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EMBRACING INDUSTRY 5.0: HUMAN-CENTRIC DESIGN OF IIoT ENABLED DIGITAL TWINS IN THE PRINTING INDUSTRY

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Purpose: Investigating the human-centered frameworks for Industry 5.0 (I5.0), such as the Industrial Internet of Things (IIoT) and Digital Twins (DTs) within the automated printing industries is the study's key. It also explores the factors impacting the industry adoption and implementation of IIoT and DTs.
Design/methodology/approach: The research follows a qualitative and conceptual approach based on systematic literature review of recent research papers and industry reports. Key technologies, such as collaborative robots and DTs, are explored in their role in enhancing Human-Machine Collaboration (HMC) especially in the printing industry sector.
Findings: I5.0 technologies like IIoT as well as DTs in the printing industry improve efficiency, product development, Predictive Maintenance (PdM), and overall performance. As per the findings, the practices and approaches required to implement IIoT in the printing industry.
Research limitations/implications: IIoT and DTs are transforming businesses' operations in today's world. The use of these technologies helps to enable real-time monitoring, PdM, optimized processes, and improved Decision-Making (DM) in automated printing industries, ultimately boosting efficiency and quality while reducing costs.
Originality/value: This study pioneers by examining I5.0 technology role in the printing industry. The study provides insights into interoperability, digital transformation and integration, PdM, optimized operations, and data-driven DM in automated printing environments.
Keywords: Industry 5.0, IIoT, Human-Centric, Printing Industry, Industry Internet of Things, Predictive maintenance.
Category of the paper: Research article.

1. Introduction

There is a constant evolution in the industrial background, determined by technological advancements and the chase of greater efficiency as well as productivity. Different industrial eras are transformed by emerging technologies. Traditional industrial practices' transformation into novel methodologies, conquered by the technologies open at that time, is termed the industrial revolution. Building upon the early '4' industrial revolutions, I5.0 introduces a paradigm emphasizing the synergy betwixt advanced technologies and human values (Bazel et al., 2024; Sarioglu, 2023; Santhi, Muthuswamy, 2023; Kumar, 2024). Unlike Industry 4.0, which prioritized automation and data exchange, I5.0 aims on engendering a Human-Centric (HC), resilient, and sustainable industrial ecosystem (Toth et al., 2023; Pacheco, Iwaszczenko, 2024). It addresses Industry 4.0's limitations by placing human well-being together with collaboration at the center of industrial processes (Alves et al., 2023; Khan et al., 2023). In this era, industrial operation convergence with technologies like the IIoT permits real-time data processing, PdM, together with enhanced DM across manufacturing environments. In Figure 1, the key benefits of IIoT implementation in industries are given.

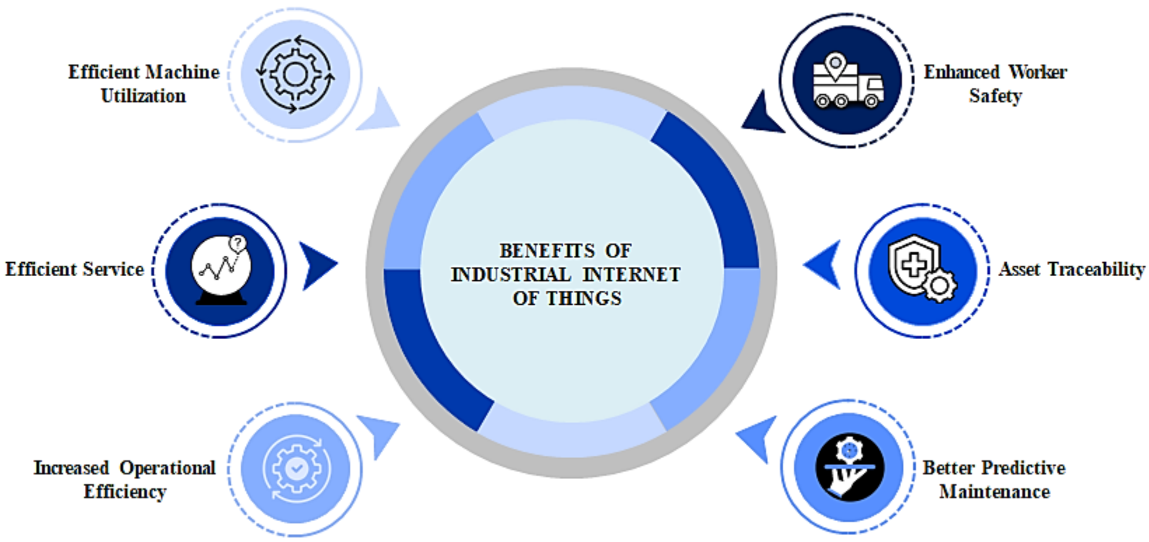

Figure 1. Benefits of IIoT systems.

Source: own elaboration.

