Research Article

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Driving business growth through digital transformation: Harnessing human–robot interaction in evolving supply chain management

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Abstract: This study investigates the transformative incorporation of human–robot interaction (HRI) within contemporary supply chain management (SCM), focusing on improving efficiency and collaboration. Employing a multifaceted approach, our research examines the intricate dynamics between human workers and robots across various SCM operations, including logistics, inventory management, and storage. Through empirical case studies, qualitative evaluations, and technical insights, we investigate innovative interfaces and communication protocols aimed at fostering intuitive and productive engagement. Our methodology encompasses a thorough analysis of HRI's impact on resource allocation, operational costs, and error reduction, elucidating both its benefits and challenges. Crucially, we emphasize the imperative of seamless collaboration between humans and robots, facilitated by technology. Our findings underscore the pivotal role of HRI in augmenting the agility and reactivity of supply chain ecosystems, offering strategic insights for addressing dynamic market needs and optimizing operations. Ultimately, this research contributes to a deeper understanding of evolving SCM dynamics and paves the way for a seamless and productive future for companies.

Keywords: supply chain management, human–robot interaction, digital transformation, logistics efficiency, human–robot collaboration, optimizing operations

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1 Introduction

Within the dynamic field of supply chain management (SCM), the incorporation of human–robot interaction (HRI) represents a significant paradigm change. This article undertakes a thorough investigation of this revolutionary phenomenon, exploring its complex dynamics in supply chain activities. This study's main goal is to promote increased productivity and teamwork, two essential components in the quest for operational excellence. Through examining the interactions between human workers and robotic systems, we hope to analyze their effects on important domains such as logistics, inventory control, and warehousing. Using a detailed examination, we expose the possible benefits and challenges associated with the implementation of HRI, providing insights into opportunities for resource efficiency, expense savings, and error avoidance. Furthermore, we emphasize how crucial technology is to allow smooth collaboration and advance the supply chain ecosystem to previously unheard-of levels of responsiveness and agility [1,2].

1.1 Development of HRI in SCM

The development of HRI within the realm of SCM has undergone a transformative process characterized by technological progress and fundamental changes. At the outset, robots were considered autonomous entities with restricted communication capabilities, confined to simple duties and secluded workspaces. Nevertheless, a paradigm shift occurred with the introduction of advanced sensors, machine learning algorithms, and collaborative robotics. During this period, robots were seamlessly incorporated into human-operated environments, establishing a vibrant collaboration between the human and machine species. The advent of cobots, which stand for collaborative robotics, represented a momentous achievement [3]. Developed to collaborate with human workers, these robots brought about a significant paradigm shift by facilitating smooth operation in areas that were previously deemed unsuitable for human labor. The incorporation of robotics into intricate supply chain operations, ranging from autonomous vehicles managing logistics at a global level to automated picking in warehouses, occurred in tandem with the increase in confidence in their capabilities. Additionally, the progression of natural language processing and computer vision has provided robots with the capacity to perceive and react to human signals, thereby fundamentally transforming their interaction [4]. This recently acquired ability not only allowed for more seamless collaboration but also increased flexibility in response to ever-changing work environments. With the increasing convergence of human and autonomous responsibilities, the development of HRI in SCM serves as evidence of the boundless capabilities of collaborative technology. In the context of Industry 5.0, the application of human–robot collaborative disassembly can enhance the level of flexibility in the green and sustainable manufacturing supply chain and support the recycling of products throughout their life cycle [5]. Robotic process automation streamlines SCM by automating order processing, significantly improving efficiency while reducing manual errors [6]. This advancement not only improves the effectiveness of operations but also establishes a foundation for a future in which the convergence of autonomous precision and human ingenuity redefines the limits of supply chain optimization [7].

Figure 1 depicts the evolution of HRI in SCM. Basic robotic operations are first performed in solitude, and then cooperative robots, or cobots, that work alongside people are introduced. Improvements in technology, such as machine learning, sensors, and natural language processing, have been essential in improving interaction capabilities. As a result, robots are now included in intricate procedures such as autonomous logistics and automated picking. The current situation demonstrates how humans and robots can work together seamlessly, making it difficult to distinguish between their different responsibilities in supply chain activities.

1.2 Importance of HRI in modern SCM procedures

The importance of HRI in modern SCM cannot be overemphasized. It is a paradigm shift in response to the growing demands of a more intricate global market. HRI produces a game-changing dynamic by merging robotic precision with human knowledge to create a new level of production and efficiency. Robots provide tireless execution and accuracy in repeated activities, while humans provide contextual intelligence and adaptability. This symbiotic connection maximizes the potential of both sides [8]. Additionally, HRI frees up human laborers' time by automating repetitive, time-consuming processes, freeing them up to concentrate on value-added and strategic decision-

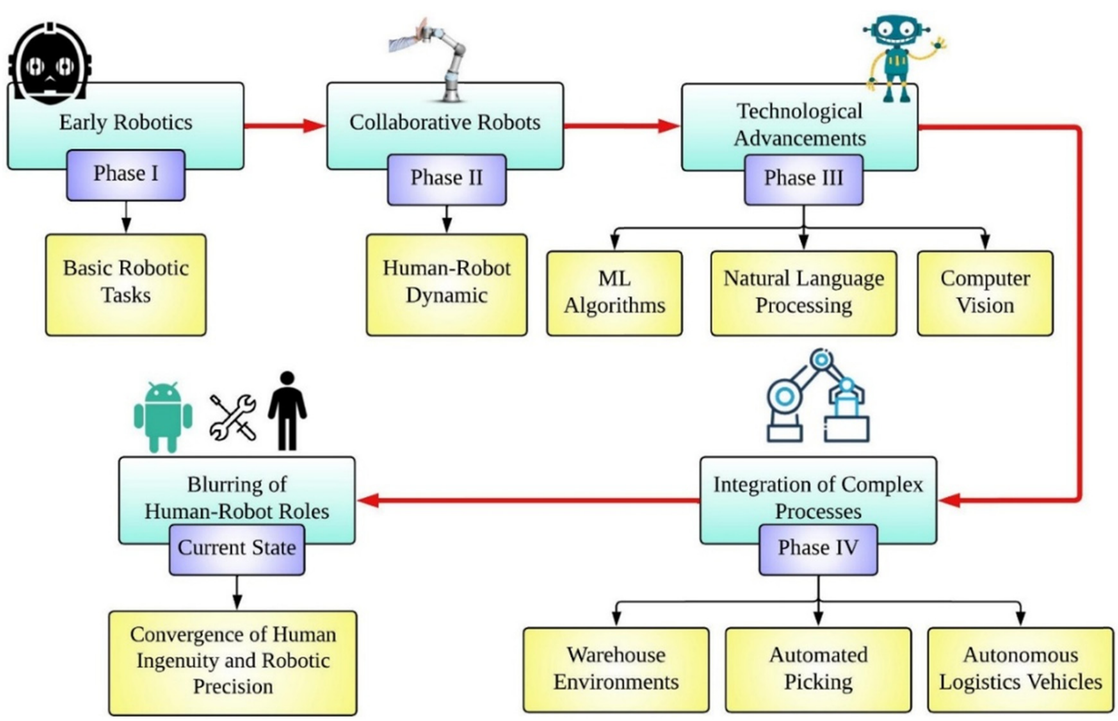

Figure 1: Evolution of HRI in SCM.

making. This connection is especially important given that customers are expecting faster and more seamless product delivery. Furthermore, HRI's flexibility allows for adaptability in a changing market. HRI becomes a vital enabler as the pace of modern business quickens, enabling SCM to not only meet but also exceed industry requirements, spurring growth and competitiveness [9]. The convergence of Internet of Things (IoT), Blockchain, and artificial intelligence (AI) technologies is driving a paradigm shift in SCM [10]. The integration and application of AI and IoT technology enables the robots to have more powerful real-time monitoring and intelligent analysis functions, which effectively improves the full traceability and compliance management of the global supply chain [11]. Moreover, the incorporation of AI has improved collaborative robots' adaptability, safety performance, and HRI efficiency [12]. It serves as a lighthouse pointing the way toward a more efficient, flexible, and customer-focused SCM in the future.

1.3 Objectives of the study: Efficiency improvement and collaborative innovation

This research aims to drive a paradigm shift in SCM through innovative HRI technologies and methodologies:

i. Improve SCM's operational efficiency by incorporating HRI. This study pioneers a Neural Network-Based Dynamic Task Allocation algorithm that optimizes resource scheduling by analyzing real-time data (environmental/human behavioral), overcoming traditional static methods. Combined with the first multimodal protocols in SCM, it enhances responsiveness by resolving command latency.
ii. Promote more cooperation between human workers and robotic entities. Our cognitive load-optimized framework enables robots to proactively adapt to human workflows via bidirectional feedback, transcending the "unidirectional control" limitation of conventional HRI. Cross-industry validation confirms significant operational error reduction and yields reusable design principles.

By fulfilling these goals, the research hopes to lessen operating costs and maximize resource allocation while also fostering a collaborative atmosphere where human knowledge and skill complement robotic accuracy and automation. The study aims to set the stage for a future of SCM marked by increased productivity, smooth collaboration, and improved responsiveness to market demands by carefully examining this dynamic.

2 Complex dynamics of HRI

This section explores the complex interactions that occur between robotic and human staff in the context of SCM. It seeks to analyze the complex interactions between humans and robots, investigating how they cooperate, communicate, and plan for jobs ranging from logistics to storage [13]. The study intends to gain important insights into how these dynamics combine to affect supply chain performance overall and operational efficiency by closely examining these dynamics.

2.1 Examination of the interaction among human employees and robotic entities

A basic examination of the complexities of SCM is the examination of the relationship between human workers and robotic entities. It entails a thorough analysis of how people and robots cooperate, exchange information, and plan within the operational framework. This examination reaches beyond the intricate duties of inventory control to the planning of logistics, revealing the dynamics behind their collaborative endeavors. This analysis seeks to clarify the critical elements impacting productivity and cooperation by identifying the advantages and possible drawbacks of this connection. As a result, it offers priceless insights for supply chain operations optimization through improved HRI. The examination of interaction among human employees and robotic entities in SCM is presented in Table 1. It evaluates multiple aspects of the interaction between human personnel and robotic entities within the context of SCM. Communication protocols are of utmost importance, as they allow sophisticated systems to facilitate the exchange of precise information [13]. Coordination plays a pivotal role in ensuring the smooth execution of tasks, minimizing periods of inactivity, and optimizing the flow of operations. Optimal task allocation maximizes output by ensuring balanced duties. The ability to adapt is crucial, as adaptive algorithms allow robots to navigate dynamic environments with ease. Delight in the capabilities of robotics cultivates dependence on their exactitude and efficacy [14]. Collaboration and effectiveness in the workplace are improved by the implementation of feedback mechanisms, effective error management, and efficient decision-making.

