It offers clear, actionable recommendations for manufactures, system designers, and policymakers aimed at creating smarted, safer, and more adaptive workplaces. This contribution is especially important in the context of next generation of manufacturing industry, where humans and robots don’t just work together, but actively collaborate to achieve shared production goals.

KEYWORDS: Human-Robot collaboration, Industry 5.0, Safety, Ergonomics, Robotic airbags

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Abbreviations

HRC	Human-Robot Collaboration
IoT	Internet of Things
SMEs	Small and medium sized enterprises
AI	Artificial Intelligence
HRI	Human-robot interaction
DTTs	Digital twin technology
HDTs	Human digital twin
LSTM	Long short-term memories
ML	Machine Learning
LED	Light Emitting Diode

1. Introduction

The section provides the research background and explains why this study is important. It sets the stage for understanding the need for this research. The following sections 1.2, 1.3 and 1.4 introduce the problem, highlight the interdisciplinary nature of the study, outline the research goals, present the research questions and define the scope. These sections clarify what the research aims to answer. Finally, sections 1.5 and 1.6 describe the research approach, method and overall structure, explaining how the study addressed those questions.

1.1. Background of Study

Manufacturing continues to depend heavily on advanced robots built for precision, speed and heavy-duty tasks particularly in industrial settings, where these machines are integrated into production lines. To ensure safety, these robot systems are typically enclosed within fenced-off zones to prevent human access to hazardous areas. While the manufacturing significantly enhances productivity it comes at the cost of reduced flexibility and long setup times. However, the growing demands for product customization shorter life cycles and an aging workforce necessitate a more adaptable approach to manufacturing.

Recent breakthroughs in robotic hardware have paved the way for the development of lightweight and more agile robots, safety-enhanced cobots capable of minimizing their risk of severe injuries in case of accidental collisions (Aaltonen et al., 2018). As a result, many companies are increasingly adopting cobotic collaborative system allowing cobots to work together According to the (Bounouar et al., 2022), the integration of collaborative robotic systems not only gives workers direct access to advanced automation but also offers interactive assistance and ergonomic support, resulting in better working conditions and greater efficiency. By combining the high productivity of robotics with the flexibility and adaptability of human workers, this approach opens the door to innovative manufacturing solutions that help reduce physical strain, ease psychological stress, and address on going labor shortages in the industry.

According to the (Keshvarparast et al., 2024) at the core of this transformation lies collaborative robotics or robots specifically designed to work safely and efficiently alongside human operators. These robots come equipped with advanced sensors, AI-driven motion control and built in safety features that enable them to share workspaces with people. This promotes greater cooperation, efficiency and flexibility across a range of industrial environments. Unlike traditional industrial robots which are typically confined to fenced-off areas for safety, robots are built to operate directly alongside human workers. They assist with tasks that demand precision, endurance and repetitive accuracy, freeing humans to concentrate on making thoughtful decisions, being creative and solving problem effectively (Coronado et al., 2022). In addition, their ability to be easily reprogrammed and redeployed makes them highly adaptable to changing production needs enhancing agility in modern manufacturing (Khan et al., 2023, pp. 19–20). While robotics presents numerous advantages, its integration into the 5.0 industry workplace introduces several challenges such as:

- Ensuring safety and shared workspaces.
- Improving how tasks are shared between humans and robots to make the most of each.
- Building worker trust and acceptance of robotic collaboration.
- Addressing ergonomic and cognitive workload concerns.

Therefore, this study aims to explore how human robot collaboration can be optimized in an industry 4.0 environment to boost efficiency, ensure safety and build trust in collaborative settings. Nevertheless, this study adopts a pragmatic research philosophy that combines both positive and interpretivist approaches. At the outer layer of the research onion, a deductive approach is used where theoretical models such as the 5C model and safety-performance trade-off are tested through empirical data. Methodologically, it follows a mixed-methods strategy combining qualitative insights from case studies and interviews with quantitative survey data and experimental settings. This combination ensures a holistic understanding of human-robot interaction within Industry 5.0.

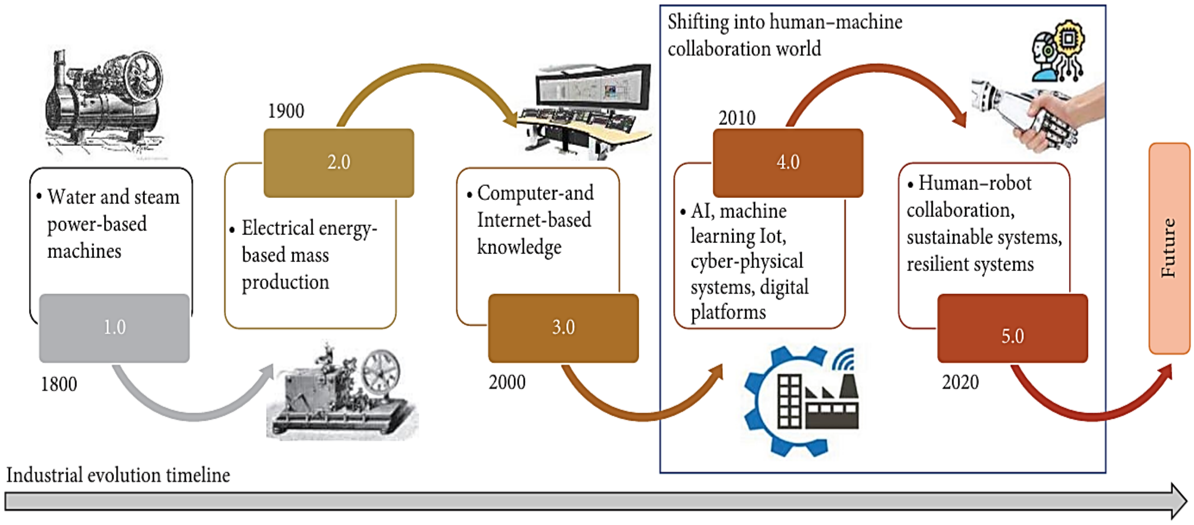

Figure 1. The transition from industry 1.0 to industry 5.0. Adapted from (Robla-Gómez et al., 2017)

1.2. Problem Statement

The increasing the growing use of collaborative robots in the industry 5.0 era raises a fundamental question: How can collaborative robotics be optimized in Industry 5.0 to boost efficiency, safety, and machine coexistence?

HRC (cobots) offers several advantages including improved productivity better safety standards, streamlined operations and enhanced worker well-being. However, their successful integration into industrial settings is not without challenges. While the promise of Human-robot collaboration (HRC) is strong real-world implementation reveals several limitations that require attention to maximize the benefits.

- Minimizing risks associated with proximity human-robot interaction without sacrificing operational efficiency.
- Ensuring cobots adapt to dynamic industrial processes without disrupting workflow and production environments.
- Developing strategies to enhance worker trust and usability of robotic systems.

- Overcoming limitations such as limited payload capacity, restricted speed under safety constraints, and sensitivity to environmental changes.
- Managing inertia-related risks, especially in shared workspaces where quick response to human motion is critical.
- Addressing programming complexity and the steep learning curve for non-expert operators.

This research recognizes that seamless human-robot coexistence is essential for Industry 5.0, requiring an interdisciplinary approach that combines robotics artificial intelligence, ergonomics, and industrial safety standards. This study assesses existing limitations and proposes optimized solutions for integrating cobotics effectively into modern industries.

1.3. Interdisciplinary Nature of the Study

This research study sits at the intersection of multiple disciplines reflecting the complex and the ongoing development of (HRC) in the context of industry 5.0. This research lies at the intersection of multiple disciplines that contribute directly to the findings and analysis.

- **Ergonomics and Human Factors:** Guides the assessment of worker comfort, trust, and fatigue through observational and survey data.
- **Robotic Engineering:** Addresses the design and performance of collaborative robots in industrial workflows.
- **Industrial Management:** Frames the deployment of HRC systems within organizational processes and operational efficiency model.

These fields are central to the development and validation of the proposed HRC framework presented in this study.

1.4. Research Questions and Objective

This research aims to maximize the performance of collaborative robotic systems while maintaining safety standards in an Industry 5.0 environment. This study is motivated by the efficiency limitations in human-robot collaboration where stringent regulations often lead to reduced operational velocity and longer cycle times. By integrating human-in-the-loop considerations, this research seeks to develop novel control methods optimization strategies and adaptive robotic systems that balance efficiency, flexibility, and safety in collaboration workbenches. So, this study aims to help improve performance while keeping safety a top priority.

- To develop a framework for safe and efficient HRC.
- To evaluate the impact of interaction dynamics on productivity and safety.
- To provide recommendations for integrating HRC into the Industry 5.0 environment.

The questions constructed for this study are as follows:

- What interaction dynamics are critical to optimizing both safety and productivity in an Industry 5.0 environment?
- How do task allocation and safety measures influence successful HRC implementation in an Industry 5.0 industrial environment?
- How can safety protocols be optimized without compromising efficiency?

The research objectives are designed to tackle the research questions. Each objective connects to sub questions, which together help answer the main research questions.

1.5. Significance of the study

As industry 5.0 takes off humans and smart robots are teaming up more than ever to get work done. The study is significant because it addresses the crucial challenges of how humans and robots can work collaboratively in shared environments while ensuring optimal performance and safety. This research adds to academic knowledge by addressing a gap in understanding how humans and smart machines interact in the world of industry 5.0 while prior studies have primarily focused on automation and technology efficiency.

This study focuses on finding the right balance between technology and putting people first as a key part of industry 5.0. When it comes to real world applications, the study provides valuable insights for industrial engineers, system designers, safety managers, and decision makers involved in deploying collaborative robotic systems. By identifying key interaction patterns, risk factors, and strategies for effective human-robot collaboration.

The research supports the development of smarter, safer, and more responsive industrial ecosystems. Furthermore, the findings may influence policy and standard development in robotics workplace safety and human-machine interface design particularly in emerging and technologically evolving industries. Ultimately, this study supports a future in which technology serves not just efficiency, but also human well-being, creativity, and trust.

1.6. Thesis structure

This study is structured into five chapters, each addressing a key aspect of the study on human-robotic interaction (HRI) in Industry 5.0. The chapters are arranged systematically beginning with the research background and progressing through the literature review, theoretical framework, methodology, results, discussion and conclusion. Figure 2 shows the structure of this study helping to clearly explain the challenges and opportunities in collaborative robotics (cobots).

Figure 2. Structure of the thesis.

2. Literature Review

In this research study, the integration of collaborative robotics (cobotics) into industrial environments has redefined the relationship between cobots particularly with the emergence of industry 5.0. According to the (Kyrarini et al., 2019) industry 4.0 is all about full automation and smart cyber physical systems while industry 5 .0 shifts the focus to human robot collaboration making sure robots support and enhance human skills instead of replacing them. As cobots become increasingly common in manufacturing, healthcare, and logistics, challenges related to safety, efficiency, trust and adaptability have emerged (Haddadin & Croft, 2016). He also claimed that ensuring seamless integration while maintaining productivity and workplace safety requires a balance between advanced robotics technology, human factors and regulatory compliance. This study provided a comprehensive review of key research areas in robotics including safety standards, task allocation strategies, cognitive ergonomics and trust in human-robot collaboration. It explores new tech breakthroughs and shows where current research falls short, helping set the stage for this study.

2.1. Evolution of human-robot collaboration (HRC)

The human-robot collaboration (HRC) has come a long way reflecting how industries, technologies, and society have evolved over time (Aaltonen et al., 2018; Adel, 2022). What started with basic automation has now grown into the advanced and dynamic interactions today in industry 5.0 (Hu et al., 2023). This journey highlights how far HRC has progressed the key technologies that have shaped it and the major milestones that have marked its development. The story of HRC begins in the 1960s, when the first industrial robots like the famous unimate were introduced (Burden et al., 2022). These early machines were built to handle repetitive or dangerous tasks, mainly in factories. Their main goal was to make work more efficient and to protect people from hazardous environments (Rosenstrauch et al., 2018). According to (Weiss et al., 2021), industry 4.0 often called the fourth industrial revolution marked a major turning point in how industries operate. It brought together cyber-physical systems, the internet of thing (IoT) and advanced data analytics, transforming traditional manufacturing and leading to rise of smart factories (Khan et al., 2023). In these modern factories machines and systems can communicate with one another and even make decisions on their own. Cyber-physical systems make it possible to monitor and control manufacturing in real time, while IoT devices ensure smooth communication between machines, systems, and human workers (Panagou et al., 2024). By using advanced data analysis and machine learning production was improved and maintenance needs could be predicted ahead of time (Soori et al., 2023). Despite the increased automation the interaction between humans and robots remained limited during this industry era. Robots were still largely isolated from human workers due to safety concerns and the primary focus was on improving efficiency and reducing costs, often at the expense of human-centric consideration (Taboada et al., 2023). The limits of traditional industrial robots and industry 4.0 opened the door for collaborative robots or cobots. These robots are designed to work right alongside humans, making teamwork and interaction much easier (Galin & Meshcheryakov, 2019).