Due to sensing, data storage, and intelligent control capabilities within innovative manufacturing environments, IIoT technologies are witnessing exponential growth (Hu et al., 2021; Hussain et al., 2021; Zheng et al., 2020; Alhuqay et al., 2024; Ayeni, 2025). IIoT incorporates huge sensors meant for smart and connected monitoring of machine conditions (Kan et al., 2018; Abuhasel, Khan, 2020). The IIoT potential automation, efficiency, and data-driven DM by real-time data collection and analysis (Jamil et al., 2024). These developments significantly increase productivity and reduce capital and operational costs in industries (Alabadi et al., 2022; Ahmed et al., 2023). However, disparities in productivity and performance still exist, especially while machine-to-machine communication is combined with big data analytics without human oversight or coordination (Jaidka et al., 2020; Hou et al., 2023). Besides, the printing industry faces critical challenges in integrating I5.0 technologies, such as IIoT and DTs, due to limited awareness, lack of implementation strategies, and interoperability issues. While previous studies have examined the adoption of IIoT in broader manufacturing contexts, there is a clear research gap in exploring human-centered frameworks for I5.0 within automated printing environments. Thus, the present research scrutinizes the role of I5.0 and IIoT in the automated printing industry.

The research objectives are:

- To investigate the IIoT's adoption and implementation in production along with manufacturing environments under the I5.0 model.
- To identify the practices together with the approaches of organizations toward implementing IIoT solutions in the printing industry.
- To assess the implementation of HC DTs technology for industrial automation scenarios that support and augment interactions among humans and machines in the printing industry.
- To identify the key technologies facilitating the collaboration of autonomous machines and robots with humans in automated printing industries.

Despite a growing body of literature exploring the integration of Industry 5.0 technologies, particularly IIoT and Digital Twins (DTs), within broader manufacturing and engineering contexts, there is a notable lack of research that directly addresses their application through a human-centric lens in the automated printing industry. Most existing studies (e.g., Arnold, Voigt, 2018; Kumar, Iyer, 2019; Paliwoda et al., 2023; Ghafari et al., 2024) focus on:

- Generic industrial sectors such as packaging, engineering, or general manufacturing without considering the specific operational, technological, and human factors of the printing domain.
- The technological feasibility and performance impact of IIoT and DTs, with limited attention to human-machine collaboration (HMC)—a core tenet of Industry 5.0.
- The challenges of IIoT adoption in SMEs, but do not distinguish or investigate sector-specific barriers (e.g., high customization needs, legacy equipment, data variability in printing processes).
- Digital transformation and interoperability challenges in general terms, without contextualizing these within the complex workflows, error margins, and quality control demands of the printing industry.

Moreover, no prior study has systematically synthesized the adoption practices, enabling technologies, implementation strategies, and socio-technical barriers specific to human-centric IIoT and DT deployment in automated printing environments. The role of collaborative technologies like cobots and human-in-the-loop Digital Twins, though often mentioned conceptually, lacks empirical or contextual analysis within the printing industry sector. According to what we were able to find, there are no studies referring and reporting on this crucial topic.

After the introduction, the paper is structured as: the paper's literature review and research methods is elucidated in Section 2 and further in Section 3. The implementation of a basic IIoT under I5.0 model together with practices along with approaches toward IIoT implementation in printing industry, technologies facilitating the HMC in the automated printing industry and elaborates of DTs' role in the printing industry, together with addressed challenges and barriers related to the implementation of I5.0 can be found in Section 4; lastly, Section 5, 6 and 7 focuses on results, discussion and conclusions.

2. Related literature review

The systematic literature review clearly reveals a significant research gap regarding the adoption and integration of Industry 5.0 (I5.0) frameworks specifically the Industrial Internet of Things (IIoT) and Digital Twins (DTs) in the automated printing industry. Although existing studies have extensively addressed IIoT and DTs within broader manufacturing contexts, such as engineering, general production environments, and packaging sectors, there remains an evident lack of focused research explicitly tailored in different printing technologies within the printing industry.

For instance, Arnold and Voigt (2018), Paliwoda et al. (2023), and Ptak and Lis (2024) primarily explored broader industrial contexts without specific attention to the nuanced demands of the printing sector. Similarly, research by Kumar and Iyer (2019), Ghafari et al. (2024), and Hsu (2023) identified general benefits and challenges of IIoT and DTs but did not specifically address the unique complexities and operational variables of the printing industry.

The thematic review also identified critical areas where research remains sparse:

- No studies have explicitly examined the human-centric implications of integrating I5.0 technologies within the automated printing sector.
- Existing literature predominantly focuses on technological adoption and implementation without adequately exploring the combined human-machine collaboration (HMC) dimensions essential to I5.0.
- Limited empirical research is available regarding the specific operational benefits, barriers, and strategic solutions unique to digital transformation in the automated printing context.