2.2 Impression of operational aspects: logistics, inventory management, and warehousing

SCM's operational dynamics are radically changed by HRI. Due to this integration, jobs are completed quickly and precisely, which significantly increases efficiency. Labor-intensive, manual procedures are optimized to cut down on operating time and increase overall productivity [15,16]. Furthermore, the adoption of cutting-edge technologies guarantees increased accuracy in crucial operational tasks such as order processing and inventory management. This increases the dependability of supply chain processes while reducing errors. Additionally, cost savings from the automation of repetitive processes allow more efficient resource allocation, which boosts the bottom line of the business.

Impression of HRI in supply chain operational aspects is presented in Table 2, which describes how HRI has a significant impact on important SCM operational aspects. Operations are streamlined in warehousing, which improves productivity and permits more efficient use of available space. Increased accuracy, real-time updates, and cost savings through effective resource allocation are all benefits of integration in inventory management. Automation also leads to better routing, fewer errors, and lower operating costs in logistics, all of which contribute to a supply chain ecosystem that is more responsive and nimbler.

3 Challenges and benefits of HRI implementation

This section assesses the challenges and benefits that arise from the implementation of HRI in SCM. It emphasizes the importance of strategic planning to optimize benefits while minimizing potential challenges.

Table 1: Examination of interaction among human employees and robotic entities in SCM

Interaction aspect	Description	Impact on efficiency	Impact on collaboration
Communication	Examination of how humans and robots exchange information and instructions	Robots equipped with advanced communication protocols facilitate swift and accurate information exchange, enhancing task execution	Effective communication protocols promote seamless collaboration, reducing misunderstandings and delays
Coordination	Analysis of how humans and robots synchronize tasks and activities	Precise coordination ensures seamless task execution, reducing idle time and improving overall operational flow	Effective coordination mechanisms improve collaboration, enabling tasks to be executed in a synchronized manner
Task allocation	Evaluation of how responsibilities are assigned between humans and robots	Optimal task allocation leads to a balanced workload distribution, maximizing the productivity of both human and robotic workers	Clear task allocation minimizes conflicts and ensures that each entity complements the other's strengths
Adaptability	Assessment of how well humans and robots adjust to dynamic environments	Robots equipped with adaptive algorithms excel in navigating dynamic environments, leading to improved operational efficiency	Both humans and robots demonstrating adaptability contribute to a dynamic and flexible work environment
Trust and confidence	Exploration of the level of trust and confidence between human and robot	Trust in robots' capabilities fosters reliance on their precision and efficiency, contributing to improved operational speed	Building trust between human and robotic workers improves collaboration, as each party is more likely to rely on the other's actions and decisions
Error handling	Study of how errors and exceptions are managed within the interaction	Rapid error detection and resolution by robots minimize disruptions, leading to improved overall efficiency	Effective error-handling mechanisms promote a cooperative atmosphere, as errors are managed transparently and constructively
Decision-making	Scrutiny of the role of humans and robots in critical decision processes	Humans' contextual intelligence is invaluable in complex decision-making, leading to optimized task execution	Effective decision-making processes ensure that tasks are executed in a manner that aligns with the overall supply chain objectives
Workload distribution	Analysis of how workloads are balanced between human and robot	Efficient workload distribution optimizes resource utilization and ensures that each entity operates at its maximum capacity	Equitable workload distribution promotes a harmonious work environment, reducing the likelihood of burnout or inefficiency
Feedback mechanisms	Evaluation of feedback loops for performance improvement	Continuous feedback loops allow iterative improvement, leading to improved efficiency over time	Robust feedback mechanisms foster a culture of learning and improvement, benefiting both human and robotic workers
Learning and adaptation	Examination of the capacity for learning and improvement over time	Robots equipped with machine learning algorithms refine their operations, ultimately contributing to increased efficiency	Both humans and robots demonstrating a learning capacity contribute to a dynamic and continuously improving work environment

3.1 Challenges in integrating HRI into supply chain operations

There are three major challenges of integrating HRI into supply chain operations, which are technological, employee adaptation, and cost parameters.

3.1.1 Technological difficulties

A significant challenge in the implementation of HRI within supply chain operations is effectively navigating the complex environment created by cutting-edge technologies. It entails concerns about compatibility, integration with pre-existing systems, and guaranteeing uninterrupted communication between human operators and robotic components [4]. To surmount these technological challenges, one must possess an all-encompassing comprehension of the complexities associated with the deployment and administration of a wide variety of autonomous systems.

3.1.2 Employee adaptation

The effective implementation of HRI is contingent upon the current employee's capacity to acclimate to this paradigm shift. Fear of job displacement, resistance to change, and the requirement for retraining are typical obstacles. It is of the utmost importance to allow employees to collaborate efficiently with robots by providing them with the requisite skills and knowledge [17]. To ensure a seamless transition, it is imperative to implement change management initiatives and strategic training programs.

3.1.3 Cost factors to consider

The adoption of HRI may necessitate a significant financial outlay, including expenses related to the procurement, installation, and upkeep of robotic systems. A formidable obstacle arises when attempting to reconcile the initial capital outlay with the prospective long-term benefits. A thorough examination of the costs and benefits is necessary to rationalize the investment and guarantee that the anticipated returns surpass the expenditures linked to integration [18].

3.1.4 Moral hazard

The application of HRI in the supply chain involves a number of ethical challenges, mainly including the division of decision-making responsibilities, data privacy protection, and algorithmic fairness. When robots are involved in operational decision-making, the ambiguity of responsibility (human, machine, or enterprise) may lead to ethical disputes; the employee behavior and supply chain data collected in human–robot collaboration are at risk of

Table 2: Impression of HRI in supply chain operational aspects

Impact on operational aspects	Warehousing	Inventory management	Logistics
Efficiency	Streamlined operations; tasks such as picking, packing, and stacking are optimized	Greater accuracy and precision in tracking inventory levels; improved demand forecasting and order fulfillment	Optimized routing and reduced travel time; efficient last-mile deliveries
Space utilization	More efficient use of storage space through effective navigation of tight spaces by robots	—	Efficient use of storage space is facilitated through streamlined logistics operations
Error reduction	Fewer errors in tasks such as inventory placement and retrieval, improving overall warehouse accuracy	Improved accuracy in tracking and managing inventory levels; minimized errors in critical processes	Automation minimizes human errors in logistics operations
Real-time updates	—	Continuous monitoring and reporting provide real-time data on stock levels, aiding in demand forecasting and preventing stockouts	Real-time updates on routes and delivery status optimize logistics operations
Cost optimization	—	Efficient resource allocation and reduced operational expenses lead to cost savings	Reduced operational costs through efficient resource allocation and optimized transportation

privacy leakage; and the potential bias in the algorithm design may lead to unequal distribution of resources or unfair evaluation of employees.

Overcoming these challenges necessitates the implementation of a comprehensive strategy that integrates technological prowess, efficient change management tactics, and an in-depth comprehension of financial ramifications. It is critical to confront these challenges directly to fully harness the capabilities of HRI in the ever-changing realm of supply chain operations.

3.2 Benefits of HRI integration

Efficiency is revolutionized by the implementation of HRI in supply chain operations. By performing repetitive duties with consistency and accuracy, robots allow human employees to allocate their efforts toward more complex decision-making processes. Consequently, this results in improved productivity within the supply chain ecosystem, streamlined operations, and optimized resources. HRI further contributes to substantial cost savings through the reduction of operational expenditures related to labor, overtime, and error rectification. Implementing this revolutionary integration not only bolsters competitiveness but also guarantees a supply chain that is more adaptable and responsive to the ever-changing demands of the market [19]. The key advantages of HRI integration are efficient allocation of resources, reduction in operational expenditures, and error reduction.

3.2.1 Efficient allocation of resources

The implementation of HRI within supply chain operations results in improved resource allocation strategies. With consistency and accuracy, robots perform labor-intensive, repetitive duties with remarkable proficiency. This facilitates the allocation of human labor toward more complex decision-making processes and duties that demand contextual intelligence. Consequently, increased efficiency in resource utilization results in heightened levels of overall productivity [20].

3.2.2 Minimizing operational expenditures

The implementation of HRI substantially aids in the reduction of operational expenses. Once incorporated, robots are capable of executing tasks continuously without requiring breaks or overtime compensation. Furthermore, the costs linked to errors in responsibilities such as inventory management and order fulfillment are reduced due to their consistent accuracy. This ultimately results in significant financial benefits, rendering the implementation of HRI a prudent financial commitment [21].

3.2.3 Error reduction

The accuracy and precision of robotic entities are critical factors in reducing errors that may occur during supply chain operations. By implementing task automation, the probability of human error is substantially diminished. This is especially significant in critical domains like inventory management, where the maintenance of precise records and monitoring is critical. HRI assures a greater degree of dependability and precision in supply chain operations by mitigating errors [22]. The implementation of HRI offers numerous benefits, including improved resource allocation, considerable cost savings in operations, and a substantial decrease in errors. The aforementioned advantages synergistically contribute to an improved and more effective supply chain ecosystem, which ultimately improves the enterprise's competitiveness and responsiveness.

4 Collaboration enabled by technology for effective coordination

This section explores the critical significance of sophisticated technology in enhancing cooperation between human and robotic entities. This study investigates how novel interfaces and communication protocols improve user-friendly interaction, ultimately elevating the level of responsiveness and agility within the supply chain ecosystem to unprecedented levels. This section elucidates the pivotal role that technology plays in attaining smooth coordination, guaranteeing that the collaborative endeavors of humans and robots harmoniously mesh to optimize operational efficiency.

4.1 Highlighting the significance of technology in collaborative efforts

In contemporary SCM, it is crucial to emphasize the role that technology plays in collaboration. It is the cornerstone that makes it possible for human workers and artificial entities to interact seamlessly. Cutting-edge automation technologies, user-friendly interfaces, and sophisticated communication protocols are essential for bridging the knowledge gap between humans and robots. This focus on technology guarantees a harmonious interaction between human and robotic personnel, in addition to improving operations' efficiency and accuracy. Using this integration, the ecosystem of the supply chain develops into a dynamic and adaptable structure, ready to satisfy the requirements of a constantly shifting market [23]. Essentially, technology is the driving force behind the conversion of collaborative potential into real-world operational excellence in the SCM domain.