Industry 5.0 marks the next stage in the evolution of industrial systems focusing on human-centered manufacturing and blending of human creativity with the precision of robots. While industry 4.0 focused on automation and improving efficiency but in industry 5.0 shifts the spotlight toward collaboration, personalization and sustainability (Panagou et al., 2024). This new phase puts people at the core of manufacturing , recognizing the importance of human creativity, judgment and problem solving (Raza Moosavi et al., 2022). The goal is to create a strong partnership between humans and machines with collaborative robots or cobots playing a key role in making that possible (Leng et al., 2022). At the same time, industry 5.0 continues the push for more sustainable industrial practices, aiming to reduce environmental impact and support greater social responsibility (Galin & Meshcheryakov, 2019).

In industry 5.0, collaborative robots known as cobots are designed to support and enhance human abilities, not replace them. With a strong focus on customization and flexibility this new industrial era makes it possible to produce highly personalized products and cobots play a key role in making that happen. They also contribute to more sustainable manufacturing by helping reduce energy use and minimize waste (Pizoń et al., 2022). According to the (Leng et al., 2022, p. 30) major technological advancements have been vital to the development of human -robot collaboration (HRC). These innovations have helped shift from traditional industrial robots to more advanced human-friendly cobots paving the way for industry 4.0 and beyond. Key technological include advanced sensing and perception systems like force/torque sensors, vision systems and proximity sensors that allow cobots to understand their surroundings respond to external forces and avoid collisions (Hu et al., 2023).

Artificial intelligence and Machine learning are helping cobots become smarter and more adaptable. These technologies allow cobots to learn from how humans work, adjust to new environments and improve how tasks are assigned and scheduled overtime (Galin & Meshcheryakov, 2019). The introduction of 5G and IoT connectivity has made real-time communication possible between cobots, human operators and other devices boosting both coordinate and efficiency (Qu et al., 2024). To make cobots more accessible especially for people without technical backgrounds, user-friendly tools like teaching pendants, graphical user interfaces and even augmented reality interfaces have been developed. These tools make interacting with cobots more intuitive and approachable (Haddadin & Croft, 2016). The development of human-robot collaboration (HRC) has also been shaped by a number of important milestones. One of the earliest was the introduction of the first industrial robots in 1960s including the unimate which marked the start of the industrial automation era (Franzel et al., 2021).

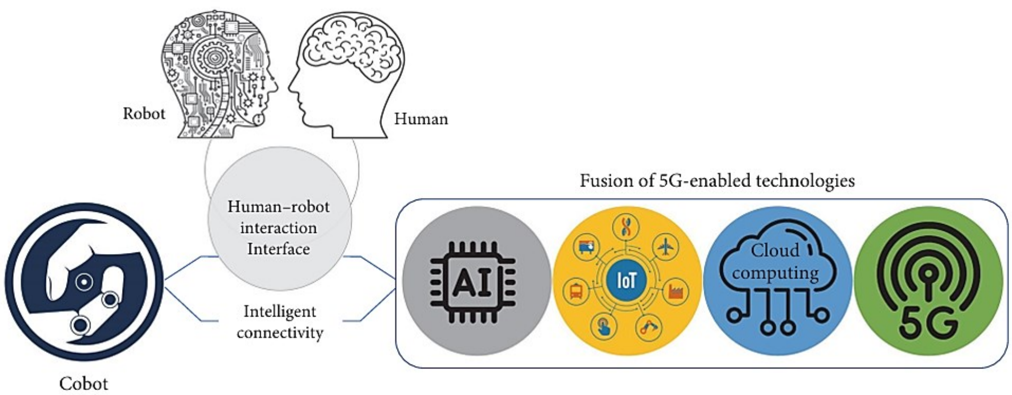

Figure 3. 5G and intelligent technologies enable by human and cobot framework. (Ionescu et al., 2020)

The 1990s saw a major step forward in industrial safety with the introduction of standards like ISO 10218 which set clear guidelines for the safe use of industrial robots (Matthias & Reisinger, 2016). In the 2000s, the arrival of collaborative robots like the UR5 from universal robot marked a turning point in human-robot collaboration (Bounouar et al., 2022). By the 2010s, the rise of industry 4.0 brought cyber physical systems the internet of things and advanced data analytics into manufacturing, transforming traditional production lines into smart, connected system (Sadeghi et al., 2017). Now, in the 2020s, the shift toward industry 5.0 is taking shape focusing on human-centered manufacturing and closer collaboration between people and machines (Galin & Meshcheryakov, 2019).

Even with all the progress in human robot collaboration (HRC) there are still important challenges that need attention before their full potential can be reached. One of the biggest concerns is keeping human worker safe while sharing workspaces with robots This calls for ongoing improvement in safety standards and technologies to help prevent accidents and injuries (Ahmed et al., 2022). There are also ethical questions to consider such as the risk of job displacement and concerns around data privacy To address these issues, clear legal frameworks and guidelines are needed to ensure cobots are used responsibly in industrial environments (Li et al., 2018). On a practical level integrating cobots with existing manufacturing systems, especially older machines, can be both complex and expensive. Component coherence and system communication issues must be resolved to allow for smooth and efficient integration (Burden et al., 2022). Adopting collaborative robots often requires a skilled workforce that can program, operate, and maintain these advanced systems. To close the skill gap there is a growing need for targeted training and education programs that prepare workers for this shift and support the successful rollout of human robot collaboration (HRC) in industry (Taboada et al., 2023). It's also important to look beyond the technology itself and consider the broader impact of HRC. Ongoing research is needed to understand how it affects job roles, workplaces dynamics and overall social well-being. Assessing the long-term economic and social effects of HRC will help ensure that this transformation benefits both industry and its workforce (Bounouar et al., 2022).

2.2. Safety Standards in HRC

Safety is a fundamental aspect of cobots collaboration particularly in workplaces where cobots operate contribute. According to the (Fu & Zhao, 2021), the growing use of collaborative robots (cobots) in industrial environments has made it essential to develop clear safety standards and protocols. These measures are designed to protect human workers while also maintaining high levels of efficiency on the production floor. Explores the key safety standards in HRC, the mechanism that ensures safe interaction and the challenges associated with implementing these standards (Ionescu et al., 2020). So, the main goal of HRC is to enable cobots to work together seamlessly leveraging the strengths of both. However, this collaboration introduces potential risks such as collisions, mechanical failure and unintended interactions. Ensuring safety in HRC is critical to preventing accidents, injuries and downtime while also fostering relationship of trust between workers and robotic systems (Proia et al., 2022). Safety standards provide guidelines detailed in Figure 4 that are eventually used for designing, implementing and operating cobots in a way that minimizes risks and ensures compliance with regulatory environment requirements (Rosenstrauch & Krüger, 2017).

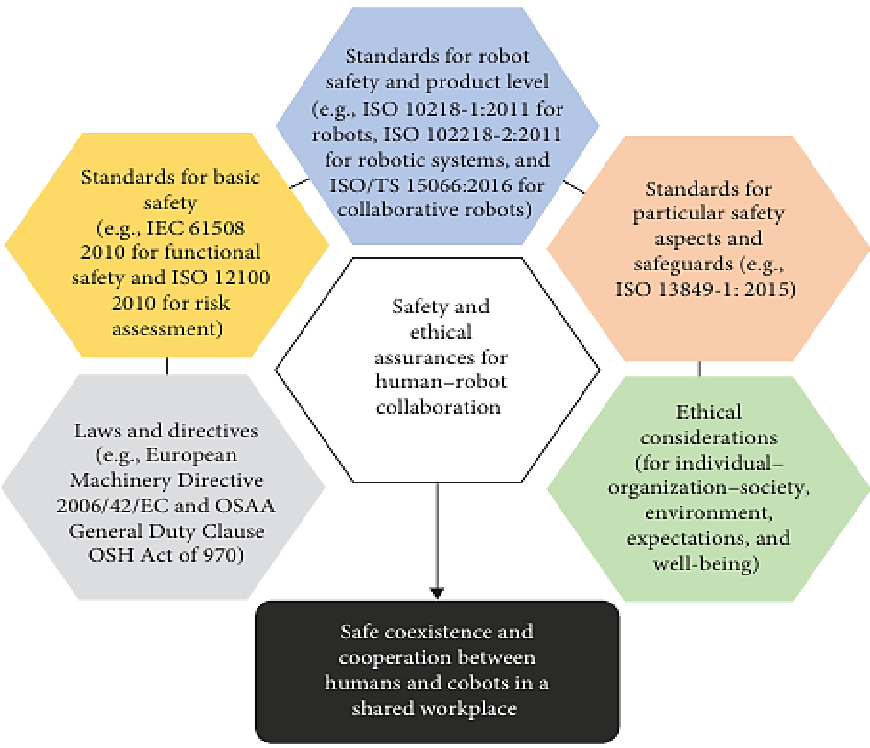

Figure 4. Safety Standard & ethical considerations for work in the cobotic system (Pauliková et al., 2021).

Several international standards have been developed to address the safety requirements of HRC. ISO 15066 is a widely recognized standard that outlines the safety requirements for industrial cobots. It covers aspects such as risk assessment, safety-rated monitored stops and protective measures (Faroni et al., 2022). He also commented that risk assessments are conducted to identify potential hazards and safety-rated monitored stops are implemented to halt robot operations in case of emergencies. Protective measures, such as barriers and safety zones are also used to prevent unauthorized access to robot workspaces. For HRC, the deployment of a collaborative system is categorized into several operational modes as outlined in ISO/TS 15066.

These Include:

- **Trusted safety stop**

  The robot automatically stops moving when a person steps into it workspace, keeping everyone safe.
- **Guided by hand**

  A human operator can manually move the robot using direct input often facilitated by a dead man’s switch for safety.
- **Safety movement control**

  A robot moves only if it maintains a minimum distance from human and doesn’t go faster than a set speed limit.
- **Power and force limiting**

  The robot is designed to stay gentle by limiting force and pressure if it ever meets a person.

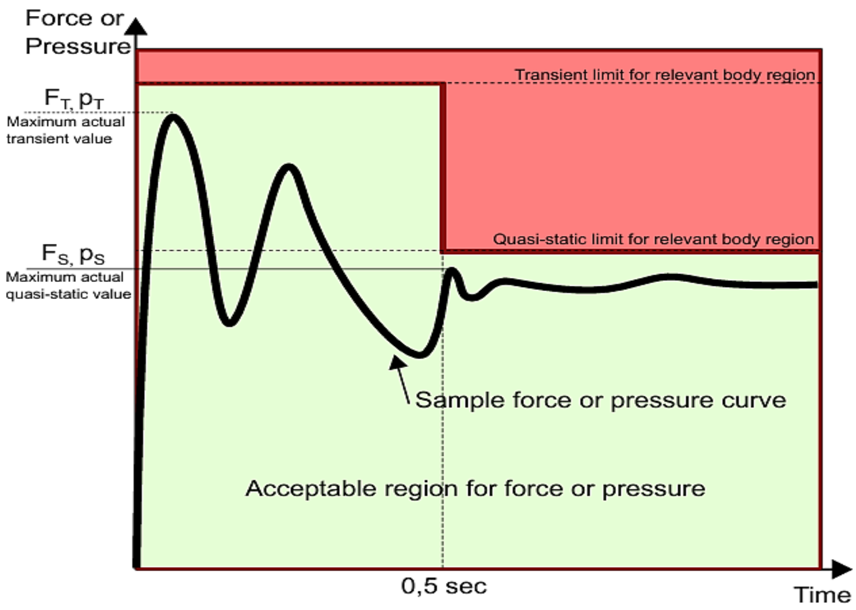

Figure 5. Limits on force and pressure. Adapted to ensure safe human interaction (Aalerud & Hovland, 2020).

To keep people safe, collaborative robots (cobots) are designed with strict limits on how they operate. For example, their top speed to 0. 23 meters per second the force they can apply is capped at 149 newtons, and they can't exceed 79 watts of dynamic power. These limits are important, they help make sure that if a robot and a person come into contact the risk of injury stays very low. As working alongside robots has become more common, international safety standards have been created to guide how this should happen. In 2016, the International Organizational for Standardized (ISO) released a technical guideline called ISO/TS 15066. This document layout clear rules for designing safe collaborative systems including how much force or pressure is acceptable if a robot accidentally bumps into a person (Vorndamme et al., 2025). This standard also defines two types of collision that can happen between a robot and a human:

- Transient contact (Fast contact): Brief, Dynamic Impact
- Quasi-Static (Slow Contact): Prolonged, Static Impacts.

Figure 5 above shows the difference between the two types of contact a robot can have with a person. To make things even safer, ISO/TS 15066 also sets clear limits on how much force and pressure can be applied to different parts of the human body, these are shown in Table 1. These limits help ensure that if contact does happen it stays within safe levels and doesn't cause harm to the person.

Table 1. ISO/TS 15066 (Lasota et al., 2017).

Body parts	**Specific body part area**	**Slow contact**		**Fast contact**	
		Max Pressure for (slow contact) ɑ *N/cm²*	Max Force for (slow contact) ƀ *N*	Pressure Limit multiplier for (fast contact) ç PT	Force Limit multiplier for (fast contact) ê FT
Head -front	Middle of forehead	120	120	No needed	No needed
	Temple area	100		No needed	
Part of Face	Jaw muscle	100	55	No needed	No needed
Part of Neck	Side of the neck	130	140	2	2
	Lower back neck muscle	200		2	
…….	……..	………	………	……..	………..