According to this, there are no existing studies comprehensively reporting on the application, integration, and implications of human-centered I5.0 frameworks, particularly IIoT and DT technologies, within automated printing environments. Therefore, this study fills an essential research gap by providing detailed insights into this unexplored area, highlighting how human-machine collaboration and advanced technologies can cohesively enhance productivity, sustainability, and operational efficiency within the automated printing industry. (Arnold, Voigt, 2018) scrutinized IIoT adoption factors. The data required for the study were gathered from 197 manufacturers through a survey questionnaire in Germany. By using logistic regression analysis, the data was tested. The study's findings showed that the factors from technology, organization, and environmental perspectives significantly impacted the adoption of the IIoT. The study included firm size as an independent variable, but it failed to differentiate the firm size between small and large companies.

Paliwoda et al. (2023) assessed the practices of organizations toward implementing IIoT solutions in the packaging industry. The quantitative data was collected through a questionnaire and Computer Assisted Telephone Interview (CATI) from 132 companies in Poland. As per the results, the companies within the packaging industry were not early adopters of IIoT. Also, the companies were digitally immature, with poor IIoT implementation and quality system digitization. Yet, the sample only consisted of companies in Poland.

Ptak and Lis (2024) scrutinized IIoT's role and impact on augmenting engineering operations via process automation. From 142 enterprises in Poland, the data was obtained based on a questionnaire survey. Descriptive statistics analyzed the data. It indicated that IIoT implementation increased the competitiveness of enterprises. Also, the lack of sufficient machine monitoring, recurrent breakdowns as well as downtime, and the high cost were the IIoT implementation challenges. Yet, survey respondents were medium-sized enterprises.

Peter et al. (2023) examined how the IIoT transformation impacted the performance of manufacturing enterprises. It was centered on a qualitative research approach. The study data was taken from 21 experts through semi-structured interviews from Morocco, the United States, Nigeria, and South Africa. The challenges of IIoT are data security and confidentiality, authenticity, data integrity, cultural behavior, and user acceptance of the technology. Yet, not all the experts were attentive in participating in an interview, which might result in bias.

Rajkumar et al. (2025) applied a HC approach to improve manufacturing's productiveness, creativity, and standard efficiency. The study included quantitative data, qualitative observations, and case research. The study found that I5.0 permitted sustainable manufacturing processes by incorporating loftier technology with collaborative robotics and Artificial Intelligence (AI); also, amplified fact with human capabilities as well as creativity.

Sivathanu (2019) scrutinized the adoption of IIoT through the Technology-Organization-Environment (TOE). The data was amassed via face-to-face interviews with 45 managers using a questionnaire. By employing PLS-SEM, the data were analyzed. As per the study, IIoT adoption was impacted by factors like IIoT expertise, relative advantage, IIoT infrastructure, compatibility, security, cost, organizational readiness, competitive pressure, top management support, as well as support from technology vendors. Yet, it failed to explore the challenges along with resistance factors inhibiting IIoT's adoption intention.

Annavarapu (2024) discovered the transformative impact of IIoT on manufacturing processes. A mixed-method approach was employed. Through surveys and interviews, the data had been collected. The data was analyzed using statistical techniques. By enabling real-time monitoring and PdM, IIoT integration improved manufacturing efficiency. Also, the integration of IIoT led to enhanced visibility into manufacturing processes, better resource utilization, and improved product quality. Yet, the study did not explore the longer-term impacts of IIoT on the manufacturing sector.

Kumar and Iyer (2019) explored the benefits and challenges of IIoT in the engineering and manufacturing industries. The data had been collected through interviews with industry experts. As per the study, the benefits of IIoT in industries were digitally connected and remote management, facility management, auto supervision, real-time asset as well as inventory management, plant safety and security, and quality control. Besides, the challenges of IIoT are security issues, connectivity, and visibility. But, the study only focused on the engineering and manufacturing industries.

Ghafari, Shourangiz and Wang (2024) aimed to conduct the cost-effectiveness of the adoption of IIoT in the manufacturing industries. The study appraised the data from the Industrial Assessment Centers database, aiming on 62 U.S. manufacturing smaller-scale enterprises across 10 states and 25 Standard Industrial Classifications. By employing inferential statistics, the data was analysed. As per the result, the adoption of IIoT wasn't just operationally beneficial for SMEs but also for financial prudence, which causes a key cost-trade-off. The study only considered the manufacturing industries. Thus, the same results were not applicable to other industries.

Hsu (2023) aimed on the interplay between IIoT and the business-to-business customer experience in the manufacturing industry. A qualitative research approach was employed. Through semi-structured interviews with 9 participants, the data required for the study were collected. To analyze the data, thematic analysis was utilized. The study highlighted that IIoT technologies contributed to significant internal business value and fostered longer-term and mutually valuable business relations in the manufacturing sector. However, the size of the sample was very limited, thus affecting the accuracy of the result.

3. Research methods

To achieve the research objectives and to identify the existing gap in the literature on Industry 5.0 implementation within the automated printing sector, this study employed a systematic literature review as the primary research method. This approach was selected because it enables a structured synthesis and critical evaluation of existing research, helping to uncover underexplored areas, trends, and theoretical and practical gaps in the field.

Search strategy and databases: The literature was searched systematically using a combination of academic databases and platforms, including Scopus, Web of Science, IEEE Xplore, SpringerLink, ScienceDirect, and Google Scholar. The search included peer-reviewed journal articles, conference proceedings, white papers and relevant industry reports.