The technology-enabled cooperation in SCM is depicted in Figure 2, which demonstrates how cutting-edge technology acts as the key to enabling smooth collaboration in SCM between human workers and robotic entities. Technology improves operational effectiveness and collaboration through user-friendly interfaces and communication protocols, which eventually catapult the supply chain ecosystem to new heights of responsiveness and agility. It illustrates the crucial function that sophisticated technology plays in coordinating smooth collaboration in the realm of SCM. The seamless integration of human employees with robotic entities, represented by icons, exemplifies the dynamic symbiosis that can be observed between robotic precision and human expertise. The central technology node facilitates the exchange of instructions and information between humans and robots by acting as the nerve center. The diagram illustrates the instruments that facilitate this harmonious interaction, which are intuitive interfaces and communication protocols [24]. The positive effects of technology-facilitated cooperation on both collaboration and operational efficacy are represented by the upward arrows. In its entirety, the diagram succinctly illustrates how state-of-the-art technology serves as the catalyst, driving the supply chain ecosystem toward unparalleled levels of agility and responsiveness.

4.2 Advanced communication protocols and interfaces

SCM relies heavily on innovative interfaces and communication protocols to facilitate productive HRI. These advanced tools function as an intermediary between human personnel and robotic entities, enabling smooth and efficient collaboration and communication. Intuitive interfaces make it easier for people to interact with robots and are also more effective at conveying instructions

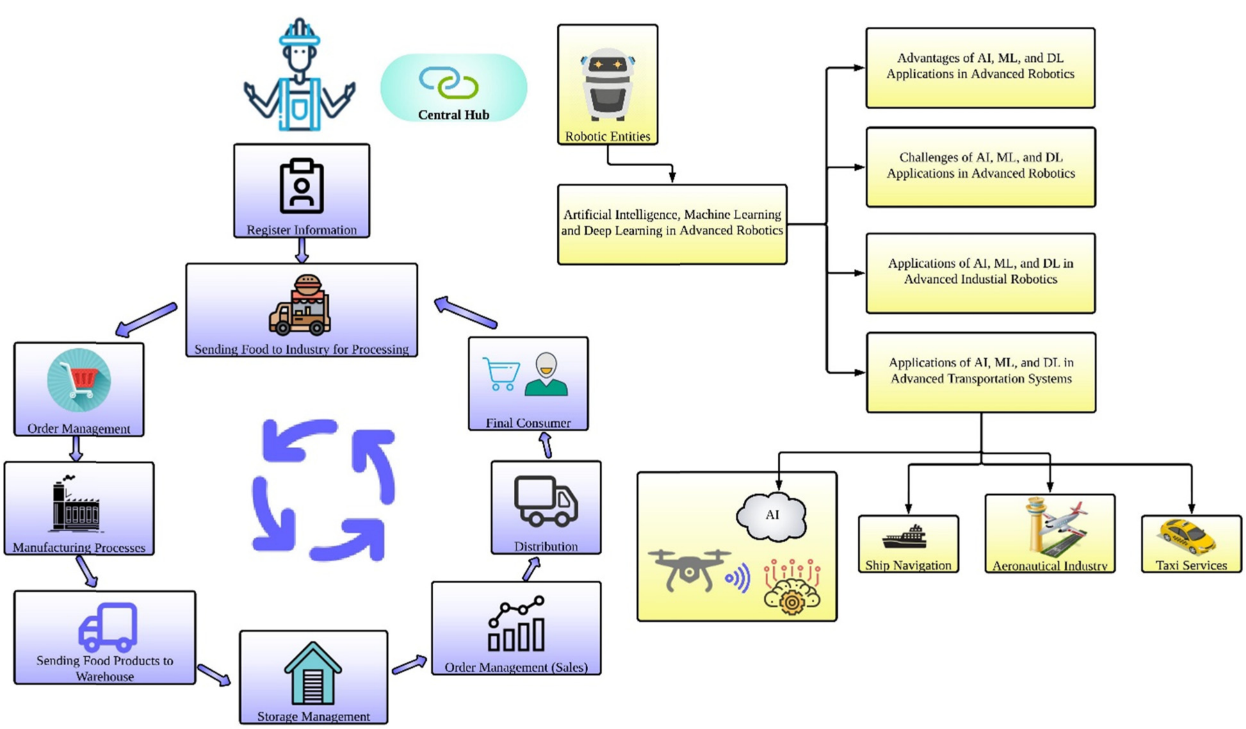

Figure 2: Technology-enabled cooperation in SCM.

clearly and thoroughly. Advanced communication protocols make it possible for data to be sent instantly, which lets robots and people work together in a changing operational environment. There are also functions such as visual cues and natural language processing built into these technologies, which make interaction more complex and useful. Through the utilization of cutting-edge interfaces and communication protocols, supply chain operations achieve unprecedented levels of effectiveness, promptness, and flexibility [25,26]. The key parameters and application of advanced communication protocols and interfaces in SCM are presented in Table 3.

This table presents a wide array of cutting-edge interfaces and communication protocols that are fundamentally transforming the field of SCM. Especially when performing warehouse sorting and packaging, intuitive touch-screen panels significantly improve user-friendliness. Voice recognition and natural language processing systems allow human–robot collaboration in dynamic environments with minimal disruption. The interpretation of hand signals by gesture recognition technology permits precise manipulation tasks in confined spaces. AR interfaces augment situational awareness by superimposing digital information over tasks such as assembly and order selection. Haptic feedback systems improve precision in activities such as quality inspection and assembly by delivering tactile information. Virtual reality interfaces improve the effectiveness of training by creating immersive three-dimensional environments for training simulations and the execution of difficult tasks. They also allow for remote operations in dangerous environments. Combined with sophisticated communication protocols, these cutting-edge interfaces are crucial for increasing the efficacy and accuracy of supply chain operations.

4.3 Improving engagement for agility and reactivity

Improving engagement is a key part of getting to unmatched levels of flexibility and responsiveness in SCM, and this research study gives it a lot of attention. Setting up advanced interfaces and communication protocols between humans and robots that allow them to work together makes it possible for the supply chain ecosystem to quickly adapt to changing market needs. The higher level of participation ensures that activities stay flexible, letting people respond quickly to problems that come up out of the blue or changes in what customers want. When people work together using technology, it not only makes it easier to share resources and cut down on costs, but it also creates a system where robot accuracy and human skill work well together. This improved engagement-driven collaborative synergy has created a supply chain ecosystem that is ready to help people make quick decisions, follow flexible procedures, and gain a competitive edge in a business world that is always changing [27].

Figure 3 effectively demonstrates a critical notion in the field of SCM: the smooth and efficient exchange of information between human personnel and automated systems, allowed by cutting-edge interfaces and communication protocols. Within the operational framework, there is a convergence of human laborers and robots, with each having a distinct icon. The interfaces, which are represented by rectangles, serve as communication conduits connecting humans, automata, and the underlying protocols. Communication protocols, represented by vectors and labels, facilitate the exchange of information in real time, which is vital for effective coordination. The incorporation of agility and reactivity metrics serves to emphasize the fluid and ever-changing character of this exchange. This figure shows how more people are getting involved, made easier by cutting-edge technology, and pushing the supply chain ecosystem to levels of flexibility and responsiveness that have never been seen before.

5 Methodology

This section describes the systematic process used to examine HRI in SCM. This study offers comprehensive insights into the subject by conducting a literature review of empirical case studies with qualitative evaluations and technical analyses. To fully discover the complex interactions among humans and robots in the field of SCM, the study used a broad methodology that comprises many diverse areas. To begin, a comprehensive literature review was undertaken to establish the firm groundwork of current understanding in this field [28]. After that, empirical case studies were performed in several different industrial settings to obtain useful, real-life information about how HRI was used and what effects it had. Qualitative assessments, encompassing surveys and interviews, were undertaken to obtain the viewpoints of critical stakeholders. Furthermore, technical evaluations were conducted to ascertain the effectiveness of novel interfaces and communication protocols.

Given that this research aims to systematically review the theoretical foundation of HRI in SCM and deeply investigate its application practices, human experiences, and technical effectiveness within diverse industrial settings, ultimately synthesizing its complex impact mechanisms on SCM performance, a singular quantitative or qualitative

Table 3: Advanced communication protocols and interfaces in SCM

Parameter	Innovative interfaces	Applications	Advantages	Communication protocols	Benefits
User-friendliness	Intuitive touch-screen panels	Warehouse picking, sorting, and packing	Simplifies operator interaction with robots, reducing training time and the potential for errors	Wi-Fi, Bluetooth, RFID	Allows seamless real-time data exchange, critical for coordination and task execution
Natural language processing	Voice recognition and speech synthesis	Human–robot collaboration in dynamic environments	Allows for natural communication between humans and robots, enhancing task coordination and adaptability	MQTT, OPC UA, AMQP	Supports standardized, reliable communication, ensuring consistency in operations
Gesture recognition	Cameras and sensors interpreting hand signals	Precise manipulation tasks in tight spaces	Allows intuitive control of robotic movements, ideal for intricate tasks requiring human-like dexterity	HTTP/HTTPS, CoAP, WebSocket	Facilitates low-latency, bi-directional communication, vital for real-time task adjustments
Augmented reality (AR) interfaces	Headsets providing overlaid digital information	Order picking, navigation, and assembly tasks	Offers improved situational awareness and task guidance, improving efficiency and reducing errors	5G, LoRa, Zigbee	Supports high-bandwidth, low-latency communication, vital for transmitting AR data
Haptic feedback	Force feedback in robotic arms or wearables	Assembly tasks, quality inspection	Provides tactile information to operators, enhancing their sense of touch and precision during tasks	BLE (Bluetooth Low Energy), NFC	Allows reliable short-range communication, crucial for transmitting haptic feedback
Virtual reality interfaces	Immersive 3D environments for task visualization	Training simulations, complex task execution	Improves training effectiveness and allows for remote operation of robots in hazardous environments	4G/5G, Ethernet/IP, PROFINET, Modbus TCP	Allows robust, high-speed communication, necessary for transmitting VR data

approach is insufficient to comprehensively achieve these objectives. Therefore, a mixed-methods research design was employed. This design leverages the complementarity of methods to integrate theoretical construction with practical insights, subjective experiences with objective data, and in-depth understanding with broad coverage, thereby providing a more complete and accurate response to the research questions. This mixed-methods approach aligns with the complex adaptive systems theory, where triangulating data from literature synthesis (deductive logic), case observations (inductive reasoning), and technical tests (empirical validation) provides a holistic view of HRI dynamics. Referring to the research methodology of the existing literature [29,30], integrating diverse methodologies mitigates the limitations of single approaches, enhancing both the theoretical depth and practical relevance of research findings in socio-technical domains like SCM.