These safety standards are the backbone of this thesis especially when it comes to designing and testing human in the loop control systems building the robots hardware and evaluating how safe and effective cobot (Matthias & Reisinger, 2016). The latest developments in robot path planning, predicting human movement and avoiding collisions. One of the most important safety references is ISO/TS 15066 which outlines how to operate collaborative robots safely. Its focuses on key aspects like limiting force and speed and using safety focused sensors and control systems (Xiong et al., 2020). Cobots are specifically built to move more slowly and gently when working near people. That's why, if they accidentally bump into someone, the chances of injury are very low. They are also equipped with detect when a person is nearby and adjust their behavior to stay safe.

In the U.S. industrial robot safety standard is the main safety standard for industrial robots. It works alongside the international standards ISO 10218 and adds extra guidance for things like risk assessments and safety system design (Keshvarparast et al., 2024). This standard highlights how important it is to have reliable emergency stop systems and control mechanisms that can handle safety issues quickly and effectively (Chander et al., 2022). While this EN ISO 13849 gives rules for making sure robotic systems and other machinery have properly designed safety control. It covers components like safety relays and controllers that are essential for keeping operation safe. Altogether, these safety standards help to ensure that collaborative robots are built with smart and responsive safety systems, slowing them to work closely with humans while keeping everyone protected. One such mechanism is force and speed limiting which ensures dashboards operate at reduced speed and force when working near humans. This minimizes the risk of injury in case of accidental contact. Another critical mechanism is collision detection and avoidance which relies on advanced sensors such as force/torque with the help of proximity sensors the robots sense obstacles and changes how it moves to steer clear (Panagou et al., 2024). Safety-rated monitored stops are also implemented to halt robot operations in case of emergencies or when a human enters a restricted zone which is shortly summarized in Table 2.

Table 2. Key Safety Standards and their features (Kyrarini et al., 2019)

Standard	Description	Key Features
ISO 10218	Guidelines for safe robot operation	Safety risk check, Safety-rated stops, protective measures
ISO 15066	Guidelines for collaborative robots' safety	Force and speed limitations, safety-rated sensors, and collaborative operation modes
ANSI/RI AR15.06	Industrial robot safety (US standards)	Risk assessment, safety-rated control systems, emergency stop functions
EN ISO 13849	Safety of machinery	Performance Level, Safety Components, Validation, and Verification.

Cobots also support hand guiding and teaching modes which allow human operators to physically move the robot through the desired task at low speed and force. These moves are beneficial for programming cobots and ensuring safe interaction during setup and operation. Furthermore, the researcher (Soori et al., 2023) protective measures such as physical barriers, safety zones and warning signs, are used to prevent unauthorized access to cobots workspaces and ensure safe operation. Despite the availability of safety standards and mechanisms, challenges remain in implementing HRC safely and effectively. One big challenge is figuring out the risks it means spotting anything that could be dangerous, understanding how serious it might be, and putting the right safety steps in place (Fu & Zhao, 2021).

Another challenge is getting cobots to work smoothly with older systems already in place. Its not just about plugging them in they have to be compatible able to communicate with each other and still meet safety standards (Haddadin & Croft, 2016). Human factors are also a big part of the safety equation. Things like how well operators are trained, how they behave and how aware they are of their surroundings can all make a big difference. If worker don't get proper training or aren't fully aware of how to work with cobots, accidents and injuries are more likely to happen (Proia et al., 2022). Beyond safety there are also ethical and legal questions to consider like whether robots might replace human jobs or how data collected by robots is handled. These concerns needs to be taken seriously to ensure that robots are used responsibly in industrial environments (R et al., 2023).

2.3. Task Allocation and Ergonomics in HRC

Human-robot collaboration (HRC) is becoming a game-changer across many industries blending the unique abilities of people and robots to boost productivity, safety and efficiency. According to the (Panagou et al., 2024) the success of these collaborations largely hinges on two key elements: task allocation and ergonomics. Task allocation is about deciding which task is better handled by robots and which are more suitable for humans. On the other hand, ergonomic focuses on creating a work environment that supports human comfort, safety and overall well-being (Xiong et al., 2020). Understanding how task allocation and ergonomic work together is essential for building truly effective cobots systems. These principles have far reached application and implications for designing workflows where both humans and robots can thrive. Table 3 below provides a comparison of the strengths of human and collaborative robots (cobots) within specific areas of industrial processes highlighting how each contributes to the workflow.

Table 3. Comparative strength of humans and robots in industrial settings (Ghobakhloo et al., 2023)

Task Type	Human Strengths	Robots Strength
Decision-Making	Creativity, Intuition, Problem Solving	Algorithm-driven, limited flexibility
Precision Assembly	Dexterity, Fine motor skills	High-speed accuracy, Consistency
Heavy Lifting	Limited strength, Risk of Injury	Endurance, Force Control, No Fatigue
Repetitive Tasks	Prone of Fatigue and Loss of focus	24/7 Operation, maintain precision
Quality Control	Experience-Based Defect Detection	AI-powered image recognition, data analysis
Complex Problem Solving	Experience-based learning, Troubleshooting	Pre-programmed Optimization technique

2.3.1. Principle of Task Allocation in HRC

Task allocation means figuring out who human or robot is best suited for a particular job. It's all about playing to each one's strengths while making sure human workers aren't overloaded physically or mentally (Goodrich & Schultz, 2008). To do this well, it's important to really understand what people and robots do best and match those abilities to the demands of the task.

- **Repetitive and High-Precision Tasks for Robots**

  According to (Niu et al., 2022) robots are especially good at tasks that require repetition precision and consistency. In manufacturing, for example they can handle jobs like welding, painting or assembling parts with impressive speed and accuracy. This not only boots overall efficiency but also helps reduce mistake that might happen when humans get tired or distracted (Chander et al., 2022). By letting robots take care of these repetitive tasks human workers are free to focus on more complex thoughtful work that requires problem-solving and decision-making.

- **Heavy Lifting and Hazardous Tasks for Robots**

Robots are especially useful for jobs that involve heavy lifting or working in risky environments. In industries like automotive manufacturing or construction, they can move heavy materials operate in hazardous conditions or taken on tasks that might be dangerous for people (Kadir et al., 2018). This not only helps keep workers safe but also reduces the physical strain on them, making the workplace safer and more manageable overall.

- **Complex Decision-Making for Humans**

While robots are great at carrying out set tasks with speed and precision, they can't match humans when it comes to thinking on their feet or solving unexpected problems. Jobs that call for decision-making, creativity or flexibility are still best handled by people. Take quality control humans can spot flaws or irregularities that robots might mis (Aalerud & Hovland, 2020). This really shows how valuable human judgment and expertise are especially when people and robots are working together.

- **Flexibility and Adaptability**

Humans have a remarkable ability to adapt on the fly and come up with solutions in unpredictable situations. According to the (Qu et al., 2024) needs clear instructions and fixed rules to do their job well. That's why tasks that involve frequent changes or need quick thinking are usually better suited for people. For example, in a warehouse, robots can take care of repetitive work like moving boxes while humans' step in to handle exceptions like dealing with fragile shaped item that require a gentler more flexible touch.

2.3.2. Ergonomics in Human-Robot Collaboration

Ergonomics are all about making sure human worker can do their jobs comfortably and safely especially when working alongside robots. When workspace aren't designed with people in mind it can lead to strain fatigue and even long-term health problems which can hurt both productivity and morale (Landry & Bihlman, 2023). To avoid that, there are a few key ergonomic principles that help shape safer, more supportive human-robot collaboration.

- **Workstation Design**

  The way a workstation is set up plays a big role in keeping workers comfortable and productive. It's important that the workstation can be adjusted to fit people of different heights and body shapes. Tools and material should also easy to reach so workers don't have to stretch or move around too much (Hopko et al., 2022). For example, on an assembly line having adjustable work surfaces and ergonomic chairs can really help reduce physical strain and make it easier for workers to do their best.

- **Human-Robot Interaction**

  For humans and robots to work well together their interaction needs to feel natural and most importantly safe. Robots should be programmed to move in smooth, predictable ways avoiding sudden or jerky motions that might surprise or startle people (Burden et al., 2022). While, having sensors that can detect when a person is nearby help robots adjust their movements making the workspace even safer for everyone.

- **Reducing Physical Load**

  A big deal of ergonomics is to lighten the physical burden on humans' workers. Robots can help by taking on heavy or awkward tasks, so people don't have to strain themselves (Goodrich & Schultz, 2008). In manufacturing, robots can lift and move heavy parts while humans concentrate on the more precise and delicate work that requires careful touch.

- **Minimizing Cognitive Load**

  Ergonomic isn’t just about physical comfort, it also helps lighten the mental load on workers by making tasks simpler and cutting down on the number of decisions they have to make. Robots can pitch in by sharing real-time information or handling routine checks so people can focus on more important complex task (Kyrarini et al., 2019). This not only eases mental stress but also helps everything run more smoothly.

- **Safety Considerations**

  Safety always comes first when humans and robots work together. Robots need to have built-in safety features like safety stop buttons and collision-sensing technology to help prevent accidents. On top of that, the workspace should be set up to lower the chance of injuries things like clear walkways and keeping robots within safe zones make a big difference (Faroni et al., 2022). Table 4 below shows how AI can track human movements in real time to help robots adjust their actions, making work easier and safer for everyone.

Table 4. How AI helps make human-robot teams more comfortable and efficient (Keshvarparast et al., 2024)

AI-Driven	Function	Impact on Ergonomics
Motion Sensors	Tracks worker movements, Flags ergonomics risks	Reduce unnecessary repetitive motions
Wearable Fatigue Sensors	Monitors muscle strain and posture	Prevents long-term injuries and strain
Adaptive Robot Interaction	Adjust speed and force based on fatigue levels	Reduce stress, improve safety, & efficiency

2.4. Gaps in Literature

This research highlights several important gaps in the current understanding of human robot collaboration (HRC). Some of the big challenges show up in area like adapting to changing tasks, smooth interaction between humans and robots system integration worker acceptance, ergonomic design and even issues (Aalerud & Hovland, 2020). Industrial environments are constantly changing but many existing task allocation models can't adjust quickly when unexpected happens like a machine breaking down or a sudden shift in workflow. This limits the responsiveness and effectiveness of cobots in practical scenarios. Another challenge in human-robot interaction remains when cobots misinterpret human interaction or lack adequate feedback mechanisms, the result can be operational inefficiencies or even safety risks (Hopko et al., 2022).

This highlights the need for intuitive interfaces and real-time communication. Therefore, integrating cobots into legacy systems is often problematic. Many existing machines were not designed for collaboration, leading to interoperability issues and the fact that it can be expensive to implement particularly for small and medium sized companies (Behrens & Elkmann, 2014).

Worker acceptance is also crucial but remains underexplored. Fear of job loss, safety concerns, and unfamiliarity with robots can hinder adoption unless addressed through proper training, transparency, and a user-involved design process (Galin & Meshcheryakov, 2019) . Ergonomic challenges are also evident poorly designed system can contribute to physical strain and cognitive overload, whereas a thoughtful, ergonomic system enhances performance and comfort (Chebotar et al., 2017). However, ergonomic factors are not prioritized in system design. There are still big questions around ethics and law such as who's at fault if something goes wrong keeping data private and concerns about job being replaced. That's why clear regulations are needed to make sure robots are used safely and responsibly (Behrens & Elkmann, 2014). These gaps underscore the necessity of interdisciplinary research and a human-centered approach to enable more effective and trustworthy collaborative robotics in

Industry 5.0. Table 5 provides a summary of the main limiting factors that researchers have identified across different studies.

Table 5. Insights from researchers on HRC challenges.

Challenge	Description	Impact	References
Dynamic Environments	Frequent changes in tasks and Workflow require flexible task allocation.	Increased complexity and need for real-time adaptability.	*(Aalerud & Hovland, 2020)*
Human-Robot Interaction	Misunderstandings or delays in communication can lead to inefficiencies.	Risk of accidents and reduced collaboration efficiency.	*(Haddadin & Croft, 2016)*
Integration with Legacy Systems	Compatibility issues with existing systems increase implementation complexity	Higher Cost and Barriers for SMEs.	*(Xiong et al., 2020)*
Worker Acceptance	Fear of job displacement or lack of trust in robotic systems	Resistance to adoption and reduced collaboration effectiveness.	*(Bounouar et al., 2022)*
Ergonomic Design	Poor Design can lead to fatigue, injuries, and reduced productivity.	Negative Impact on worker well-being and performance.	*(Proia et al., 2022)*
Ethical and Legal Considerations	Job displacement, data privacy, and liability issues.	Need for clear regulations and ethical guidelines.	*(Witherell, 2023)*

3. Theoretical Framework

Bringing collaborative robots (cobots) into industry 5.0 depends on a solid foundation of ideas that cover how humans and robots interact, how to keep workspace safe and comfortable and how to balance safety with performance. While industry 4.0 which focused mainly on full automation, Industry 5.0 is all about creating a productive partnership between people and machines making sure both safety and efficiency are prioritized in industrial settings (Langås et al., 2025). To make this shift successful, it’s important to build on clear structured concepts like sharing ergonomic design trust in automation and the trade-offs between speed and safety.