Search keywords: The search was guided by a combination of terms such as: ("Industry 5.0" OR "Fifth Industrial Revolution") AND ("IIoT" OR "Industrial Internet of Things") AND ("Digital Twins" OR "DT") AND ("printing industry" OR "automated printing") AND ("human-machine collaboration" OR "human-centric").

Inclusion and exclusion criteria

Inclusion criteria were:

- Peer-reviewed articles, book chapters, or conference papers.
- Publications in English.
- Articles published between 2018 and 2025 to reflect the most recent developments.
- Studies related to IIoT, DTs, and human-centric applications in industrial or manufacturing contexts.

Exclusion criteria included:

- Non-English publications.
- Articles not addressing IIoT, DTs, or human-centric approaches.
- Studies focusing solely on Industry 4.0 without implications for Industry 5.0.

Review and analysis procedure: After the initial screening, abstracts and titles were reviewed to assess relevance. Selected articles were then subjected to full-text analysis. A thematic analysis approach was employed to identify recurring themes, implementation practices, enabling technologies, benefits, and barriers. The studies were categorized by sector, focus area (e.g., technological, organizational, human-centric), and geographical scope to gain a holistic understanding of the field.

Justification of method selection: The systematic literature review was deemed appropriate due to the conceptual and exploratory nature of the topic, and the scarcity of direct empirical studies in the specific context of automated printing within I5.0. This method allowed for the collection, classification, and interpretation of a wide range of insights to establish a comprehensive understanding of the current knowledge landscape and its limitations. The results derived from this method supported the formulation of informed conclusions regarding the technological readiness, socio-technical integration challenges, and strategic pathways for adopting I5.0 technologies in the printing industry.

4. A Human-centric design of IIoT enabled digital twins in the printing industry

Industry 5.0: A Human-Centric Approach a comparison to Industry 4.0

I5.0 represents the new evolution in industrial development, building upon Industry 4.0's advancements in (1) automation, (2) data exchange, and (3) smart technologies. It presents a human-focused model that includes the creative and cognitive strengths of people with the capabilities of advanced systems. For utilizing human brainpower along with creativity to augment process efficiency by joining workflows with intelligent systems, the 5th Industrial Revolution paired humans and machines. The new era focuses on fostering a collaborative partnership betwixt humans and machines, boosting productivity while emphasizing human well-being together with sustainable industrial practices.

This HC direction shifts focus away from purely technology-driven outcomes and gives more weight to individual needs, worker development, and ethical responsibilities. As a result, industry workers can take on new roles as their value is increasingly recognized not as a cost, but as a strategic investment. Golovianko et al. (2023) critically explore the conceptual and technological evolution from Industry 4.0 (I4.0) to Industry 5.0 (I5.0), emphasizing the importance of a hybrid model that integrates the efficiency of automation with the ethical, resilient, and human-centric values of modern industrial development. The paper highlights that while I4.0 focuses on machine autonomy, cyber-physical systems, and data-driven decision-making with humans largely "out of the loop", I5.0 reintroduces the "human-in-the-loop" paradigm to address societal, ecological, and workplace challenges. In line with this vision, It is crucial to extend this insights to the printing industry by presenting a comparative analysis of how these two industrial paradigms manifest differently in practice.

Table 1.
Comparison of Industry 4.0 and Industry 5.0 in the Printing Industry

Aspect	Industry 4.0 in Printing Industry	Industry 5.0 in Printing Industry
Core Focus	Automation, digitization, and data exchange	Human-centricity, sustainability, and human-machine collaboration
Role of Humans	Marginalized; seen mainly as operators	Central; seen as collaborators and creative contributors
Technology Use	IoT, cloud computing, big data	Builds on I4.0 tech + IIoT, DTs, cobots, AI-human synergy
Objective	Efficiency and autonomous operation	Balance of productivity and human well-being
Human-Machine Interaction	Limited; full automation focus	Collaborative HMC with shared tasks
Decision-Making	Data-driven with minimal human input	Data-informed, with ethical and cognitive human oversight
Digital Twin Role	Simulation and monitoring	Real-time interaction, predictive capabilities, human-in-the-loop decisions
PdM Capabilities	Emerging, machine-based analytics	Real-time sensor integration with human response

Cont. table 1.

Customization Flexibility	Emphasis on mass production	Supports mass personalization and rapid adaptation
Workplace Impact	Job displacement risk, limited creative roles	Empowerment, safer and more meaningful human work
Challenges	Data integration, system complexity, cybersecurity	Adds ethics, talent gaps, interoperability, regulation uncertainty
Sustainability Goals	Often implicit	Explicit and essential component of strategy
View of Workforce	Operational cost to optimize	Strategic asset and innovation driver

Source: own elaboration.