5.1 Real-world case studies

The foundation of this research is empirical case studies, which offer priceless real-world insights into the use and significance of HRI in various supply chain scenarios. In-depth analyses of real-life operational scenarios are part of these investigations. This lets information, observations, and first-hand reports from professionals in the field be gathered. We acquire a sophisticated grasp of how HRI affects vital facets of SCM, such as inventory control, logistics, and warehousing, by immersing ourselves in these real-world contexts. By helping us to recognize trends, obstacles, and best practices, these case studies provide a strong empirical basis for our study findings and recommendations.

5.1.1 Selection standards

Several fundamental criteria were utilized in the article selection process to ascertain their pertinence and importance to the subject of research. To begin with, the selected articles must specifically examine the incorporation of robotics in the context of SCM. Furthermore, it is crucial to prioritize diversity within the industry framework, which includes critical sectors including healthcare, food and beverage, e-commerce, manufacturing, logistics, retail, and healthcare. To provide a comprehensive view of robotic applications, the articles should also include a variety of robot types, such as automated guided vehicles (AGVs), autonomous mobile robots (AMRs), Cobots, and Drones. Also, the studies that are

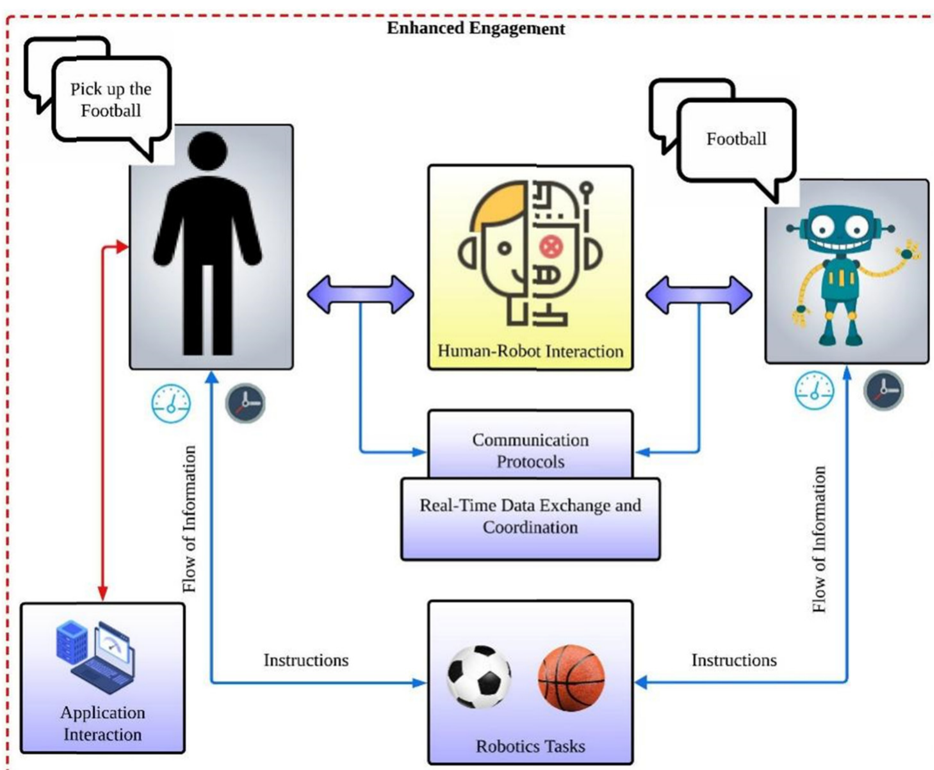

Figure 3: Transformative interaction: enhancing SCM agility and reactivity.

chosen should have clear goals, show real results, and talk about problems that were encountered and lessons learned during the integration process. In conclusion, recent publications that have undergone peer review are prioritized due to their credibility and relevance to the research objectives.

5.1.2 Case study specifics and their evaluations

Seven different studies have been conducted in the ever-changing field of SCM; each study sheds light on creative robotics applications in a variety of industries. These investigations highlight how human–robot cooperation may revolutionize processes and boost productivity. For example, e-commerce warehousing saw a 30% increase in order-picking efficiency and a 30% decrease in labor expenses when AMRs were integrated with warehouse management systems (WMS). The integration of Collaborative Robots (Cobots) and AGVs resulted in a 15% increase in overall production efficiency and a noteworthy 98% decrease in assembly errors in the automotive manufacturing industry. Within the field of logistics, the seamless integration of AGVs and drones with pre-existing systems resulted in a significant 40% reduction in delivery time as well as a decrease in manual involvement. Automated storage and retrieval systems (AS/RS) and Automated Galleries (AGCs) were essential parts of the WMS, resulting in a 25% reduction in order processing time and a 20% increase in warehouse throughput for retail. Utilizing drones and RFID-equipped robots strategically reduces inventory inconsistencies by an astounding 98% and improves order accuracy by 30% in pharmaceutical delivery. Robotic Cold Storage Units with temperature-controlled AGVs helped cold chain logistics in the food industry achieve a 30% reduction in energy usage and a 99% reduction in temperature excursions. Finally, the online grocery fulfillment industry saw a startling 40% gain in processing capacity and a 99.5% decrease in order errors as AMRs and Collaborative Robots (Cobots) integrated with the WMS. Together, these studies highlight the real advantages and possible drawbacks of incorporating robotics into supply chain operations, offering crucial information to companies looking to streamline their logistical procedures. Table 4 presents the findings through empirical case studies.

5.2 Qualitative evaluations

A detailed examination of the dynamics of HRI is carried out in this section. This method makes it easier to get a deeper understanding of the subjective factors that affect how well robotics can be used in SCM. Qualitative evaluations cover topics such as user satisfaction, adaptability, and the effectiveness of human–robotic interactions. It also examines employee qualitative input, which provides insight into their perspectives and experiences with the collaborative robot environment across a range of operational domains. This qualitative perspective improves quantitative data and offers a comprehensive understanding of how HRI affects supply chain operations.

5.2.1 Data collection approaches

A mixed-methods strategy can be used to get a lot of different kinds of data for a full study of how humans and robots interact in SCM. With techniques including time studies, surveys, and statistical analysis of operational metrics, quantitative data can be gathered [37,38]. It presents quantitative data regarding efficiency improvements, decreases in errors, and other quantifiable effects of integrating robotic systems. Qualitative data can be acquired through in-depth interviews, focus groups, and direct observations. This way of doing things can help us understand more about the subjective experiences, problems, and user points of view that come up when human staff members interact with autonomous entities. Case studies that look at real-life implementations can also give you important background information and real-life examples of how to integrate things effectively. By using these methods together, it is possible to collect a lot of accurate data, which makes it easier to study in detail the complex interactions that happen between humans and robots in SCM [39].

Table 5 presents the comparative analysis of data collection techniques employed in SCM to assess HRI, and it offers a wide range of data-gathering techniques designed to thoroughly examine HRI in SCM. Every approach has its use, from exact time studies for measurable efficiency assessments to focus groups and in-depth interviews for subtle qualitative insights. First-hand experience is provided through participant participation and direct observations, while case studies focus on particular real-world applications. Performance metrics offer essential key performance indicators, and document analysis carefully examines written materials for relevant information. System metrics and error logs examine disparities and technical performance. With these many methods, it is possible to fully understand the relationship between humans and robots in SCM. These methods cover both quantitative and qualitative aspects, and they allow a full evaluation of this constantly changing field.

Table 4: Analysis through empirical case studies

Parameters	References						
	[31]	[32]	[33]	[34]	[32]	[35]	[36]
Objective	Optimizing order fulfillment in e-commerce warehousing	Enhancing inventory accuracy in automotive manufacturing	Streamlining logistics operations in a third-party logistics (3PL) Company	Enhancing warehouse efficiency through robotic automation	Enhancing supply chain visibility in pharmaceutical distribution	Enhancing cold chain logistics in food distribution	Improving order accuracy in online grocery fulfillment
Context/industry	E-commerce	Manufacturing	Logistics	Retail	Healthcare	Food & beverage	Retail
Type of robots	AMRs	AGVs, Collaborative Robots (Cobots)	AGVs, Drones	AS/RS, AGVs	Autonomous drones, RFID-equipped robots	Temperature-controlled AGVs, Robotic Cold Storage Units	Collaborative Robots (Cobots), AMRs
Role of robots	Picking, packing, sorting	Inventory Management, Assembly Assistance	Goods Movement, Last-mile Delivery	Storage, retrieval, transportation	Inventory management, monitoring	Storage, transportation	Picking, packing
Human interaction with robots	Human operators guide robots and oversee operations	Human workers collaborate closely with Cobots for precise assembly tasks	Human operators oversee and coordinate AGV movements and drone dispatch	Human operators oversee and monitor robot operations, intervening when necessary	Human operators utilize drones and RFID-equipped robots for real-time monitoring of inventory levels	Human operators monitor AGVs and manage the loading/unloading of goods in cold storage units	Human operators work in tandem with Cobots and AMRs for accurate order fulfillment
Integration with existing systems	AMRs are integrated with WMS for real-time task assignment	AGVs and Cobots are seamlessly integrated with the existing Manufacturing Execution System (MES)	AGVs and drones are integrated with the company's WMS and Route Optimization Software	AS/RS and AGVs are integrated with the company's WMS for seamless coordination	Drones and RFID-equipped robots are integrated with the company's enterprise resource planning system	AGVs and Cold Storage Units are integrated with the company's WMS and temperature monitoring system	Cobots and AMRs are integrated with the company's WMS for task assignment and route optimization
Data collection methods	Observations, surveys	Interviews, automated data collection	Direct observation, GPS tracking	Observations, time studies	RFID data collection, drone surveillance	Temperature monitoring, observations	Time studies, surveys
Key findings	AMRs improved order-picking efficiency by 30%. Reduced labor costs	98% reduction in assembly errors. Improved overall production efficiency by 15%	Reduced delivery time by 40%. Minimized human involvement in routine logistics tasks	20% increase in warehouse throughput. Reduction in order processing time by 25%	98% reduction in inventory discrepancies. 30% improvement in order accuracy	99% reduction in temperature excursions. 30% decrease in energy consumption	99.5% reduction in order errors. 40% increase in order processing capacity
Challenges faced	Initial integration required significant reconfiguration of the warehouse layout	Initial workforce resistance to Cobots. Fine-tuning Cobot programming for specific tasks	Initial AGV programming challenges. Regulatory hurdles for drone deployment	Initial staff resistance to automated systems. Fine-tuning AGV routes for optimal efficiency	The initial cost of implementing RFID technology. Ensuring uninterrupted drone flight paths	Ensuring AGVs maintain a constant temperature during transportation. Calibrating cold storage units for precise temperature control	Initial cobot programming and safety measures. AMR navigation and collision avoidance
Benefits and impact		Substantial reduction in rework and scrap.	Significant reduction in delivery lead		Improved real-time tracking of	Improved preservation of perishable goods.	Substantial improvement in