Several well-established theories are helping shape how cobots are being developed for industry 5.0. The 5C model of human robot interaction layout different levels of collaboration between human and robots from simply working side by side to more advanced, co-evolving system (Kadir et al., 2018). The safety performance trade-off model explains how to strike the right balance running operations efficiently and keeping workers safe. Then there's the cognitive ergonomic framework, which focuses on things like mental workload trust and how well people can interact with AI-driven machines (Qu et al., 2024). Tools like digital twin simulations also play a big role. These allow companies to test and fine tune human-robot interaction in a virtual setting before bringing them onto the factory floor (Boschert & Rosen, 2016). This helps in refining who does what improving safety and making sure ergonomic standards are met (Xiong et al., 2020) . Together, these models and tools provide a well-rounded guide for designing smart human-centered workspace ones that not only get the job done efficiently but also support the well-being of the people involved.

3.1. Human-Robot Interaction (HRI)

Human-robot interaction (HRI) is all about how people and robots work together in shared spaces. The aim is to make that collaboration as smooth and natural as possible boosting productivity without sacrificing safety, efficiency or flexibility (Lasota et al., 2017). With the rise of industry 5.0 which focuses more on human-centered automation, HRI has evolved. It's no longer just about programming robots to do tasks but about creating systems that can adapt respond and work safely right alongside people.

According to the (El Zaatari et al., 2019) traditional industrial robots were usually kept separate from humans often behind safety fences. However, today's collaborative robots or cobots are built to work directly with humans. That shift calls for new HRI models that support real-time decisions to build trust and consider how people think and interact with machines. These updated models offer structured ways to understand how tasks can be shared between humans and robots, how they can communicate and how to get the best performance from both while keeping the workplace safe and efficient.

3.2. The 5C Model of Human-Robot Collaboration

This research used the 5C model of human-robot collaboration (HRC) (Proia et al., 2022), as a key framework for exploring how human-robot interaction develops overtime. The model fits well with the goals of industry 5.0 which focuses on creating human centered automation and encouraging smooth cooperation between people and machines in shared workspaces. The 5C model shows how robots have progressed from basic passive tools to smart adaptable partner that can grow and evolve alongside human workers. Each stage connection, coordination, collaboration, cognition and coevolution marks a step forward in how deeply humans and robots work together improving both interaction and adaptability as the relationship becomes more integrated (Kumar et al., 2021).

In the first stage, human connections and robots are in the same workspace but they operate independently. There is little to no interaction between them, and safety is mostly maintained by keeping them physically apart using barriers or designated zones. As we move to coordination, robots and humans working toward a common goal, through their tasks remain distinct. This stage focused on planning what flows were human, and robot actions would support each other. In the collaboration stage, the boundary narrows further, humans and robots perform shared tasks, adjusting roles dynamically and contracting in real time. The fourth stage, cognition, is where robots start adapting to human physical and cognitive needs. They use data from their environment and from humans like posture, fatigue, or stress to adjust their behavior and offer support, reducing strain and improving comfort. Finally, co-evolution is the most advanced stage, where robots continuously learn from human feedback and experience. Here, the collaboration becomes truly adaptive and personalized, with both humans and robots evolving together over time to improve performance and safety. Therefore, this model is particularly relevant in next industry evolution, where the main focus is now from replacing humans and enhancing human capabilities through intelligent empathetic technology.

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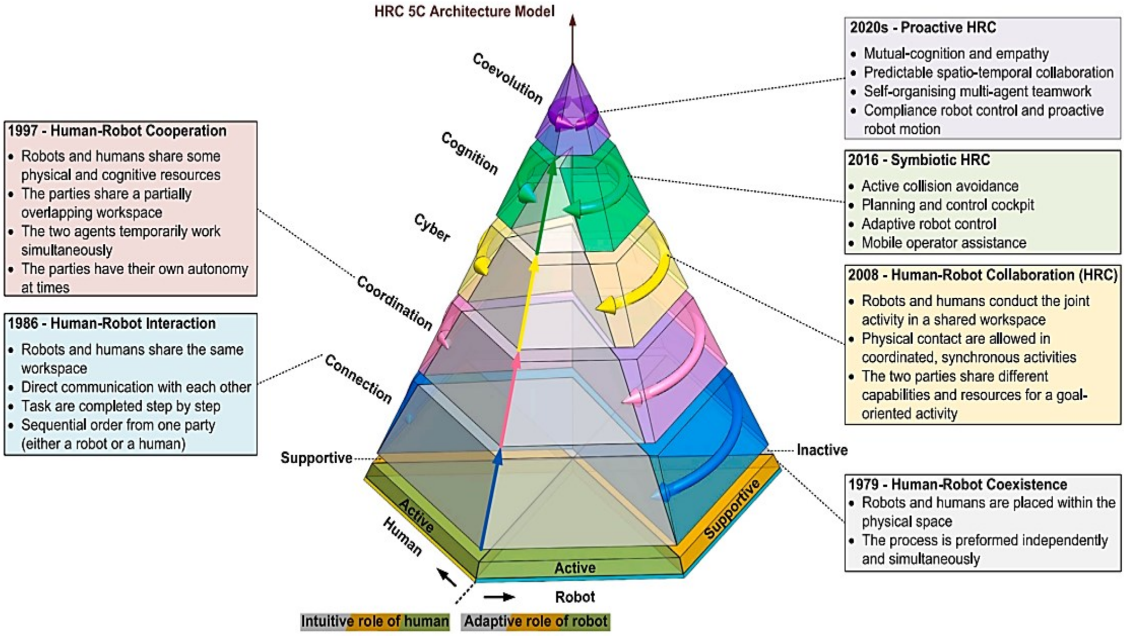


Figure 6. An evolution pathway towards Proactive HRC of 5C model. Adapted from (Pauliková et al., 2021).

3.1. Safety-Performance Trade-Off in HRI

A major challenge in human robot interaction (HRI) is balancing safety and performance in industrial settings. Robots are designed to enhance efficiency, speed, and precision, but their interaction with human workers introduces safety concerns (Goodrich & Schultz, 2008). If robots operate at high speeds and full force, they risk injuring human operators. On the other hand, when robots slow down or use less force to stay safe, it can slow down the whole production process and reduce efficiency (Haddadin & Croft, 2016). This challenge called the safety-performance trade-off means manufacturers hace to strike the right balance between keeping workers safe and maintaining high productivity (Lippi & Marino, 2020). In industry 5.0 this is balance is made possible through AI -powered safety features smart speed adjustments and real-time monitoring of human workers. These tools help robots adapt their actions on the spot depending on where people are used what they are doing (Langås et al., 2024).

3.1.1. Balancing safety and performance in human robot interaction

The safety-performance trade-off comes from the fact that safety and efficiency often work against each other. Here are the main ways this relationship plays out:

1. **Higher Speed & Efficiency = Increased Risk**

Robots built for quick, precise work usually run at full speed and power, which can raise the chances of accidental collision bumps and even workers get tired more quickly. Without smart safety features that can adjust on the fly cobots might accidentally lead to workplace accidents mistakes or stress for the people working alongside them (Coronado et al., 2022).

2. **Lower Speed & Force = Safer, But Less Efficient**

If robots are programmed to slow down excessively for safety, they reduce overall productivity. Workers may feel frustrated with longer cycle times, and companies may experience lower output, increased costs, and inefficient workflow integration.

3. **AI-Driven safety = Optimized Performance & Risk Reduction**

To balance this trade-off, industry 5.0 adopts AI-based safety measures, allowing cobots to:

- Adjust speed and force dynamically based on real-time data.
- Predict and avoid collisions using motion sensors and AI algorithms.
- Provide haptic and visual feedback to notify workers of potential risks.

By leveraging AI-driven safety mechanisms, robots can maintain high productivity levels without compromising worker well-being.

3.2. The Safety-Performance Trade-Off Model

The Safety-Performance Trade-Off Model explains how different robotic settings impact efficiency and risk levels. This model is widely used in manufacturing, logistics, and healthcare robotics, where human-robot collaboration is essential (Lasota et al., 2017). He also claimed that it highlights the inverse relationship between safety and performance: as safety measures increase, efficiency often decreases, and vice versa. In this section, we explored the theoretical foundations of the model, its practical implications, and strategies to resolve this trade-off using advanced technologies like AI and adaptive systems.

In the dynamics and safety (Lippi & Marino, 2020), key concerns with humans and robots working together in industry robots bring advantages like speed, precision, and power, while humans contribute intelligence, flexibility, and dexterity. Both humans and robots have challenges. Robots can sometimes stop unexpectedly slowing down production, while humans might worry about safety or have trouble trusting the machines. When they work together on busy industrial lines with unpredictable movements and changing obstacles, there are real risk of accident like collisions or injuries (Niu et al., 2022). To tackle this, two main safety strategies are used, Pre-collision strategies rely on sensor, prediction models, and careful motion planning to stop accidents before they happen (Sadeghi et al., 2017). While post-collision strategies focus on minimizing the impact if a collision does occur, using things like force control and flexible compliance. By combining both approaches human robot teams can work together more safely and efficiently.

3.2.1. Theoretical Foundations of the Safety-Performance Trade-Off

The safety-performance trade-of model is based on the idea that making robots safer usually means they have to slow down, keep more distance from people and follow tighter rules (Burden et al., 2022). While these step helps prevent accidents they can also slow down production and lower efficiency. However, focusing on speed and cutting back on physical barriers can boost productivity but it might put worker’s safety at risk (Lippi & Marino, 2020).

- **Safety Compliance**

According to the (Soori et al., 2023) measures like slowing down robots speed, limiting their force, and using physical barrier help keep worker safe but they often mean tasks take longer to complete. I.e. A cobots operating at a slow speed to avoid collisions with human workers.

- **Performance Optimization**

According to the (Coronado et al., 2022, p. 11) maximizing efficiency through faster robot speeds, closer human-robot interaction, and streamlined workflows can increase productivity but may raise safety risks. For example, a cobot working at high speed to finish tasks faster can also raise the chance of accidents happening.

- **Adaptive Systems**

Technologies such as AI, machine learning and real time monitoring help robots work smarter and effectively adjust their actions on the fly, finding the right balance between safety and efficiency (Niu et al., 2022). For example, a cobot might slow down when a person is close by and speed up again once the area is clear.

3.2.2. Balance Safety and Efficiency with help of Artificial Intelligence

To tackle this trade-off industry 5.0 uses AI-powered safety systems that let robots adjust how they behave in real-time based on what's happening around them (Aalerud & Hovland, 2020). For example, a cobot on an assembly line can use sensors and AI to keep track of where people are. If a worker steps into the robot's workspace the cobot will slow down or stop to keep things safe (Ghobakhloo et al., 2023). Then, as soon as the worker moves away the cobot speeds back to keep productivity high.

Advantages of AI-Driven Solutions

- **Real-Time Adaptation:**
  Robots can change their speed and strength on the spot keeping people safe while still working efficiently.
- **Predictive Safety:**
  AI can spot possible dangers before they happen and act like stopping or changing the robot's path to avoid accidents.
- **Enhanced Worker Confidence:**
  When robots respond and adapt in real time, workers feel safer and more comfortable working alongside them.

Outcome:

- **Increased Productivity:** Faster task completion with minimal downtime.
- **Improved Safety:** Reduced risk of accidents and injuries.
- **Optimized Workflows:** Smooth teamwork between people and robots

The safety-performance trade-off is a key challenge when humans and robots work together especially on manufacturing assembly lines. Putting safety first creates a secure workplace but can slow down production. On the other hand, focusing on speed and efficiency can boost output but also raise the risk of accidents. Thanks to AI-driven safety systems industries can now strike a better balance letting robots work quickly without compromising work safety (Langås et al., 2024, pp. 4–7). This technology helps create a smoother, more productive work environment which is a core idea behind industry 5.0, where collaboration between humans and robots is both efficient and centered around people.

3.2.3. Advanced Solution for Safer and Smarter Collaboration

The safety-performance trade-off industry 5.0 relies on cutting-edge technologies like AI, machines learning and real time monitoring. These tools allow robots to adjust their behavior on the fly based on what's happening around them, so they can stay safe without slowing down work (Ghobakhloo et al., 2023). One important method is real-time AI adaptation, where robots change their speed, force and movements depending on how close people are and what they are doing. For example, a cobot on an assembly line might slow down when a worker enters its area and speed up again once the space is clear keeping safety and productivity in balance.

Another key approach is predictive safety monitoring. Here AI predicts possible dangers and acts beforehand like stopping or changing the robot's path to avoid accidents. (Faroni et al., 2022). Haptic and visual feedback systems also play a big role in keeping workers alert and safe. Robots can send out warnings, like signal before moving fast, so worker always know what the robot is about to do (Pauliková et al., 2021). Personalized safety settings help robots adjust to each worker's preference and comfort levels, making the workplace safer and more comfortable. For example, a cobot can change its height or speed to fit a worker's ergonomic needs which reduces strain and boosts well-being (Kokkalis et al., 2018).