This integration illustrates how Golovianko et al. (2023) approach can directly inform sector-specific implementations such as printing by harmonizing technical progress with human involvement. The table serves as a practical lens for visualizing the shift from efficiency-centric to human-centric industrial systems

Industrial Internet of Things (IIoT) as a Core Enabler of Industry 5.0

I5.0 is enabled by various technologies, namely (1) Internet of Things, (2) AI, (3) big data analytics, (4) cloud computing, along with (5) collaborative robots. The IIoT is a specific application of IoT within the industrial sector, focusing on connecting and analyzing data from industrial equipment, machines, and processes. It has already ushered in transformative changes across industries by connecting machines, systems, and processes. IIoT plays a key role in enabling along with driving advancements of I5.0 as it connects machines, systems, and methods, allowing for better communication and collaboration betwixt humans as well as machines. IIoT could subsidize to more sustainable industrial practices by enabling energy efficiency, resource optimization, and real-time monitoring of environmental impacts.

Determinants of IIoT Adoption in manufacturing and production environment

The industry's success and growth depend on the individual performance in an organization and the adoption of technology in the environment. Adopting IIoT in the manufacturing along with production industry leads to growth and success with enhanced productivity, efficiency, and competitiveness. Yet, several factors could influence IIoT's successful adoption in the industry. The adoption of IIoT in industries is influenced by technological, organizational, environmental, and individual factors.

Individual Factors

- Individual factors are personal attributes like knowledge, trust, skills, ability, acceptability, adaptability, self-efficiency, and reliability, that affect individuals' behavior, including the employees and clients in the industry.
- Individuals in the industries must possess the necessary knowledge along with skills to use and adapt to the technology effectively.
- In many small and medium enterprises, personal willingness to accept changes often influences how new tools are introduced.

Organizational Factors

- The organizational factors influencing the adoption of IIoT include growth rate, cost, information sharing, compatibility, readiness, support, training, and infrastructure. Organizations must consider these factors for successful adoption.
- These factors can improve the manufacturing and production industry's productivity, efficiency, and overall performance.

Technological factors

- Competitive pressure, complexity, big data, real-time tracking, privacy and security, innovation, efficiency, scalability, robustness, and Technical support are the technological factors influencing IIoT adoption.
- The organization should address these factors to unlock IIoT's potential to increase productivity, efficiency, along with competitiveness in industrial operations.

Environmental Factors

- The environmental factors impact the performance and functions of an industry. The environmental factors include government policy, legal and ethical issues, regulatory support, operational intelligence, resources, and sustainability.
- Public regulations and national goals also affect how and when organizations begin using IIoT systems.

Practices and approaches towards the implementation of IIoT in the printing industry

The IIoT is transforming sectors like industrial printing by linking physical devices through sensors and internet-enabled technology to facilitate data exchange. In industrial settings, IIoT leverages smart machines and advanced analytics to optimize operations, reduce downtime, and enhance productivity. It also enables the development of flexible, efficient production lines that could rapidly adapt to shifting demands. Implementing IIoT in the printing industry requires a focus on interoperability, digital transformation, integration, PdM, optimized operations, along with data-driven DM to enhance efficiency and productivity (Table 2). In Figure 2, a pictorial illustration of the IIoT model of the printing industry is depicted.

Table 2.
Practices and Approaches to Implementing IIoT

Practices and Approaches	Definition	Importance	IIoT Implementation
Focus on interoperability	Interoperability ensures that different systems and devices can communicate and share data effectively.	Various machines, software, and networks in the printing industry can work together seamlessly, thus enabling efficient workflows and data exchange.	Implement standardized protocols and communication interfaces to facilitate data exchange between devices and systems.

Cont. table 2.

Digital Transformation and Integration	Digital transformation involves leveraging technology to improve processes, business models, and customer experiences.	In the printing industry, digital technologies are adopted to streamline workflows, automate tasks, and enhance data analysis capabilities.	Integrate IIoT technologies with existing systems to create a connected and data-driven environment.
PdM	PdM employs data analytics and machine learning for detecting potential equipment failures before they happen.	This proactive approach diminishes downtime, lessens maintenance costs, and optimizes resource utilization.	Equip printing equipment with sensors to crease real-time data on performance and condition; then, this data is wielded to detect potential issues.
Optimized operations and Data-Driven Decision Making	Optimizing operations involves streamlining workflows, improving efficiency, and reducing costs.	Data-driven DM uses insights from collected data to make informed choices that improve performance and reduce waste.	Use IIoT data to detect bottlenecks, optimize resource allocation, and make data-driven decisions to augment operational efficiency.

Source: own elaboration.