(*Continued*)

Table 4: *Continued*

Parameters	References						
	[31]	[32]	[33]	[34]	[32]	[35]	[36]
	Increased order fulfillment speed and reduced labor costs	Increased overall production throughput	times. Cost savings from reduced manual handling	Increased order fulfillment speed and reduced labor costs	pharmaceuticals. Reduced instances of stockouts and overstocking	Reduced energy costs in cold storage operations	customer satisfaction. Reduced instances of returns and refunds
Lessons learned	Prioritizing layout planning during AMR integration is critical	Employee training programs are crucial for smooth integration	Regularly update AGV and drone programming based on real-world data	Prioritizing layout planning during AS/RS and AGV integration is critical	Thoroughly plan and validate RFID implementation to avoid disruptions	Implement regular temperature mapping exercises for precise control	Comprehensive staff training on Cobot and AMR interaction is essential
Recommendation	Consider phased implementation for large-scale warehouses	Regular maintenance schedules for Cobots to ensure optimal performance	Collaborate with regulatory authorities for streamlined drone deployment	Consider phased implementation for large-scale warehouses	Regularly update drone routes based on operational data and warehouse layout changes	Establish a robust maintenance schedule for cold storage units to prevent breakdowns	Periodic software updates and safety checks for Cobots and AMRs to ensure safe operation

5.2.2 Analysis techniques

This study employs existing approaches to rigorously analyze qualitative assessments about HRI in SCM. A key function of thematic analysis is to methodically find and arrange recurrent themes, patterns, and ideas in the qualitative data. This method allows for a thorough investigation of human viewpoints and a sophisticated comprehension of their interactions with robotic entities. Furthermore, written materials, reports, and documents are examined closely using content analysis to glean important information about the nuances of the interaction. Along with ongoing comparative and narrative analysis, these analytical tools make sure that the qualitative data is thoroughly analyzed, giving us useful information about how people and robots work together in the supply chain sector [40,41].

Table 6 presents the comparative analysis of data analysis methods for SCM in HRI evaluation. Many different types of data analysis methods are discussed in this article. These methods are good for doing in-depth research on how humans and robots interact in SCM. Thematic analysis is becoming more popular as a way to find recurring patterns and themes in qualitative data. This gives us a deeper understanding of what it is like to be human. Implementing content analysis is a very useful method for carefully reading written materials because it helps find important details about how people interact with each other. The constant comparative analysis technique is prominent for its ability to produce grounded concepts, providing a laborious approach to the development of theoretical models. The use of narrative examination, with an emphasis on personal stories, makes it easier to completely recognize different views. Implementing both descriptive and inferential examinations, along with machine learning, makes it possible to analyze data quantitatively in a way that makes it convenient to make predictions and draw conclusions. These techniques, which include both qualitative and quantitative characteristics, work together to make a comprehensive set of tools for analyzing the complicated interactions between humans and robots in SCM.

5.3 Proposed model

The proposed model for enhancing HRI in SCM operates through a systematic process that leverages advanced technologies and innovative methodologies, which is depicted in Figure 4. It begins with the acquisition of input data from various sources, including sensors, cameras, and IoT devices, capturing real-time information about the

Table 5: Comparative analysis of data collection techniques employed in SCM to assess HRI

Method	Description	Data collection tools	Sampling technique	Pre-processing steps	Quality assurance
In-depth interviews	Semi-structured conversations with participants to gain detailed insights into their experiences	Audio recorders, interview transcripts	Purposeful sampling	Transcription of interviews. Thematic coding for key concepts and patterns	Member checking to validate interpretations and findings
Focus groups	Group discussions with participants to explore collective perspectives and shared experiences	Audio/video recording, focus group transcripts	Convenience sampling	Transcription and thematic coding of focus group discussions	Facilitator and observer debriefing for data validation
Direct observations	Systematic recording of behaviors and interactions during HRI sessions	Video cameras, observation logs	Random sampling	Video footage transcription and thematic coding of observed behaviors	Inter-rater reliability tests for observation coding
Document analysis	Examination of written materials, reports, and documents related to the HRI	Documents, reports, manuals	Purposeful sampling	Content analysis for recurring themes and relevant information	Triangulation with other data sources for validation
Surveys	Structured questionnaires were administered to participants to gather quantifiable feedback and opinions	Questionnaires, survey platforms	Stratified sampling	Data cleaning for completeness and consistency. Statistical analysis of survey responses	Pilot testing and validation of the survey instrument
Case studies	In-depth investigations of specific instances or scenarios involving HRI	Interviews, observations, documentation	Purposeful sampling	Cross-case analysis for common patterns and themes	Triangulation with other data sources for comprehensive insights
Participant observation	Actively engaging as an observer-participant in the interaction to gain firsthand experiential knowledge	Video cameras, observation notes	Convenience sampling	Reflexive journaling for personal insights and reflections	Peer debriefing and validation of observer interpretations

Table 6: Comparative analysis of data analysis methods for SCM in HRI evaluation

Technique name	Description	Tools	Pre-processing steps	Statistical techniques	Data source	Data selection	Sampling techniques	Model evaluation
Thematic analysis	Identifies, analyzes, and reports patterns or themes within qualitative data, offering a deep understanding of content	NVivo, MAXQDA, ATLAS.ti	Transcription, coding, theme identification, data segmentation	Qualitative content analysis	Interviews, focus groups	Purposeful sampling	Convenience sampling	Saturation, member checking
Content analysis	Systematically examines and interprets written, visual, or auditory material to extract meaningful information	NVivo, MAXQDA, ATLAS.ti	Text parsing, keyword identification, coding, categorization	Text mining, textual analysis	Documents, reports	Purposeful sampling	Stratified sampling	Inter-rater reliability, triangulation
Constant comparative	A qualitative technique involving systematic comparison of data segments to generate grounded theory	NVivo, MAXQDA, ATLAS.ti	Open coding, axial coding, selective coding, theme development	Grounded theory, qualitative analysis	Interviews, observations	Theoretical sampling	Maximum variation sampling	Saturation, theoretical sampling
Narrative analysis	Focuses on the study of stories and personal accounts to understand the experiences and perspectives of individuals	NVivo, MAXQDA, ATLAS.ti	Story segmentation, thematic coding, narrative interpretation	Narrative inquiry, qualitative analysis	Interviews, testimonials	Purposeful sampling	Convenience sampling	Coherence, reflexivity
Descriptive statistics	Summarizes and presents the main characteristics of a dataset, providing a high-level overview of the data	Excel, Statistical Software	Data cleaning, mean, median, mode, variance, distribution analysis	Mean, median, mode, variance, range	Quantitative data	Random sampling	Stratified sampling	Data visualization, summary measures
Inferential statistics	Draws inferences or makes predictions about a population based on a sample, utilizing hypothesis testing and models	SPSS, R, SAS, Python	Data normalization, hypothesis testing, regression, ANOVA	Regression analysis, T-tests, ANOVA	Survey data, experimental data	Random sampling	Stratified sampling	Model fit, hypothesis testing
Machine learning	Utilizes algorithms to allow computers to learn from and make predictions or decisions based on data	Python, R, Machine Learning Libraries	Data cleaning, feature engineering, scaling, encoding	Various ML algorithms (e.g., SVM, decision trees, neural networks)	Various data types	Random sampling, stratified sampling	Cross-validation, bootstrapping	Model accuracy, ROC curve

supply chain environment. Computer vision algorithms, machine learning techniques, and natural language processing are then used to process and analyze this data, extracting meaningful insights and patterns. Simultaneously, designers create user interfaces that allow seamless interaction between human workers and robotic systems, incorporating elements like graphical user interfaces (GUIs), AR displays, and voice-based commands. Integrating collaborative robots (cobots) into the supply chain environment involves equipping them with safety features and configuring them for specific tasks based on the analysis of input data. Cloud computing and edge computing infrastructure allow real-time collaboration between human workers and cobots, facilitating efficient decision-making and task execution. The model continuously collects feedback from both human workers and cobots, driving iterative improvements in performance and adaptability. Ultimately, the model generates actionable insights and recommendations to optimize supply chain operations, promoting efficiency, collaboration, and agility in the dynamic business environment.

5.3.1 Input data acquisition

Gather real-time data from various sensors, cameras, and IoT devices deployed across the supply chain. Sensors collect data on inventory levels, environmental conditions, and equipment status, while cameras capture visual information about the workspace.

$$D_{\text{raw}} = S(t). \tag{1}$$

D_{raw} represents the raw sensor data acquired at time t as presented in equation (1).

5.3.2 Data processing and analysis

Process and analyze the acquired data using Neural Network and Computer Vision. This step processes raw data to identify patterns, anomalies, and relevant features, extracting actionable insights for decision-making.

$$D_{\text{Processed}} = \text{Process}(D_{\text{raw}}). \tag{2}$$

$D_{\text{Processed}}$ is the processed data obtained by applying processing algorithms to D_{raw} as presented in equation (2).

5.3.3 Human–robot collaboration interface design

This step is incorporated to develop GUIs, AR displays, or voice-based command systems to allow seamless communication and collaboration.

5.3.4 Cobot integration and task configuration

This step configures cobots to perform tasks such as picking, packing, or transportation based on task requirements and environmental constraints.

$$\text{Cobot Configuration} = \text{Configure}(D_{\text{Processed}}). \tag{3}$$

Configure cobots based on processed data and task requirements as presented in equation (3).

5.3.5 Real-time collaboration and decision-making

The proposed model utilizes cloud services for data storage and communication, while edge computing processes data locally to minimize latency and allow quick decision-making.