All these advanced technologies work together to help robot's operate smoothly while keeping worker safe, effectively solving the safer-performance trade-off (Heredia et al., 2020). By combining AI-driven safety features, predictive monitoring real time feedback and personalized settings industries can create a workplace that both productive and centered around people exactly what industry 5,0 aims for in human robot collaboration.

4. Trust in Robots and Cognitive Ergonomics

The introduction of collaborative robots or cobots into industrial workplace has changed how humans and machines work together. But their success isn't just about how advanced the cobots are technically it depends on how well they fit with human mental processes and comfort needs (Vorndamme et al., 2025). Two important factors in making these systems work well are cognitive ergonomics and trust. Cognitive ergonomics ensures cobots are designed and operated to reduce mental strain improve the user experience and support worker well-being while trust makes sure worker feel safe and confident when working alongside cobots (Doyle-Kent, 2021, pp. 11–12). Together, these elements build te foundation for smooth, productive teamwork between humans and robots key to achieving safety and high performance in industry 5.0 (Heredia et al., 2020). According to the (Aalerud & Hovland, 2020) focuses on how humans interact with robotic systems mentally covering decision-making problem solving and processing information. For cobots this mean designing them to lessen mental wokload be predictable and offer adaptable interfaces tailored to individual worker's need (R et al., 2023). For example, cobots can take on repetitive or precision tasks freeing humans to concentrate on more difficult decisions. This not only cuts down on mental fatigue but also boosts overall anticipation, using clear visual or auditory signals to communicate their next moves reducing any uncertainty or confusion.

Cobots with adaptive interfaces that adjust to the skills and preference of different users make the interaction smoother and easier (Kadir et al., 2018). They should also include error prevention and quick recovery features to minimize mistakes and allow fast fixes when things go wrong. By integrating these principles, cobots can significantly enhance worker well-being and productivity in industrial settings. Trust plays a vital role in human-robot collaboration (Goodrich & Schultz, 2008). Workers need to feel sure that cobots will perform their jobs safety, reliably and effectively. Building this trust involves both technical reliability and addressing workers psychological comfort (Panagou et al., 2024). Reliability means cobots consistently do their tasks correctly. Robots that repeatedly assemble parts accurately will naturally earn workers confidence. Transparency is just a s important cobots should openly communicate their actions intention and decision making through real-time feedback like visual displays or warning signals, so workers always know what's happening next. According to the (Ionescu et al., 2020, pp. 22–24), safety is another cornerstone of trust and cobot must operate safely in shared space to prevent accidents. The cobot that slows down or stops when a worker enters its area show a strong commitment to safety, which helps build trust among workers, and personalized settings that adapt to individual preferences further boost comfort and confidence in the workplace.

4.1. Trust and Human Factors in Robotics

Trust is a key part of human-robot collaboration (HRC) and plays a vital role in successfully bringing cobots into the industrial workplaces. For workers to work well alongside cobots, they need to feel confident that these robots will perform their task safely, reliably and efficiently (El Zaatari et al., 2019). Building and keeping that trust means addressing both technical and psychological aspects, so workers feel secure and comfortable interacting with these machines. Trust is essential to encourage acceptance of lower resistance to automation and unlock the full benefits of human-robot teamwork in industry 5.0.

- Reliability is the foundation of trust (Ahmed et al., 2022). Cobots need to do their jobs consistently and accurately. When they deliver steady error-free results, workers naturally start to trust and depend on them more.
- Transparency is also crucial. Cobots should clearly communicate what they are doing, why they are doing it and what they plan to do next. When workers understand a cobot's actions and decision trust grows (Ghobakhloo et al., 2023). This can be done through signals or alerts that keep the worker informed about the robot's status.
- Safety might be the most important factor. Cobots must operate safely in shared spaces minimizing any chance of accidents or injuries (Langås et al., 2025). Workers need to know that cobots prioritize their safety, even in fast-changing unpredictable situations. For example, cobots equipped with advanced sensors and AI can detect when a person is nearby and adjust their speed or force to avoid harm.

- Ease of Use matters too. Cobots should be simple to program, control and interact with. Intuitive interfaces and easy to use controls help workers learn quickly and feel comfortable using the technology (Pizoń et al., 2022).
- Personalization boosts trust by letting cobots adjust to each worker's unique preference and needs. When a cobots adapts its behavior to match a worker ergonomic comfort or specific tasks, it creates a more tailored, positive experience which build confidence and acceptance (Paraszczak et al., 2015).

To build and maintain trust in cobotic systems a few key strategies can help:

- Explainable AI (XAI) is powerful tool that improves transparency by allowing cobots to clear explain their actions and decision (Aalerud & Hovland, 2020). When workers understand why a cobot behaves a certain way, they are more likely to trust it.

- Haptic and visual feedback systems provide real time signals that help workers stay aware of what the cobot is doing and prepare for its next moves.

- Training and worker involvement are crucial. Hands on training sessions help workers get familiar with cobots and build confidence reducing hesitation and resistance to using the technology (Rosenstrauch & Krüger, 2017).

- Transparent communication keeps workers informed about the cobot's status intentions and any issues. Real time updates through screens or auditory alerts help maintain smooth collaboration and boost trust.

Together these factors and strategies create an environment where human workers feel secure, respected and supported by their robotic coworkers making human-robot collaboration truly effective and safe.

Table 6. Wide range of industrial applications where cobots are making a real difference (Weiss et al., 2021).

Industrial Sectors	Applications	Description
Manufacturing	• Automotive Industry • Electronic manufacturing	• Cobots handle tasks like welding and assembly working with humans to boost precision and speed. • They assist with soldering and circuit assembly improving quality and efficiency.
Logistics and Manufacturing	• Warehouse support • Logistics supports	• Cobots help with picking, packing, and inventory by bringing items to workers speeding up order fulfillment, • They move heavy loads in warehouses and factories, easing physical strain and improving workflow.
Healthcare	• Surgery • Rehabilitation	• Robotic systems like Da Vinci assist surgeons in performing precise minimally invasive procedures. • Exoskeleton support patients in regaining movement and strength during therapy.
Agriculture	• Precision agriculture • Greenhouse	• Cobots help with planting, harvesting, and weeding, boosting crop yields and easing labor. • Cobots handle tasks like pruning and monitoring plant health supporting more crop maintenance.
Food Industry	• Food Processing • Beverage Production	• Cobots handle sorting, cutting and packaging while maintaining hygiene and reducing contamination risk. • They assist with bottling, labeling and inspections ensuring consistent quality and faster production.
Construction	• Masonry and Bricklaying • Site Inspection	• Cobots use precision tools to handle tasks like bricklaying, speeding up work and easing manual labor. • Cobotic drones help survey construction sites boosting safety and delivering data,
Mining and Exploration	• Underground mining • Exploration	• Cobots handle risky tasks like drilling and inspection in underground mines keeping miners safer. • In deep sea and space mission cobots help with mapping, sampling and data collection in harsh unreachable areas.

5. Methodology

This chapter outlines the research design mixed – method approach, and analysis techniques used in this study. The introduction of collaborative robots (cobots) into industrial settings marks a significant shift in how humans and machines work together. While, industrial robots that operate behind safety barriers, cobots are built to work together with people, enabling shared task and close collaboration. This shift highlights the importance of a clear and robust research approach. The main goal of this study is to explore the key factors influencing the integration of cobots in industrial environments, focusing on how to improve operational efficiency while maintaining worker safety and wellbeing.

5.1. Research methodology

The research methodology used in this study provides a clear and organized approach to exploring human-robot collaboration (HRC). It lays out a detailed plan for gathering and analyzing data, helping to uncover well-founded insights into complex interactions between humans and robots. This approach strikes a balance between being thorough and adaptable, allowing the study to examine HRC from different angles. By combining qualitative and quantitative data like how robotic airbag technology worked and safe for cobots and humans and human robot performance analysis, the research aims to develop a complete and well-rounded understanding of how cobots are integrated.

This method aligns with the goals of industry 5.0 supporting the improvement of both technology and human factors. The mixed method framework enables methodological triangulation, enhancing the reliability and validity of findings while providing an in-depth understanding of both operational efficiencies and human-centric dimensions in HRC environments.

This research methodology is structured around one primary component:

Simulation-based experimentation:

Utilizing digital twin technology to develop a virtual replica of an industrial environment, this approach allows for the assessment of cobot performance under varying operational conditions. Such a simulation facilitates the evaluation of system efficiency and adaptability without interpreting live production processes. The development of the robotic airbag system, including its conceptual design, simulation, and impact force validation, was conducted solely. All digital twin simulations and ergonomic data analysis were created independently using platforms like Rhino software, Tecnomatix simulation, and variable sensor inputs.

5.2. Research Design and Approach

This study uses a mixed method approach, collecting data at the same but analyzing them separately. The results are then combined during the interpretation stage to give a well-rounded understanding of how human robot collaboration (HRC) performs and how suers experience it. This design framework effectively balances objective system performance metrics with subjective simulation, both of which are essential for the true assessments of collaborative technologies that operate in direct interaction with human users. The research is situated within a pragmatic paradigm, which endorses methodological pluralism and emphasizes the practical resolution of real-world problems through the application of the most appropriate tools and techniques.

This paradigm is particularly well suited to the present study as it accommodates both the technical evolution of robotic systems and human-centered ergonomic assessments. The qualitative inquiry investigates human perception of collaboration quality, safety, and comfort. Data is collected via direct observation during simulation trials. Table 7 presents a summary of the research design, outlining the four principal aspects of the study and the corresponding methodologies employed, and the holistic evolution of HRC integration currently stored and utilized solely for research purposes as outlined in this study protocol.

Table 7. Overview of Research Design

Research Aspect	Methodology	Purpose
HRC performance analysis	Digital Twin Simulation	Evaluate the cobot's efficiency and safety
Enhancing Safety in HRC	Robotic Airbag Technology	New robotic safety measures

5.5. Experimental Procedure for Robotic Airbag Validation

To experimentally validate the safety performance of the proposed robotic airbag systems, a controlled virtual testing environment was developed using Rhinoceros 3D software integrated with physics-based simulation tools. The test setup replicated an atypical human-robot collision scenario where the robotic arm, equipped with a deployable airbag, moved at varying speeds toward a virtual human body model. The force and velocity airbag deployed. Multiple trials were conducted under different operating speeds to record the maximum force transfer during simulated collisions. These measurements were used to evaluate the airbag's ability to absorb kinetic energy and reduce peak force. The experiment aimed to quantify improvements in human safety while maintaining acceptable robotic task speeds and served as the foundation for the performance analysis presented in section 10.

6. Data Analysis

The data analysis in this study was key to uncovering valuable insights from the collected information helping to create a well-rounded understanding of cobots in industry 5.0 settings. By using a approach that combines both numbers and personal experience the research offers a complete picture. Descriptive statistics help summarize the data, providing averages, percentages and graphs to establish strength and general patterns.

To better understand how key factors like productivity and safety are connected this research uses statistical tools such as correlation analysis and regression models. The tecnomatix software about topics like performance analysis of digital twin (collaborative robot) integration, safety and trust. Tools like Octave and Python help process this data and bring it to life through visuals like bar charts and histograms and pie charts making it easier to spot trends and areas that need attention.

Alongside the numbers they study, they also take a closer look at qualitative data gathered from direct observation from softwares. Here recurring themes like concerns about cobot autonomy or appreciation for reduced physical strain reveal valuable insights into the human experience of working with cobots.

7. Results & Analysis

The results of this study are based on both statistic numbers and provide valuable insight into how collaborative robots (cobots) can be successfully integrated into the 5.0 industry workplaces. The research findings are derived from structured simulation-based evaluations, and safety with robotic air bag introduce a new technology of safety measure for labor and other workers. The quantitative analysis focuses on data from industry statistics and excel for performing analysis work for finding better results, measuring perceptions of safety, trust, task allocation, cognitive ergonomics, and cobot efficiency.

8. HRC Performance Analysis

8.1. Digital Twin technology

In this study, Siemens Process Simulate (Tecnomatix) was used to create a digital twin of a collaborative human-robot workstation. The simulation focused on modeling the cobots movements planning its path managing spatial interactions and organizing task sequences. These simulations followed a rule-based approach carefully mirroring the physical and logical steps of tasks as they would occur in the real world. While Tecnomatix itself doesn't use artificial intelligence (AI), these technology techniques were added later during the analysis phase. Specifically, the researcher developed an adaptive task scheduling system and a fatigue prediction module which were applied to the simulation data.

These AI tools helped the system predict how the cobots could adjust its speed or change task assignments based on signs of human fatigue ergonomic strain. The main goal of using a digital twin was to shorten development time, improve the accuracy of the workstation design, and reduce risks tied to real-world testing. The simulation was carried out using the Tecnomatix Process Simulate Human (PSH) module which supports in depth ergonomic analysis track human motion and helps design safe and efficient collaborative between humans and robots in shared workspaces.