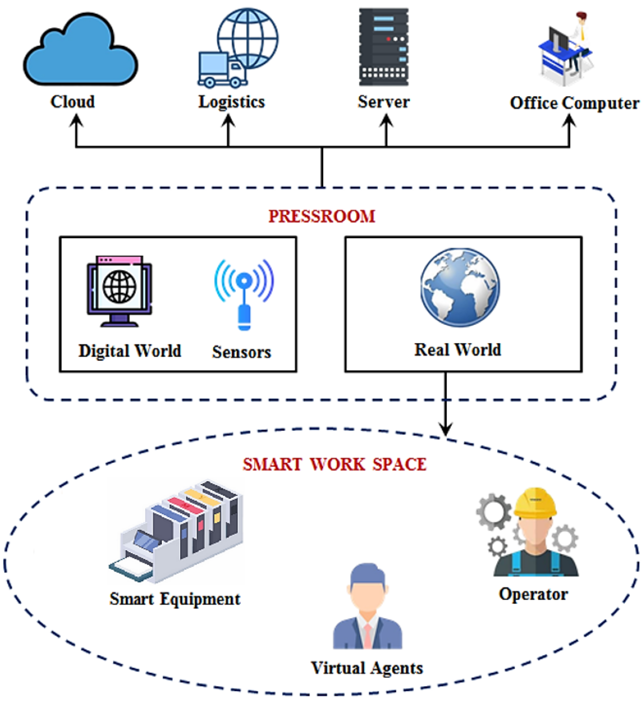

Figure 2. Basic IIoT model of a printing industry.

Source: own elaboration.

Technologies facilitating human-machine collaboration in the automated printing industry

A kind of association betwixt a human and a machine is HMC. It highlights humans as well as machines co-operating simultaneously on tasks and goals, permitting robots to influence their strength, repeatability, as well as accuracy. But, humans fund their higher-level (1) cognition, (2) flexibility, and (3) adaptability. I5.0 takes humans to the workspace's center, avoiding their involvement in non-added value tasks, which machines can automate. The I5.0 technologies that facilitate HMC are collaborative robots (cobots) along with DTs. The IIoT powers both cobots and DTs.

Collaborative robots

Cobots, unlike conventional industrial robots confined behind safety barriers, are built to collaborate with humans within a shared workspace. HMC using cobots involves robots and humans working together in shared workspaces in the printing industry, thus enhancing productivity, safety, and flexibility by automating repetitive or hazardous tasks. In contrast, humans focus on more complex tasks. Equipped with advanced sensors and vision systems, these robots can adjust to changing environments and operate safely alongside humans. This close collaboration enhances efficiency and unlocks new opportunities for more flexible printing processes.

Digital twins

They are central to enabling HMC in I5.0. They provide user-friendly interfaces, real-time data, and collaborative tools that empower human operators to enhance processes and make well-informed decisions. As I5.0 evolves, HC DTs play a key role in bridging the gap betwixt humans and technology, aligning their strengths in joint applications. They offer a holistic view of the printing process, helping operators track performance, detect issues early, and implement real-time adjustments.

The Role of Digital Twins in the Human-Centric Transition for Industry 5.0

DT technology, which gained prominence during Industry 4.0, has seen significant advancements and plays a key role in the emerging paradigm of I5.0. It is one of the essential technological enablers of I5.0. Nine initial technological pillars, including IIoT, Autonomous Robots, Big Data Analytics, Simulation, Additive Manufacturing, Horizontal and Vertical Cybersecurity, System Integration, the Cloud, and Augmented Reality, are identified within the Industry 4.0 context. These pillars are the enabling technologies that drive the evolution of DTs along with their applications in industrial systems. Constructing on DTs' foundation, the Human DTs has arisen as a transformative notion tailored to support the HC focus of I5.0. DTs are changing to more advanced architectures, including sensors to attain real-time data from a product or else its environment in the entire lifecycle to deal with complexity and unpredictable events. Simultaneously, DTs enable automated real-time analysis across interconnected machines and data sources, rushing the detection and resolution of errors. Moreover, DTs contribute significantly to enhancing efficiency and reducing costs in industrial manufacturing.

Factors to be considered before implementing digital twins in the printing industry

In the printing industry, high initial capital costs, the complexity of workflows, the need for reliable data, and the management of multiple variables in physical assets should be considered before implementing DTs. Ensuring a thorough assessment of these factors is crucial for a successful implementation.

Heavy capital cost: Implementing DTs requires significant upfront investment in sensors, IIoT devices, modeling tools, analytics platforms, and IT infrastructure. Beyond the initial investment, ongoing costs are associated with maintenance, updates, and data management. Thus, their deployment is justifiable, in which capital-intensive machinery as well as operations like printing and deadlines, are significant. Moreover, logistics depend upon the material's timely delivery.

Requirement of reliable data: The DTs must be input with higher-quality data meant for physical assets' accurate virtual image. For data regarding physical assets to be useful, it must be consistent, measurable, as well as reliable across each parameter. Also, peculiar problems can arise during printing, where precise data is required to initiate the corrective action.

Complicated workflow: In printing, where products are unique and influenced by factors, such as pressroom atmospheric conditions, designs of punches, time factor, substrate properties, and finishing operations, DTs can be beneficial by providing a virtual replica of the printing process.

Multiple variables in the physical assets: The numerous and complex variables inherent in physical assets within the printing industry are equipment, materials, and processes. DTs need real-time data from the physical assets to reflect their current state along with behavior accurately. Each physical asset must be accurately modeled in the DT, including its physical characteristics, operational parameters, and potential failure modes.