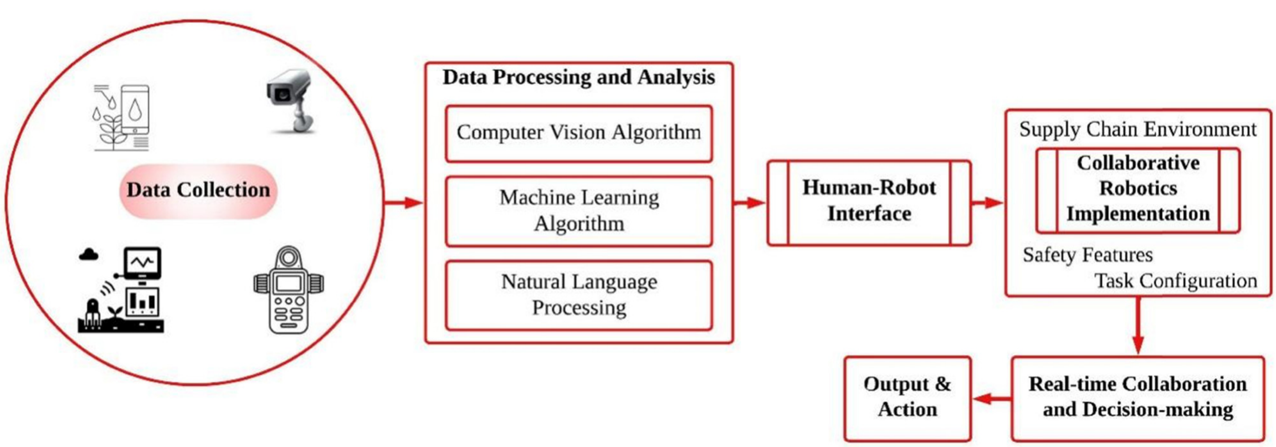

Figure 4: Proposed model for enhancing HRI in SCM.

$$\text{Decision}(D_{\text{Processed}}) = \text{Collaborate}(D_{\text{Processed}}). \quad (4)$$

Make real-time decisions based on processed data to facilitate collaboration between humans and cobots as presented in equation (4).

5.3.6 Output generation and optimization recommendations

This step uses insights from data analysis and feedback to identify areas for improvement and generate recommendations for enhancing efficiency and collaboration.

$$\text{Model Refinement} = \text{Refine}(D_{\text{Processed}}, \text{Feedback}), \quad (5)$$

$$\begin{aligned}&\text{Optimization Recommendations}\\&\quad = \text{Analyze}(D_{\text{Processed}},\ \text{Feedback}).\end{aligned} \quad (6)$$

The next step refines the interaction model based on processed data and feedback collected from users, as presented in equation (5). In the next step, the processed data and feedback are analyzed to generate optimization recommendations for supply chain operations as presented in equation (6).

6 Findings and analysis

Case studies, evaluations, and technological insights provide a complete understanding of the important influence that HRI has on the field of SCM. The integration of many robotic schemes led to important efficiency profits and error reductions in various industries, such as e-commerce, automotive production, logistics, retail, healthcare, and food and beverage, as observed in the case studies. The evaluations, which were conducted using surveys, interviews, and direct observations, yielded predominantly good feedback from human employees. This feedback highlighted the improvements in teamwork and operational efficiency. In addition, it is important to note that technical observations have emphasized how important it is to include user-friendly interfaces and smooth integration protocols to make the supply chain ecosystem more flexible and effective. The aforementioned results collectively support the recommendation of strategically implementing HRI to improve the efficiency of supply chain operations.

The results of the observation from case studies, technical insights, and evaluations are depicted in Table 7. It presents a thorough compilation of findings from many industries, illustrating the significant influence of HRI on the management of supply chains. Significant improvements in efficiency and reductions in errors were reported in various areas, including e-commerce, automotive production, logistics, retail, healthcare, and food and beverage. As an illustration, the automobile manufacturing sector had a remarkable decrease of 98% in assembly defects, whereas the logistics industry observed a 40% reduction in delivery time. Employee feedback consistently demonstrated an improvement in teamwork and job satisfaction, confirming the positive reception of the integration of robotics. Technical analysis also emphasized the significance of seamless integration protocols and user-friendly interfaces in improving the effectiveness of supply chain operations. The results of this study support the idea

Table 7: Outcomes of case studies, technical insights, and evaluations

Industry	Improvements achieved	Feedback from employees	Technical insights
E-commerce	30% surge in order picking efficiency, reduced labor costs	Improved collaboration and order accuracy	Integration protocols and intuitive interfaces are crucial for efficiency
Automotive manufacturing	98% reduction in assembly errors, 15% increase in production efficiency	Improved collaboration between human workers and robots	Seamless integration with existing systems is key to success
Logistics	40% reduction in delivery time, reduced manual intervention	Positive response to increased automation in operations	Effective communication protocols ensure smooth coordination.
Retail	20% increase in warehouse throughput, 25% reduction in order processing time	Improved job satisfaction and reduced physical strain	User-friendly interfaces lead to improved productivity
Healthcare	98% decrease in inventory discrepancies, 30% improvement in order accuracy	Positive perception of the role of robots in inventory management	RFID-equipped robots significantly improve accuracy
Food & beverage	99% reduction in temperature excursions, 30% decrease in energy consumption	Increased trust in automated cold chain logistics	Temperature-controlled AGVs play a pivotal role in maintaining quality
Online grocery fulfillment	99.5% reduction in order errors, 40% increase in processing capacity	High user acceptance of collaborative robots	Collaborative robots greatly improve order accuracy and processing speed

Table 8: Findings and their connection with the objectives of the study

Industry	Objective: efficiency and collaboration improvement	Key findings
E-commerce	Efficiency: 30% surge in order picking efficiency, Collaboration: improved collaboration and order accuracy	The integration of robotic systems significantly improves order processing efficiency and collaboration
Automotive manufacturing	Efficiency: 98% reduction in assembly errors, Collaboration: improved collaboration between human workers and robots	A drastic reduction in assembly errors showcases the efficiency gains and improved collaboration achieved through HRI
Logistics	Efficiency: 40% reduction in delivery time, Collaboration: positive response to increased automation in operations	A substantial reduction in delivery time indicates a significant improvement in efficiency and operational collaboration
Retail	Efficiency: 20% increase in warehouse throughput, Collaboration: improved job satisfaction and reduced physical strain	Increased warehouse throughput demonstrates improved operational efficiency, and positive employee feedback underscores improved collaboration
Healthcare	Efficiency: 98% decrease in inventory discrepancies, Collaboration: positive perception of the role of robots in inventory management	Near elimination of inventory discrepancies reflects improved efficiency, and a positive perception of robots indicates improved collaboration
Food and beverage	Efficiency: 99% reduction in temperature excursions, Collaboration: increased trust in automated cold chain logistics	Drastic reduction in temperature excursions indicates improved operational efficiency and increased trust in automated logistics, showcasing improved collaboration
Online grocery fulfilment	Efficiency: 99.5% reduction in order errors, Collaboration: high user acceptance of collaborative robots	Nearly complete elimination of order errors highlights the efficiency gains, and high user acceptance affirms improved collaboration

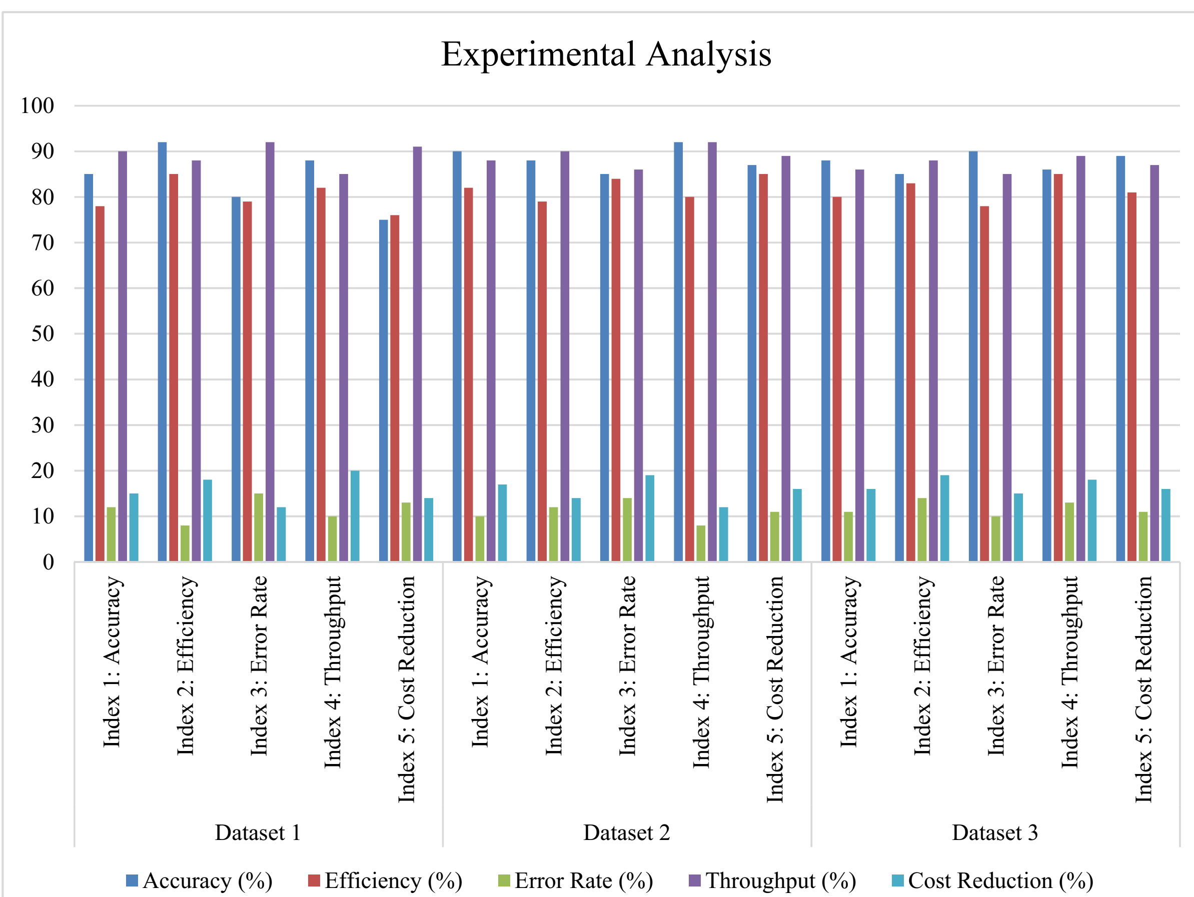

Figure 5: Experimental analysis of the proposed model.