8.2. Simulation Objective and Metrics

The main goals of the simulation were to see how well collaborative robots (cobots) could adapt to changes in tasks in real time, identify areas of ergonomics strains for human workers, and improve how tasks are shared between humans and robots. To measure this, several key performance indicators (KPIs) were tracked during the simulation. These included task cycle time how long human workers were idle, the robot's response delay joint torque data and the distance moved by both human and robot arms. While human posture was analyzed using ergonomic scoring methods to assess physical strain. Altogether, these metrics offered a well-rounded view of both operational efficiency and worker comfort within the collaborative setup. However, working with a physical twin, the actual robot system in a real-world environment can be much more demanding. Building industrial robot applications usually means setting up a controlled space where robots interact with sensors, camera, and other equipment often through a trail and error approach. For example, teaching a robot to pick up large parts from a bin typically involves collecting thousands of images of those parts in various positions manually labeling them and then using that data to train vision algorithms. This is a time consuming ana labor intensive process. Make sure the robot does not damage parts or crash into nearby objects during setup stretch the process out over weeks or even months, often requiring expensive equipment adjustments and delaying the system rollout.

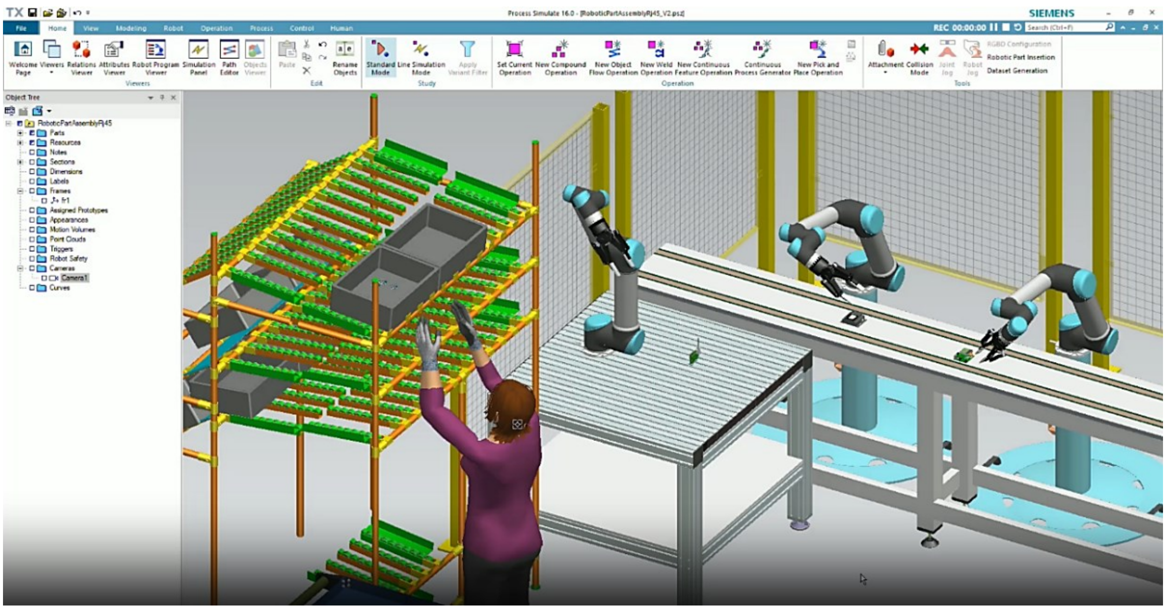


Figure 7. Part insertion by the robot was simulated as part of a human-robot collaboration in tecnomatix.

In contrast, the digital twin enabled me to simulate complex interactions between robots, human operators, and workpieces in a virtual environment. This allowed rapid experimentation, validation, and iteration without the risks or costs of physical prototyping. In this research, a simulation-based intersection strategy as shown in Figure 7, in which an external AI learning model was used to simulate human-aware adaptations during robotic part placement.

This approach made it possible to see how the robot adjusts its movements or actions based on changes in a person's posture or workload. Once the AI has been trained in the digital twin environments, transferring the knowledge to the physical robot requires significantly fewer real-world training examples. The AI model, having already been refined in simulation, needs only slight adjustments with real data to become fully operational. This reduces commissionaire time, minimizes production downtime and enhances overall efficiency. In essence, digital twins have become a game-changer for scaling industrial robotic by creating a safe cost-effective playground for robots to learn and perfect their tasks before stepping into the real world.

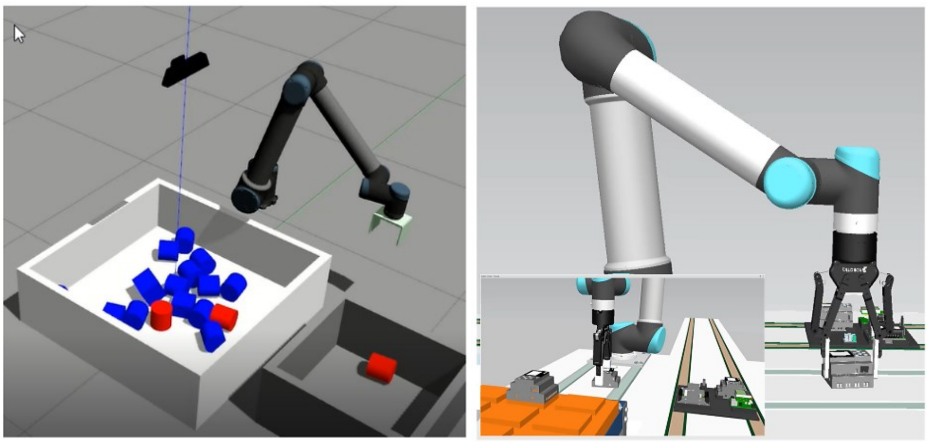


Figure 8. Robot picking parts from a bin based on camera input.

This convergence of AI, simulation, and robotics paves the way for smarter, faster, and more agile manufacturing processes, making industrial automation more accessible and efficient than ever before. One of the most promising applications of digital twins is in Reinforcement Learning (RL). A machine learning technique where robots learn through trial and error. In this steup, the robot learns by receiving rewards or penalties and changes its behavior to get the most rewards. However, using reinforcement learning (RL) with real robots has traditionally been tough because it takes a lot of repeated trails to learn effectively. However, training robots in physical environments could take months, and repeated failures might damage equipment. Digital Twins solve this by shifting the learning process into the virtual world where robots can practice endlessly without physical consequences.

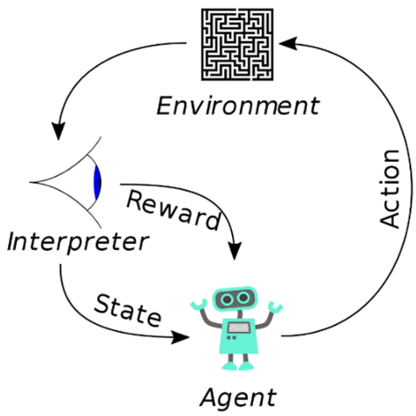


Figure 9. Reinforcement learning loop with interpret layer

A key challenge in transferring these skills to real-world robots lies in Sim2Real Transfer, bridging the gap between simulated environments and the real world. For a digital twin to effectively train a robot, it must accurately replicate physical properties such as friction, gravity, and force dynamics. However, sensory inputs like vision and touch need to be realistically simulated to ensure that robots trained in digital environments perform reliably once deployed in physical spaces. Advanced simulators now incorporate detailed physical engines and virtual sensors that mimic real-world feedback, enabling smoother Sim2Real transfer and reducing the need for extensive real-world fine-tuning.

Digital Twins offer several advantages in scaling industrial robotics AI. First, they accelerate deployment by shortening the training period and enabling robots to arrive on-site ready to perform complex tasks. Second, reduce costs by eliminating the need for physical prototypes and minimizing downtime, and highly flexible development environment for human-robot collaboration. This approach let me explore AI-driven adjustments that assess ergonomic effects and train a reinforcement learning model before moving to real world implementation. The result is a smarter, more flexible robotic system that can adapt to human needs, paving the way for safer and more efficient industrial automation.

9. Robotic Airbags: Enhancing Safety in HRC

As robots become more common in industrial and commercial settings, concerns about workplace safety are growing. While automation brings clear benefits like greater efficiency, precision and productivity it also introduces risks especially when robots work closely alongside people. Striking the right balance between keeping workers safe and maintaining productivity is one of the biggest challenges in the shift toward industry 5.0., which focuses on human-centered automation. One promising solution is the use of robotic airbags safety systems designed to reduce the risk of injury during close interactions between humans and robots. So, the concept, working mechanisms, benefits, performance analysis, and development of robotic airbags demonstrate how they can be key to improving safety in HRC environments.

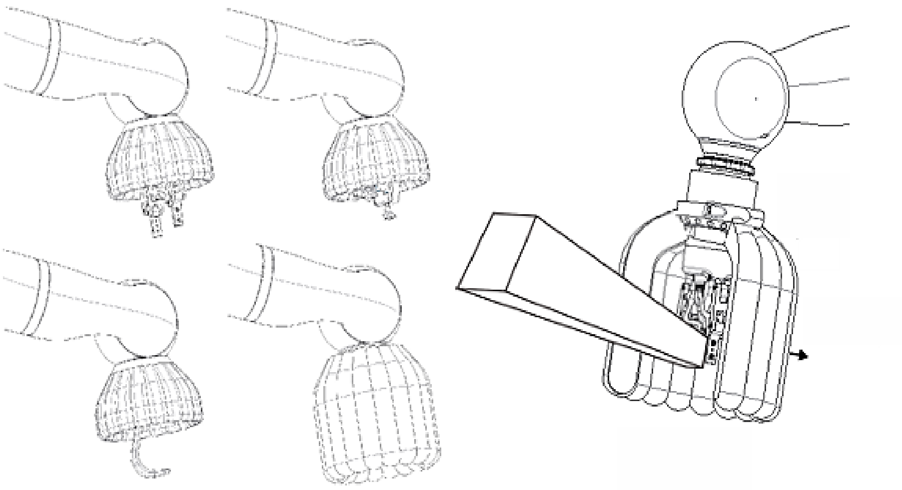
9.1. Conceptual Approach

One of the biggest challenges in human-robot collaboration is handling tools with sharp or hazardous edges which can still pose a danger even when the robot is moving slowly. Drawing inspiration from automotive airbag systems proven to prevent severe injuries in collision dissolution processes, using inflatable protection for robotic tools. Unlike conventional airbags, deployed only during emergencies, the system maintains constant inflation during unsafe braking motion while allowing deflation when full tool functionality is required.

This system addresses three critical requirements for collaborative robotics:

- Complete tool coverage during high-speed operation
- Unrestricted tool access where needed for precise manipulation
- Protection maintenance, even when handling objects

The robotic airbag achieved this through a pressurized air system readily available in an industrial environment, combined with elastic interaction mechanisms. When deflated, springs or elastic bands retract the cover completely, offering unobstructed tool access, a significant advantage over permanent form covers that always impiety functionality. The inflation process is carefully controlled to balance speed and safety too rapid inflation could potentially harm nearby workers or dislodge carried objects. Deflation occurs as quickly as possible since it presents no safety risks.



(a) Completely closed cylinder design (b) Design with an open section

Figure 10. Safety modular configuration and tools (Rhinoceros software, 2024).

In figure 11 mentioned above the chosen material for robotic airbag is ''Polyamide'' since it is a well-proven and structured material for airbags used in bicycle helmets or cars, respectively. This clever structure provides three key advantages:

- Smaller air volume enables lightning-fast inflation/deflation
- Flexible adaptation to different tool shapes.
- Complete protective coverage for both tools and handle objects

The inflation process is carefully controlled to balance speed and safety. Inflation could potentially harm nearby workers or dislodge carried objects. Deflation occurs as quickly as possible since it presents no safety risks.

9.2. Robotic Airbag Design

The robotic airbag features are highly adaptable design, allowing customization for diverse robotic applications. Its final configuration depends on this special tool and object being handled with key design parameters, including gripper dimensions and payload size. As shown in Figure 11, the initial prototype explored with shapes, including a spherical design inspired by Hovding cycle airbags. However, testing revealed this approach was impractical. These spherical forms proved difficult to retract the required excessive air volume, and the optimal solution emerged as a cylindrical design offering superior flexibility for different tool payloads. For larger objects, a fully enclosed airbag design was ineffective. This direct approach ensured the airbags always positioned themselves as a protective barrier between the moving tool object and nearby workers, maintaining safety while accommodating bulky payloads. The system automatically adjusts coverage to shield only collagen-prone areas during operation.

Figure 11: Experimental sample of airbag

9.3. Experimental Validation for Enhanced Human Safety

The rigorous testing to verify the robotic airbag's effectiveness in real-world collision scenarios. Crash tests were conducted using an anthropomorphic test dummy to simulate higher-risk human-robot interactions. A well-established method borrowed from automotive safety testing that accurately replicates human body dynamics. Given that head impacts pose the most severe injury risk in collaborative workspaces, particularly for bench-mounted assistant robots, the experiment specifically evaluates compliance with ISO/T S 15066 hand protection standards. Thus, Figure 10 illustrates the experiment of testing the collision of robot airbags with the help of Rhinoceros software.