Advantages of using Digital Twin in the Printing Industry

DTs could be extremely useful in optimizing process parameters in printing by observing the process along with detecting possible faults by employing in situ sensors' data as input. DTs offer significant advantages, including increased production efficiency, PdM capabilities, improved product development, and easier testing and optimization of processes in the printing industry.

Increased efficiency of the production system

- DTs provide a real-time, virtual representation of printing processes, allowing for continuous monitoring of equipment and operations.
- By collecting data from the DT, printing companies can optimize their processes to enhance workflows and improve overall production efficiency.

Predictive maintenance

- DTs can predict potential equipment failures by appraising real-time data from sensors as well as historical performance data.
- By anticipating failures, printing companies can schedule maintenance proactively, minimizing downtime and production disruptions.

- PdM permits for targeted maintenance efforts, minimizing the requirement for costly emergency repairs along with augmenting overall maintenance efficiency.

Improved product development

- DTs enable printing companies to test new products and processes in a virtual environment before physical production, reducing risks as well as costs.
- By identifying potential issues early in the development process, DTs can accelerate product development cycles and time-to-market.

Ease of testing

- DTs permit printing companies to simulate different scenarios along with test various parameters without disrupting real-world operations.
- DTs can reduce the requirement for costly as well as time-consuming real-world testing by providing a virtual testing environment.

Challenges and barriers associated with the implementation of Industry 5.0

I5.0 holds considerable promise for improved sustainability, increased efficiency, and customized production; yet, its implementation is complex. Some of the challenges are:

- ***Technology integration complexity*****:** Combining tools like IIoT, AI, robotics, along with DTs into existing systems could be resource-intensive as well as technically challenging. Likewise, incorporating I5.0 technologies faces scalability, compatibility, and standardization challenges.
- ***Moral and sociological aspects of Human-Machine collaboration:*** I5.0 highlights HMC, requiring careful consideration of moral along with sociological aspects to ensure a responsible as well as sustainable transition. Automation and the employment of technologies could cause job losses in certain sectors, exacerbating economic inequality.
- ***Workforce education and training talent shortages:*** The workforce of I5.0 must be proficient in technology and human-centered production techniques. Large-scale retraining and education may be necessary because many workers lack the requisite skills.

Challenges with Regulation and Standards:

- ***Lack of Standardization:*** I5.0 technologies may not be widely adopted without global standards, which can cause inconsistent results.
- ***Regulatory ambiguity:*** Businesses may have ambiguity regarding sophisticated technologies due to unclear instructions from governments and regulatory agencies.

5. Results

The research brings together key insights about how Industry 5.0 technologies, especially the Industrial Internet of Things (IIoT) and Digital Twins (DTs) which are being used in the automated printing industry. The findings are organized into three main areas: what influences the adoption of IIoT, how companies are putting these technologies into practice, and how collaborative tools like robots and digital models are helping people and machines work better together.

Adoption of IIoT in Automated Printing

- ***Individual Factors***: Employee knowledge, trust in technology, adaptability, and digital skills significantly influence IIoT uptake. In particular, small and medium-sized printing enterprises exhibit varied readiness levels, often constrained by skill gaps and limited exposure to digital tools.
- ***Organizational Factors****:* Infrastructure readiness, implementation cost, digital maturity, and training availability emerged as critical enablers or barriers. Organizational inertia and budget limitations often slow down the integration of IIoT technologies, particularly in enterprises with legacy systems or limited IT expertise.
- ***Technological Factors****:* The complexity of IIoT systems, requirements for real-time tracking, and concerns around data privacy and cybersecurity were consistently cited as implementation hurdles. Additionally, the need for scalable and interoperable systems that can adapt to diverse printing equipment was emphasized.
- ***Environmental Factors****:* Government policy, legal compliance, and sustainability objectives increasingly shape IIoT strategies. Regulatory ambiguity and the absence of industry-specific standards often delay adoption, particularly among SMEs.

Multiple studies, including those by Arnold and Voigt (2018) and Paliwoda et al. (2023), highlight that digital immaturity, poor interoperability, and underdeveloped infrastructure remain the primary obstacles in smaller enterprises attempting to modernize their operations using IIoT.

Identified Practices and Implementation Approaches

- ***Interoperability Enablement****:* Standardized communication protocols and data exchange frameworks are prioritized to ensure smooth interaction among diverse machines and digital systems.
- ***Digital Transformation and Integration****:* Enterprises are progressively integrating IIoT platforms with existing infrastructure, allowing for more holistic and data-driven workflows. Automation and system connectivity are key themes in facilitating smoother operations.

- ***Predictive Maintenance (PdM)**:* The use of sensors and real-time data analytics enables early fault detection, minimizing machine downtime and supporting proactive maintenance regimes. PdM contributes to reduced operational disruptions and improved asset longevity.
- ***Data-Driven Decision-Making (DM*)**: Collected data is increasingly utilized for optimizing production planning, resource allocation, and performance monitoring. Insights derived from IIoT platforms support faster and more informed decision-making processes.