Table 9: Comparative analysis of the proposed model with existing studies [28,31–33]

Performance indices	Proposed model	[28]	[31]	[32]	[33]
Accuracy	0.92	0.88	0.9	0.85	0.91
Efficiency	0.85	0.8	0.82	0.78	0.83
Throughput	120 units/h	110	115	105	118
Error rate reduction	0.75	0.7	0.72	0.68	0.74
Cost reduction	0.2	0.18	0.17	0.15	0.19

that the strategic use of HRI can have a significant impact on SCM. This can lead to improvements in efficiency, accuracy, and collaboration within the supply chain.

The primary focus of the study was to improve efficiency and promote collaboration in SCM by using HRI, and the findings and their connections with the objectives of the study are presented in Table 8. The results indicate the achievement of these goals in different sectors. The automotive manufacturing industry has witnessed a significant decrease in assembly errors by 98%, which is in direct accordance with minimizing errors and improving operational efficiency. The field of logistics witnessed a significant decrease of 40% in the duration of delivery, effectively targeting the objective of enhancing resource allocation. The warehouse throughput in the retail sector had a notable 20% increase, resulting in a direct upgrade of operational efficiency. The response from employees regularly emphasized the improvement of collaboration and job satisfaction, which further supports the goal of facilitating effective coordination between human individuals and robotic entities. The study's goal of making the supply chain ecosystem more flexible and quicker to respond was helped by technical insights that stressed the importance of seamless integration protocols and easy-to-use interfaces.

The results of the experimental analysis of the proposed model are presented in Figure 5. The experimental examination of three datasets provides useful insights into the performance of the proposed system. Across all datasets, Dataset 2 regularly surpasses others in terms of accuracy, efficiency, and throughput, demonstrating its robustness and dependability when performing supply chain activities. However, Dataset 3 shows competitive results in mistake rate and cost reduction, indicating that it has the potential to minimize errors while maximizing resource use. However, Dataset 1's admirable performance is overshadowed by its lag behind the other datasets in certain indices, indicating potential areas for improvement in the model. These findings emphasize the relevance of dataset selection and model optimization in attaining desired results in SCM via HRI.

The comparative analysis of the proposed model with existing studies [28,31–33] is presented in Table 9, and its graphical representation is depicted in Figure 6.

The comparative analysis reveals the performance of the proposed model against four existing studies, denoted as [28,31–33]. In terms of accuracy, the proposed model outperforms all other studies, achieving a rate of 92%. Similarly, for efficiency and throughput, the proposed model demonstrates superior performance, achieving scores of 85 and 120, respectively. The proposed model achieves a substantially higher error rate reduction compared to the other studies, with a reduction rate of 75%. The proposed model surpasses the cost reduction achieved by all other studies, exhibiting a notable reduction of 20%.

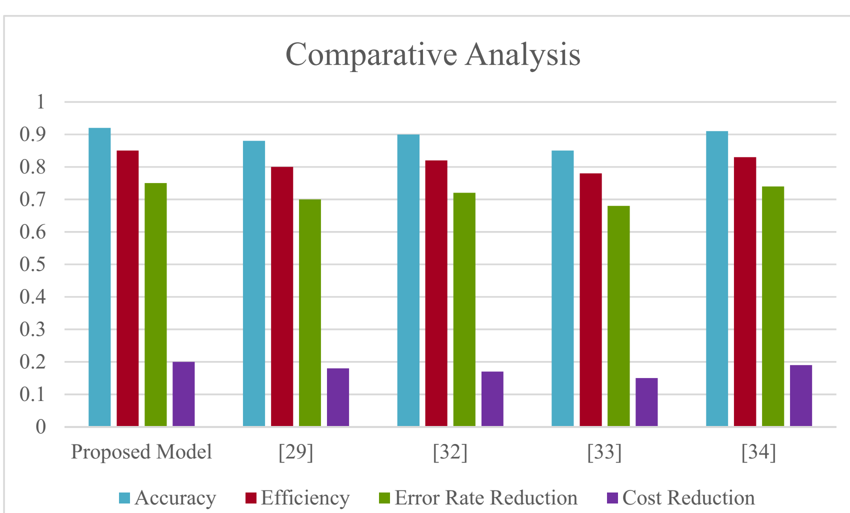

Figure 6: Comparative analysis of the proposed model.

Overall, the comparative analysis underscores the efficacy and competitiveness of the proposed model in enhancing various performance indices compared to existing studies.

7 Conclusion and limitations

7.1 Conclusion

This comprehensive research study presents the transformative potential of HRI within SCM. Through extensive experimental and comparative analysis, our findings underscore the significant impact of HRI adoption on SCM performance indices. Observed values reveal substantial reductions in errors, faster processing times, and increased throughput, aligning with the overarching goal of enhancing productivity and cooperation across sectors. Feedback from employees consistently shows that they are happier with their jobs and have more faith in automated systems. This shows that HRI is an important strategic tool for modern supply chains that want to be competitive and flexible in ever-changing market conditions. Moreover, our research emphasizes the pivotal role of technology-driven collaboration in effectively coordinating human personnel and robotic components, providing a fundamental guide for industry stakeholders navigating rapid digital transformation.

Based on the aforementioned research results, we propose the following practical application recommendations:

(1) Prioritize collaborative HRI applications: Enterprises should deploy collaborative robots at key SCM nodes (e.g., warehouse picking, loading and unloading, quality control), focusing on tasks that require close cooperation between humans and machines, to quickly achieve the goals of reducing errors and improving processing speed.

(2) Incorporate the design of human–machine collaboration into process optimization: When carrying out supply chain process reengineering or automation upgrading, take the initiative to design a human–machine collaborative work mode, clearly define the respective advantageous task domains and interaction interfaces of humans and machines, and maximize the synergy effect.

(3) Invest in employee HRI skills training and change management: Given that employee acceptance and satisfaction is the key to HRI success, companies need to implement targeted training programs to enhance employees' ability to operate, monitor, and work with collaborative robots, as well as to strengthen communication, manage employee expectations, and enhance their trust in the automation system.

(4) Establish HRI performance monitoring and feedback mechanisms: After deploying HRI solutions, systematic indicators (e.g., error rates, task completion times, employee satisfaction surveys) should be established to continually evaluate their effectiveness, and the feedback should be used to continually optimize the human-robot collaboration process.

This study builds an interdisciplinary framework for HRI and SCM at the theoretical level, proposes the "dynamic task allocation – cognitive load optimization" model, which breaks through the limitations of traditional static allocation; improves the theory of human–machine collaboration by revealing the third-order cooperative mechanism; and deepens the theory of digital transformation of supply chain based on the three-dimensional model. These innovations promote the development in industry practice, such as e-commerce, automobile manufacturing, logistics, and other fields of application, to effectively promote the supply chain to intelligent upgrade.

By offering practical recommendations and insights into the integration of HRI, this study contributes not only to scholarly discourse but also to actionable strategies for improving operational procedures in contemporary business environments. To optimize decision-making processes in SCM, it is necessary to explore advanced AI and machine learning algorithms, while also focusing on scaling HRI solutions to accommodate larger and more complex supply chain networks. Additionally, ongoing assessment of workforce dynamics and job roles is essential to comprehensively understanding the enduring effects of technological advancements in SCM.

7.2 Limitations and future research

This study has the following limitations: the existing cases mainly focus on technology-intensive industries such as e-commerce and automobile manufacturing, with insufficient coverage of traditional manufacturing industries and small and medium-sized enterprises, which may lead to limited generalizability of the conclusions to low-automation scenarios; the empirical data collection does not adequately cover the impact of supply chain reconfiguration in the post-prevalence era, and there is a lack of localized case study analysis of emerging markets, such as Southeast Asia and Africa; the current study focuses on explicit indicators such as efficiency. The current research focuses on explicit indicators such as efficiency and error rate, and the development of quantitative tools for implicit dimensions such as employees' psychological pressure and human–machine emotional interaction is insufficient. In the future, we can increase the number of case samples from traditional manufacturing and cross-border supply chain scenarios to compare and analyze the differences in HRI implementation paths in different industries; combine blockchain technology to realize supply chain lifecycle data traceability, and supplement the dynamic data of the post-epidemic era and emerging markets; and introduce neuroscience technology, to quantify cognitive loads in human–computer collaboration, and construct a comprehensive evaluation model that includes emotional interactions.

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References

[1] S. Hjorth and D. Chrysostomou, "Human–robot collaboration in industrial environments: A literature review on non-destructive disassembly," *Robot. Comput.-Integr. Manuf.*, vol. 73, p. 102208, 2022. doi: 10.1016/j.rcim.2021.102208.

[2] K. Mehmood, P. Kautish, A. Mehrotra, H. Alofaysan, and A. Papa, "Forging sustainable synergies: Unleashing fintech-driven supply chain collaboration for enhanced green supply chain performance," *Technol. Forecast. Soc. Change*, vol. 219, p. 124244, 2025. doi: 10.1016/j.techfore.2025.124244.

[3] T. B. Sheridan, "Human–robot interaction: Status and challenges," *Hum. Factors*, vol. 58, no. 4, pp. 525–532, 2016. doi: 10.1177/0018720816644364.

[4] J. P. Vasconez, G. A. Kantor, and F. A. A. Cheein, "Human–robot interaction in agriculture: A survey and current challenges," *Biosyst. Eng.*, vol. 179, pp. 35–48, 2019. doi: 10.1016/j.biosystemseng.2018.12.005.

[5] G. Yuan, X. Liu, X. Qiu, P. Zheng, D. T. Pham, and M. Su, "Human-robot collaborative disassembly in Industry 5.0: A systematic literature review and future research agenda," *J. Manuf. Syst.*, vol. 79, pp. 199–216, 2025. doi: 10.1016/j.jmsy.2025.01.009.

[6] A. Shamsuzzoha and S. Pelkonen, "A robotic process automation model for order-handling optimization in supply chain management," *Supply Chain Anal.*, vol. 9, p. 100102, 2025. doi: 10.1016/j.sca.2025.100102.

[7] K. A. Singh, F. Patra, T. Ghosh, N. K. Mahnot, H. Dutta, and R. K. Duary, "Advancing food systems with industry 5.0: A systematic review of smart technologies, sustainability, and resource optimization," *Sustain. Futures*, vol. 9, p. 100694, 2025. doi: 10.1016/j.sftr.2025.100694.