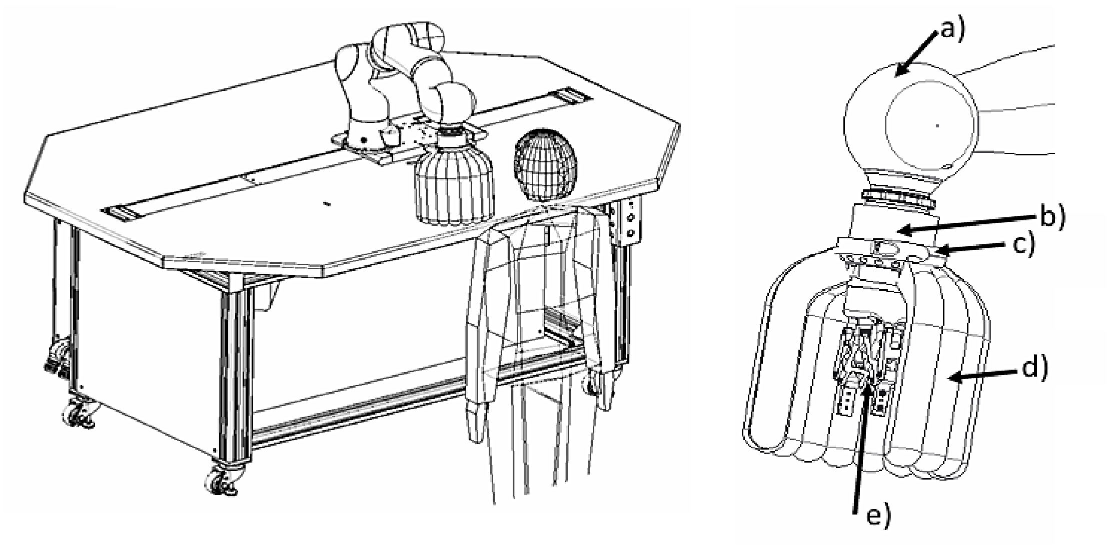


Figure 12. Experiment test setup for robotic airbag collision validation (Rhinoceros software, 2024)

In figure 12 provides a brief overview of the octagon workbench integrated with a 3-axis LWR robot. The key components are described as follows:

a) A component mounted on the linear axis, which enables the System to achieve maximum speeds.

b) A force-torque sensor attached to the robot's tool center point, used to measure the forces generated during collisions.
c) A flange connects airbags to robots; this flange also houses sensors and valves for controlling the airbags.
d) The force-moment sensor mounting setup.
e) Employed a standard robotic hand for safety testing.

This research provided critical data on how the airbag performs during worst-case scenarios while maintaining realistic industrial operating conditions. The complaint response mechanism offers additional safety advantages over conventional emergency stops by reducing whiplash risks during collisions.

- Mimics real factory environments with industry-standard workbench heights and robot operating zones.
- Enables extended acceleration phases to reach maximum robot speeds during impact testing.
- Ensures precise velocity measurement through redundant positional sensors on both robotic joints and linear axis.

9.4. Maximum Force Analysis

To validate the protective capabilities of robotic airbag systems, A conducted a series of controlled impact tests using a crash test dummy instrumented with precision measurement equipment. A highly accurate JR 3 force-torque sensors utilizing strain gauge technology was strategically positioned between the robotic arms and airbag assembly to capture both direct collision forces and the airbag's inherent stabilization forces generated by its internal pressure. The experimental protocol examined impacts across a carefully selected velocity range from 4.1 meters per second to 2.1 meters per second with help of (appendix 1) statistics analysis and finding the octave values graphs representing both typical and extreme operational scenarios in collaborative workspaces. The comparative analysis revealed striking safety performance differences between conventional unprotected tools and doors equipped with the airbag system.

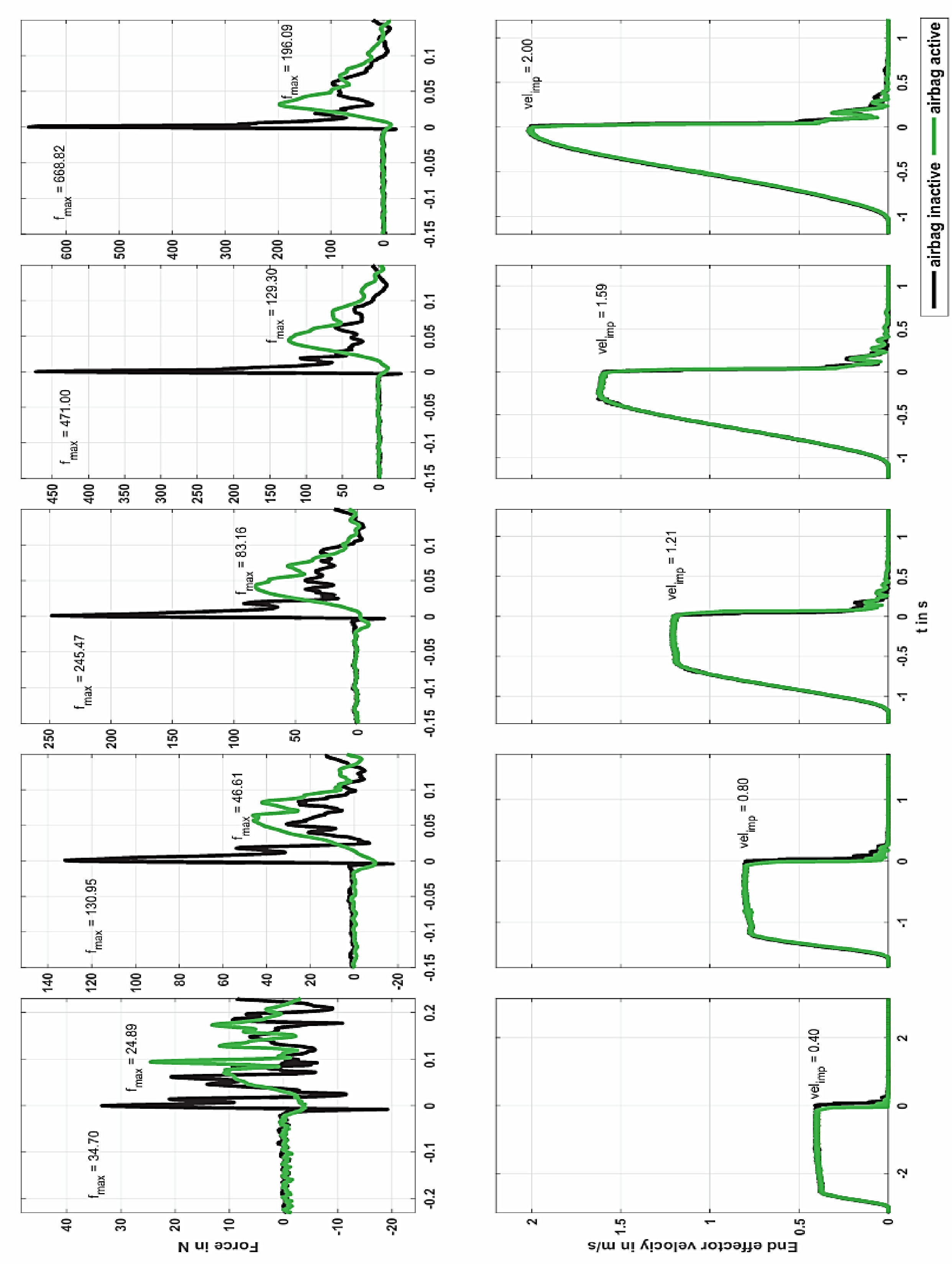


Figure 13. Force/Velocity measurements show the airbag's impact reduction.

Therefore, Figure 13 above shows the force/velocity measurements of airbag impacts also in Figure 14 below shows the performance of airbags at operational speed. At the lower speeds (0.4m/s), the airbag's presence results in only marginal force reduction (Δ Fmax = 9.79 N), with both configurations remaining well within Iso/Ts 15066 safety thresholds. However, as velocities increased to 0.8 m/s, the airbag demonstrated its critical protective value, reducing peak impact forces by 84.05 N and maintaining compliance while the unprotected tool exceeded safety limits. These protective benefits became even more pronounced at higher velocities (1.21-2.20m/s), where force reductions ranging from 161 N to 472 N were observed.

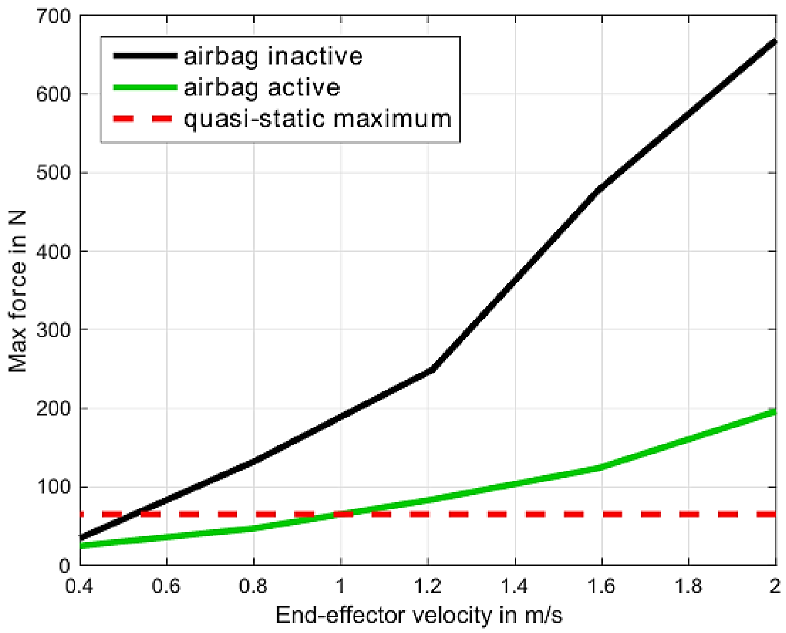


Figure 14. Airbag performance across operational speeds (Octave. 2023)

The force-velocity relationship analysis provided particularly valuable insights. While traditional robotic tools exceeded head impact safety limits (Fmax = 64 N) at just 0.5m/s shown in Figure 13, the airbag-equipped system-maintained compliance up to 1.0 m/s, effectively doubling the safe operational velocity range. This performance enhancement is especially significant given that transient force multipliers permitted for other body regions do not apply to critical head impacts. These findings clearly demonstrate that the robotic airbag system can substantially improve workplace safety by allowing higher operational speeds while maintaining rigorous safety standards addressing one of the fundamental limitations in current collaborative robotics implementations. The next phase of this research focuses on analysing pressure distribution patterns during impacts to further optimize the system's protective performance.

9.5. Performance Analysis

The robotic airbag system shows a significant improvement in operational safety while maintaining productivity in collaborative workspaces. By enabling robots to move up to five times faster than conventional safety limits allow, the airbag technology substantially enhances work efficiency. However, this performance boost comes with a small trade-off; the system requires approximately 0.52 seconds each for inflation and deflation, during which the robot must briefly pause, since most industrial robotic systems cannot currently adjust trajectories in real-time to accommodate these safety transitions. Analysis of typical pick-and-pace operations reveals an interesting dynamic in time efficiency. For longer movements, generally those exceeding 1.2 seconds in duration, the ability to operate at a higher speed more than compensates for the brief inflation/ deflation pauses, resulting in net time savings because of the equation.

For instance, in a 0.51 m transfer at 0.21 m/s, this system achieves a full second-time reduction. However, for very short movements where the inflation/deflation time represents a significant portion of the total cycle time, the airbag system may not provide immediate time benefits.

Distance Δx in m	Velocity $v_{n}a$ in m/s							
	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40
0.1	-00.90	00.10	00.43	00.60	00.70	00.77	00.81	00.85
0.2	-02.80	-00.80	-00.13	00.20	00.40	00.53	00.63	00.70
0.3	-04.70	-01.70	-00.70	-00.20	00.10	00.30	00.44	00.55
0.4	-06.60	-02.60	-01.27	-00.60	-00.20	00.07	00.26	00.40
0.5	-08.50	-03.50	-01.83	-01.00	-00.50	-00.17	00.07	00.25
0.6	-10.40	-04.40	-02.40	-01.40	-00.80	-00.40	-00.11	00.10
0.7	-12.30	-05.30	-02.97	-01.40	-01.10	-00.63	-00.30	-00.05
0.8	-14.20	-06.20	-03.53	-02.20	-01.40	-00.87	-00.49	-00.20
0.9	-16.10	-07.10	-04.10	-02.60	-01.70	-01.10	-00.67	-00.35
1.0	-18.00	-08.00	-04.67	-03.00	-02.00	-01.33	-00.86	-00.50
1.1	-19.90	-08.90	-05.23	-03.40	-02.30	-01.57	-01.04	-00.65
1.2	-21.80	-09.80	-05.80	-03.80	-02.60	-01.80	-01.23	-00.80
1.3	-23.70	-10.70	-06.37	-04.20	-02.90	-02.03	-01.41	-00.95
1.4	-25.60	-11.60	-06.93	-04.60	-03.20	-02.27	-01.60	-01.10
1.5	-27.50	-12.50	-07.50	-05.00	-03.50	-02.50	-01.79	-01.25
1.6	-29.40	-13.40	-08.07	-05.40	-03.80	-02.73	-01.97	-01.40
1.7	-31.30	-14.30	-08.63	-05.80	-04.10	-02.97	-02.16	-01.55
1.8	-33.20	-15.20	-09.20	-06.20	-04.40	-03.20	-02.34	-01.70
1.9	-35.10	-16.10	-09.77	-06.60	-04.70	-03.43	-02.53	-01.85
2.0	-37.00	-17.00	-10.33	-07.00	-05.00	-03.67	-02.71	-02.00

Figure 15. Benchmarking analysis for airbag usage (Excel.,2023)

The research of this study indicates that integrating the airbag with an advanced motion planning system that can optimize velocity profiles in real-time could further enhance performance, particularly by minimizing the impact of the necessary safety pauses. This mainly applies to movements that take more than 1.21 seconds counting the time it takes to deflate and inflate.

9.6. Discussion

A robotic airbag system represents a breakthrough in saving human-robot collaboration, particularly when handling sharp or hazardous objects. By allowing partial inflation in the direction of motion, this system mitigates the limitations of object geometry while maintaining protection. Experimental results confirmed significant force reduction during impacts, though measurement accuracy may be slightly affected by the strain-gauge force sensors' inherent low-pass filtering. Notably, the data suggests that while uncovered tools generate sustainability and higher impact forces, the airbag consistently deeps forces within safe thresholds. This system's performance is influenced by several factors, including sensor placement (which may not fully capture dynamic inertial forces) and the specific robot-tool dynamics. However, the result remained representative of applications involving sharp-edged tools demonstrating the airbag's ability to enhance safety without sacrificing efficiency.

Adaptive Protection: The chambered design ensures rapid inflation/deflation (~0,5 s), creating a rigid yet compliant barrier. An open-bottom configuration prevents clamping hazards during downward motions.

Enhanced Productivity: Benchmark tests show that the airbags' higher allowed velocities (up to 5x faster than conventional limits) outweigh inflation delays, reducing cycle times in pick-and-place tasks.

Intuitive Feedback: Integrated LED indicators provide real-time status alerts (e.g., safety errors), improving user awareness.

Therefore, testing impacts on real people isn't possible, only a brief impression of such impact can be shared here. Controlled tests showed that impacts at speeds up to 1.62 m/s felt very light almost like gentle touch. At 2.1 m/s, the impact was clearly noticeable and could feel unpleasant or uncomfortable like getting hit a punch from a beginner boxer. Finally, follow this pattern and no injuries were observed even at maximum velocity, aligning with the ISO/TS 15066 pressure limits. The robotic airbag bridges safety and performance, unlocking new collaborative applications while setting a foundation for future advancements in adaptive protection systems.

10. Conclusion & Recommendations

10.1. Future Directions

As this thesis has shown, collaborative robotics as a part of industry 5.0 offers a promising path towards safer, more adaptive, and more human-centered manufacturing environments. However, the potential of human-robot collaboration at (HRC) remains only partially realized, and several areas require further exploration to validate and extend the current understanding. One of the most essential directions for future research lies in conducting longitudinal field studies within actual industrial environments. While this thesis relied on secondary data and theoretical modeling, it's important to conduct long-term studies in a real-life setting that measure how cobot deployment influences worker safety, productivity, trust, and load over time. Such studies would offer richer, evidence-based insights into the sustained impact of (HRC), revealing not only initial effects but also adaptation trends, learning curves and potential issues such as trust erosion or unforeseen ergonomic strain. Mixed-method approaches combining sensor data, worker service, performance analytics and observational techniques would yield the most holistic understanding of human-robot dynamics.

Furthermore, future research should prioritize building direct collaboration with industrial partners to enable access to primary data. Most existing literature, including this work, depends on publicly available sources or generalized case models. Working with companies emerging tech adopters could allow researchers to collect valuable empirical data through interviews, workshops and embedded field observation.

This would also make it possible to study context-specific challenges, such as managerial resistance, workforce diversity and technological integration with the legacy system factors often invisible in secondary research. This collaboration could further facilitate testing of specific HRC innovations, such as adaptive interfaces are safety modules in live settings, thereby increasing the practical relevance of research outcomes. Another key direction involves exploring the design of more intuitive and empathetic human-machine interfaces with a particular emphasis on cognitive ergonomics. As robotic systems become more intelligent and embedded in collaborative workflows, they must also become easier for humans to understand, control, and trust. Future research could examine the effectiveness of voice control interfaces, gesture recognition systems and emotion-aware feedback mechanisms. Particularly in high-stress or multitasking environments human-centered design principles need to be embedded into robotic interface architecture ensuring their workers of various skill levels can safely and confidently interact with these technologies.

Adaptive interfaces that change based on user behavior and fatigue level task complexity represent a particularly promising area for cognitive ergonomic research. A study combining industrial design, human computer interaction, and cognitive science could pave the way for an emotionally intelligent robotic system that supports not just physical but mental well-being in the workplace. The issue of scalability also presents a critical challenge that deserves deeper study. While large enterprises like kuka can afford to invest in advanced supporting infrastructure, many small and medium-sized companies run into challenges when trying to adopt it.

Future research should investigate how HRC solutions can be simplified, modularized, and economically scaled for SMEs. This includes exploring low-cost cobot alternatives, plug-and-play systems requiring minimal programming and flexible workstations that support shared use of cobots across multiple production lines. Research in this area could help democratize access to collaborative robotics enabling wider adoption across industries and regions and prevent the emergence of the digital divide in manufacturing capability.

Lastly, there is an urgent need for research that supports the development of policy frameworks, regulatory standards, and education initiatives around HRC. As new collaborative technology emerges, national and international regulatory bodies will need to expand existing safety standards to include not only physical safety but also cognitive and emotional safety. Researchers can contribute by working with standard organizations like ISO and IEC, governmental agencies and vocational institutions to develop training modules, ergonomic guidelines, and a certification system that ensures safe, ethical and productive human-robot interaction. A coordinated effort across academia, industry and public policy could lay the foundation for responsible innovation in the future of industrial work. In conclusion, the future of human robot collaboration is a rich with potential but it also present complex challenges that must be approached with both technical precision and human empathy as this thesis has shown, HRC can improve operational outcomes when designed around human needs but to fully realized its promised research must continue to push the boundaries of how machine and human interact Co-adapt and Co-evolve in the workplace.

10.2. Challenges and Limitations

This study uses primary data from interviews and surveys to explore humans and robots work together in industry 5.0. However, it’s important to recognize some challenges and limitations that influenced the scope and results of the study. Recognizing these factors, not only the strengths and academic rigor of the study but also informs future research directions. While these companies provide an excellent example of industry 5.0 oriented cobots deployment of their size, resources and technological capabilities may not reflect the constraints and realities of small and medium-sized enterprises (SMEs). SMEs often face tough challenges, including cost, skills shortage, and infrastructure gaps. Although the study provides insight into high-level applications of HRC, caution must be exercised when applying the insight to smaller-scale or less digitally advanced organizations.

Another limitation involved the technological focus of this study. This thesis focused primarily on physical collaboration, cognitive ergonomics and safety interfaces within cobot systems. Other new industry technologies like emotion-aware AI, wearable robotics, extended reality (XR) and blockchain based traceability were not covered in depth in this study. Because of this research might not fully capture all the ways humans and technology come together in industry 5.0. Future studies should investigate how these technologies work alongside collaborative robots to make industrial environments even more human-centered.

Moreover, while the robotic airbag concept was a valuable design proposal reflecting forward-thinking safety innovation it remains a conceptual model rather than an implemented feature. Though supported by ergonomic theory and emerging robotic research, it has not yet been empirically tested or adopted in the field. While this concept adds theoretical value to the thesis, its real-world impact remains hypothetical for now. It's important to make that distinction to maintain both academic honesty and clarity. Another challenge lies in the limitations of self-reported data. To get a fuller picture future study could combine these approaches with observational data or digital performance tracking which would help validate the findings and provide a more well-rounded understanding. Lastly, the research did not deeply examine cultural, demographic, and psychological factors that can influence each HRC outcome.

Difference in age, experience, educational background, or attitudes toward automation may play a significant role in shaping how workers interact with robots, trust automated systems, and adapt through technological changes. These variables, though acknowledged, were not a central focus of the research and thus remain an opportunity for further exploration. In conclusion, while this thesis is strengthened by its use of primary data and its integration of theory and it’s important to in a case-based approach recognize the limitations inherent in sample scope, conceptual modeling, and industry diversity. These challenges do not undermine the findings but rather point to the necessity for continued, more expensive research that can validate the expansion of the contribution made here. As HRC continues to evolve, future studies must aim for deeper inclusion, broader representation and closer alignment with the lived realities of workers across all levels of the industrial ecosystems.

10.3. Conclusion

This thesis sets out to explore how collaborative robots (cobots), when integrated with a human-centric design philosophy, can enhance industrial productivity, safety, and worker well-being, core pillars of the industry 5.0 vision. Through a combination human robot collaboration, the research demonstrates that successful human robot collaboration is not only solely a matter of advanced voting but of thoughtful integration that values the human role as central rather than peripheral. This study found that cobots can significantly reduce both physical and cognitive strain when designed with adaptive interfaces, ergonomic workspaces, and clear communication channels.

Safety and efficiency were conceptualized through forward-thinking ideas such as robotic airbags and hybrid workstations and use of intuitive control, voice command and a co-evaluation AI system showcased how cobots can respond to people's behavior and instant preferences. These cases validated the idea that productive safety needs are not opposing forces but can be mutually reinforced through intelligent design. The application of theoretical models such as the 5C HRC maturity model, the safety performance tradeoff, and socio-technical system theory provides a strong conceptual foundation for analyzing the contextualization of the observed outcomes. This highlights that technological readiness must go hand in hand with social and organizational readiness.

Nevertheless, these limitations highlight potential directions for future study particularly concerning the scalability of human robot collaboration (HRC) solutions for (SMEs), the integration of emotion-aware systems and the broader cultural and psychological effects of robotics on the workforce. In conclusion, this study supports the premise that the future of industrial innovation resides not in substituting human labor with machines but in augmenting human capabilities through collaboration with intelligent systems.

Industry 5.0 offers a compelling framework for this shift, one that places human dignity, trust, and creativity at the heart of technological progress. By designing cobots that are safe, adaptable and empathetic organizations can unlock a new era of manufacturing that is not only smarter but also more humane. This thesis contributes to the vision of demonstrating that the most sustainable and successful industrial feed features will be built not just by robots but with people, for people.

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12. Appendices

12.1 Appendix # 1

Gnu Octave and Python

https://www.dropbox.com/scl/fo/nc9wnihxnea9rk8jbkopz/AKTD-p4Dz6U9vGLo7aseXtk?rlkey=7a6kgnpyiuiwbl1narphjaj9i&st=44xg0cpa&dl=0

.NET Script

```
// Copyright 2020 Siemens Industry Software Ltd.
using System;
using System.IO;
using System.Windows.Forms;
using System.Collections.Generic;
using Tecnomatix.Engineering;
using Tecnomatix.Engineering.PrivateImplementationDetails.Utilities.Rgbd;
using Tecnomatix.Engineering.PrivateImplementationDetails.Utilities.AiGym.DatasetCreator;

public class MainScript
{
    public static void MainWithOutput(ref StringWriter output)
    {
        List<string> list1 = new List<string>()
        {
            "keypad",
            "cover",
            "pcb",
            "display unit"
        };
        TxPhysicalRoot root = TxApplication.ActiveDocument.PhysicalRoot;
        TxObjectList cameras = root.GetAllDescendants(new TxTypeFilter(typeof(TxViewCamera)));


        if(cameras.Count > 0){
            TxViewCamera camera = cameras[0] as TxViewCamera;
            TxRgbdViewCamera rgbdCamera = new TxRgbdViewCamera(camera);
            TxDatasetGeneratorMng mng = new TxDatasetGeneratorMng(rgbdCamera);
            TxObjectList parts = root.GetAllDescendants(new TxTypeFilter(typeof(TxComponent)));
            Random random = new Random();

            for (int i=0; i<10; i++){
                foreach (TxComponent part in parts)
                {
                    if(!list1.Contains(part.Name)) continue;
                    TxTransformation rotationRef = part.GeometricCenter;
                    part.AbsoluteLocation = rotationRef * new TxTransformation(
                        new TxVector(random.Next(-5, 5), random.Next(-5, 5), 0), // Translation: X, Y, Z
                        new TxVector(0, 0, random.Next(0, 360)), // Rotation: X, Y, Z
                        TxTransformation.TxRotationType.EulerZYZ
                    ) * rotationRef.Inverse * part.AbsoluteLocation;
                }
                TxApplication.RefreshDisplay();
                mng.GenerateSamples("C:\\Users\\y9abuv\\Desktop\\My Dataset");
            }
        }else{
            TxMessageBox.Show(
                "No camera has been selected", "Dataset Generation",
                MessageBoxButtons.OK, MessageBoxIcon.Information
            );
        }
    }
}

public static class RandomExtensions
{
    public static int NextDouble(this Random random, int minValue, int maxValue)
    {
        return random.Next() * (maxValue - minValue) + minValue;
    }
}
```