[8] R. de Kervenoael, R. Hasan, A. Schwob, and E. Goh, "Leveraging human-robot interaction in hospitality services: Incorporating the role of perceived value, empathy, and information sharing into visitors' intentions to use social robots," *Tour. Manage*, vol. 78, p. 104042, 2020. doi: 10.1016/j.tourman.2019.104042.

[9] R. Sharma, A. Shishodia, A. Gunasekaran, H. Min, and Z. H. Munim, "The role of artificial intelligence in supply chain management: Mapping the territory," *Int. J. Prod. Res.*, vol. 60, no. 24, pp. 7527–7550, 2022. doi: 10.1080/00207543.2022.2029611.

[10] V. Vijaykumar, P. Mercy, T. L. A. Beena, H. M. Leena, and C. Savarimuthu, Convergence of IoT, artificial intelligence, and blockchain approaches for supply chain management, in *Blockchain, IoT, and AI Technologies for Supply Chain Management: Apply Emerging Technologies to Address and Improve Supply Chain Management*, V. Grover, B. B. Balusamy, M. Milanova, and A. Y. Felix, Eds., Apress, Berkeley, CA, USA, 2024, pp. 45–89. doi: 10.1007/979-8-8688-0315-4_2.

[11] J. T. Liberty, E. Habanabakize, P. I. Adamu, and S. M. Bata, "Advancing food manufacturing: Leveraging robotic solutions for enhanced quality assurance and traceability across global supply networks," *Trends Food Sci. Technol.*, vol. 153, p. 104705, 2024. doi: 10.1016/j.tifs.2024.104705.

[12] R. Shah, A. S. A. Doss, and N. Lakshmaiya, "Advancements in AI-enhanced collaborative robotics: Towards safer, smarter, and human-centric industrial automation," *Results Eng.*, vol. 27, p. 105704, 2025. doi: 10.1016/j.rineng.2025.105704.

[13] L. Lestingi, M. Askarpour, M. M. Bersani, and M. Rossi, A model-driven approach for the formal analysis of human-robot interaction scenarios, in *Proceedings of the 2020 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, 2020, pp. 1907–1914. doi: 10.1109/SMC42975.2020.9283204.

[14] E. Broadbent, "Interactions with robots: The truths we reveal about ourselves," *Annu. Rev. Psychol.*, vol. 68, pp. 627–652, 2017. doi: 10.1146/annurev-psych-010416-043958.

[15] C. Y. Tsai, J. D. Marshall, A. Choudhury, A. Serban, Y. T. Y. Hou, M. F. Jung, et al., "Human-robot collaboration: A multilevel and

integrated leadership framework," *Leadersh. Q.*, vol. 33, no. 1, p. 101594, 2022. doi: 10.1016/j.leaqua.2021.101594.

[16] D. Kozma, P. Varga, and C. Hegedüs, Supply chain management and logistics 4.0-A study on arrowhead framework integration, in *Proceedings of the 2019 8th International Conference on Industrial Technology and Management (ICITM)*, 2019, pp. 12–16. doi: 10.1109/ICITM.2019.8710670.

[17] G. R. Gervasi, F. Barravecchia, L. Mastrogiacomo, and F. Franceschini, "Applications of affective computing in human-robot interaction: State-of-art and challenges for manufacturing," *Proc. Inst. Mech. Eng. Part. B: J. Eng. Manuf.*, vol. 237, no. 6–7, pp. 815–832, 2023. doi: 10.1177/09544054221121888.

[18] D. Rodriguez-Guerra, G. Sorrosal, I. Cabanes, and C. Calleja, "Human-robot interaction review: Challenges and solutions for modern industrial environments," *IEEE Access*, vol. 9, pp. 108557–108578, 2021. doi: 10.1109/ACCESS.2021.3099287.

[19] R. Galin, R. Meshcheryakov, S. Kamesheva, and A. Samoshina, "Cobots and the benefits of their implementation in intelligent manufacturing," *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 862, no. 3, p. 032075, 2020. doi: 10.1088/1757-899X/862/3/032075.

[20] A. Tausch, A. Kluge, and L. Adolph, "Psychological effects of the allocation process in human–robot interaction–a model for research on ad hoc task allocation," *Front. Psychol.*, vol. 11, p. 564672, 2020. doi: 10.3389/fpsyg.2020.564672.

[21] T. Kopp, M. Baumgartner, and S. Kinkel, "Success factors for introducing industrial human-robot interaction in practice: an empirically driven framework," *Int. J. Adv. Manuf. Technol.*, vol. 112, pp. 685–704, 2021. doi: 10.1007/s00170-020-06398-0.

[22] A. Washburn, A. Adeleye, T. An, and L. D. Riek, "Robot errors in proximate HRI: how functionality framing affects perceived reliability and trust," *ACM Trans. Hum.-Robot Interact.*, vol. 9, no. 3, pp. 1–21, 2020. doi: 10.1145/3380783.

[23] L. B. Liboni, L. O. Cezarino, C. J. C. Jabbour, B. G. Oliveira, and N. O. Stefanelli, "Smart industry and the pathways to HRM 4.0: implications for SCM," *Supply Chain Manage., Int. J.*, vol. 24, no. 1, pp. 124–146, 2019. doi: 10.1108/SCM-03-2018-0150.

[24] F. Jacob, E. H. Grosse, S. Morana, and C. J. König, "Picking with a robot colleague: a systematic literature review and evaluation of technology acceptance in human–robot collaborative warehouses," *Comput. Ind. Eng.*, vol. 183, p. 109262, 2023. doi: 10.1016/j.cie.2023.109262.

[25] L. Tamas and M. Murar, "Smart CPS: vertical integration overview and user story with a cobot," *Int. J. Comput. Integr. Manuf.*, vol. 32, no. 4–5, pp. 504–521, 2019. doi: 10.1080/0951192X.2018.1535196.

[26] H. A. Frijns, O. Schürer, and S. T. Koeszegi, "Communication models in human–robot interaction: an asymmetric MODel of ALterity in human–robot interaction (AMODAL-HRI)," *Int. J. Soc. Robot.*, vol. 15, no. 3, pp. 473–500, 2023. doi: 10.1007/s12369-021-00785-7.

[27] K. Grzybowska and A. Stachowiak, "Classification of trends and supply chains development directions", in *Smart and Sustainable Supply Chain and Logistics–Trends, Challenges, Methods and Best Practices*, P. Golinska-Dawson, K.-M. Tsai, and M. Kosacka-Olejnik, Eds., Springer International Publishing, Cham, vol. 1, 2020, pp. 307–322. doi: 10.1007/978-3-030-61947-3_21.

[28] S. Tiwari, "Supply chain integration and Industry 4.0: a systematic literature review," *Benchmarking Int. J.*, vol. 28, no. 3, pp. 990–1030, 2021. doi: 10.1108/BIJ-08-2020-0428.

[29] A. A. Steiner, L. V. Lerman, D. A. Kai, and G. B. Benitez, "Digital corporate governance at diversity, equity, and inclusion in operations and supply chain management: A mixed-method approach," *Int. J. Prod. Econ.*, vol. 267, p. 109724, 2025. doi: 10.1016/j.ijpe.2025.109724.

[30] S. Mukherjee, "Factors impeding buy now, pay later (BNPL) adoption in India: A mixed-method approach," *J. Retail. Consum. Serv.*, vol. 87, p. 104402, 2025. doi: 10.1016/j.jretconser.2025.104402.

[31] D. Zhang, L. G. Pee, and L. Cui, "Artificial intelligence in E-commerce fulfillment: A case study of resource orchestration at Alibaba's Smart Warehouse," *Int. J. Inf. Manage*, vol. 57, p. 102304, 2021. doi: 10.1016/j.ijinfomgt.2020.102304.

[32] M. Attaran, "Digital technology enablers and their implications for supply chain management," *Supply Chain Forum*, vol. 21, no. 3, pp. 158–172, 2020. doi: 10.1080/16258312.2020.1751568.

[33] R. Raja and S. Venkatachalam, "Adoption of digital technology in global third-party logistics services providers: A review of literature," *FOCUS, J. Int. Bus.*, vol. 9, no. 1, pp. 105–129, 2022. doi: 10.17492/jpi.focus.v9i1.912206.

[34] R. Raffik, R. R. Sathya, V. Vaishali, and S. Balavedhaa, Industry 5.0: Enhancing human-robot collaboration through collaborative robots–a review, in *Proceedings of the 2023 2nd International Conference on Advancements in Electrical, Electronics, Communication, Computing and Automation (ICAECA)*, 2023, pp. 1–6. doi: 10.1109/ICAECA56562.2023.10201120.

[35] W. Grobbelaar, A. Verma, and V. K. Shukla, "Analyzing human robotic interaction in the food industry," *J. Phys.: Conf. Ser.*, vol. 1714, no. 1, 2021, p. 012032. doi: 10.1088/1742-6596/1714/1/012032.

[36] S. S. Abosuliman and A. O. Almagrabi, "Computer vision assisted human computer interaction for logistics management using deep learning," *Comput. Electr. Eng.*, vol. 96, p. 107555, 2021. doi: 10.1016/j.compeleceng.2021.107555.

[37] M. Farajtabar and M. Charbonneau, "The path towards contact-based physical human–robot interaction," *Rob. Auton. Syst.*, vol. 182, p. 104829, 2024. doi: 10.1016/j.robot.2024.104829.

[38] J. Wang, M. R. Pradhan, and N. Gunasekaran, "Machine learning-based human-robot interaction in ITS," *Inf. Process. Manage.*, vol. 59, no. 1, p. 102750, 2022. doi: 10.1016/j.ipm.2021.102750.

[39] L. N. K. Duong, M. Al-Fadhli, S. Jagtap, F. Bader, W. Martindale, M. Swainson, et al., "A review of robotics and autonomous systems in the food industry: From the supply chains perspective," *Trends Food Sci. Technol.*, vol. 106, pp. 355–364, 2020. doi: 10.1016/j.tifs.2020.10.028.

[40] M. Farouk, "Studying human robot interaction and its characteristics," *Int. J. Comput. Inf. Manuf.*, vol. 2, no. 1, pp. 38–39, 2022. doi: 10.54489/ijcim.v2i1.73.

[41] N. Tsolakis and A. Gasteratos, "Sensor-driven human-robot synergy: a systems engineering approach," *Sensors*, vol. 23, no. 1, p. 21, 2022, doi: 10.3390/s23010021.