Role of Collaborative Technologies in Human-Machine Collaboration (HMC)

- ***Collaborative Robots (Cobots)**:* Cobots support shared workspaces by automating repetitive or hazardous tasks. These robots operate safely alongside humans and are equipped with adaptive sensing technologies. Their use allows human workers to concentrate on complex, high-value tasks, improving both productivity and safety.
- ***Digital Twins (DTs)**:* DTs enable real-time monitoring, process visualization, and data analysis, supporting informed decision-making by both operators and managers. These systems create digital replicas of machines or entire workflows, enabling better oversight and optimization.

The integration of these technologies plays a pivotal role in transitioning from traditional automation models to more inclusive, human-centered production ecosystems.

Application of Digital Twins in Printing

- ***Predictive Maintenance**:* DTs use real-time data inputs from IIoT sensors to detect potential issues before they impact production, enabling condition-based maintenance strategies.
- ***Virtual Testing**:* DTs allow the simulation of various production scenarios, minimizing disruptions in real-world operations and facilitating safer and faster innovation cycles.
- ***Product Development**:* By simulating product behavior and identifying defects in early stages, DTs reduce the time-to-market and support rapid prototyping in design processes.

However, the effective implementation of DTs requires addressing several prerequisites such as:

- High-quality and reliable data is essential to maintain an accurate virtual representation of physical systems.
- Significant upfront investments are needed for sensor networks, modeling software, and supporting IT infrastructure.
- The complexity and variability of workflows in printing environments demand highly customizable and sophisticated modeling capabilities.

These findings underscore the transformative potential of DTs when supported by robust data ecosystems and well-integrated infrastructure.

6. Discussion

This research significantly addresses a notable gap in the literature, emphasizing human-centric frameworks of Industry 5.0 (I5.0), particularly examining the roles of Industrial Internet of Things (IIoT) and Digital Twins (DTs) in the automated printing industry. By highlighting human-machine collaboration (HMC), the study responds effectively to contemporary demands for integrating human values into technologically sophisticated industrial environments (Rajkumar et al., 2025; Alves et al., 2023).

A critical insight derived from this study is the essential role of interoperability, especially when we mix the printing techniques and technologies which we want to implement in the pressroom. Successful IIoT implementation fundamentally requires seamless integration across various systems and platforms (Hussain et al., 2021; Hou et al., 2023). Enhanced interoperability supports data-driven decision-making (DM) capabilities, robust predictive maintenance (PdM), optimized resource allocation, and reduced downtime, significantly improving overall productivity and cost efficiency within the printing industry (Jamil et al., 2024; Ptak, Lis, 2024).

Furthermore, the study emphasizes that the human-centric aspect of Industry 5.0 extends beyond technological advancement, encompassing socio-technical factors such as workforce training, ethical considerations, and human welfare. The human-centric approach redefines traditional automation-driven perspectives of Industry 4.0 by integrating advanced technologies with human skill enhancement (Rajkumar et al., 2025; Kumar, 2024). Technologies such as collaborative robots (cobots) and DTs significantly enhance human capabilities, ensuring safer, more ergonomic, and creatively stimulating workplaces vital for sustainable human-machine synergy (Santhi, Muthuswamy, 2023; Sarioglu, 2023).

The integration of DTs within the printing industry, highlighted by this research, is crucial for developing predictive capabilities, enhancing real-time monitoring, and promoting proactive maintenance strategies (Ghafari et al., 2024; Annavarapu, 2024). However, substantial challenges, including high initial investments, data reliability issues, and complexity in managing physical and operational variables, pose barriers requiring strategic solutions (Peter et al., 2023; Kumar, Iyer, 2019). Therefore, implementing robust data collection practices and cybersecurity measures is essential for safeguarding sensitive industrial information like intellectual property of design, graphics which are still not known as printed and released to the market (Kumar, Iyer, 2019; Sivathanu, 2019).

Additionally, this study highlights the urgent need for consistent global standards and regulatory frameworks to streamline the adoption and integration of new technologies. Without these standards, implementations could be fragmented, leading to inefficiencies and heightened risks of interoperability issues and cybersecurity threats (Arnold, Voigt, 2018; Hou et al., 2023).

Moreover, the research identifies a substantial gap in workforce preparedness for Industry 5.0 technologies. Organizations must therefore prioritize extensive training programs and continuous skill enhancement strategies, maintaining a workforce that remains agile, adaptable, and competent in integrating advanced technological tools into daily operations (Rajkumar et al., 2025; Paliwoda et al., 2023). Policy-makers and industry leaders must collaboratively establish educational frameworks and training initiatives explicitly targeted at technology integration and human-centric industrial principles. To further contextualize these insights specifically for the printing industry, Table 3 summarizes key technological considerations essential to the successful implementation of Industry 5.0 in printing.

Table 3.
Key technological considerations essential to the successful implementation of Industry 5.0 in printing (own elaboration)

Technological consideration	Importance	Implementation strategy
Interoperability	Ensures seamless communication between diverse systems and devices	Adopt standardized communication protocols and integration frameworks
Predictive Maintenance (PdM)	Reduces downtime, enhances operational efficiency, and lowers maintenance costs	Deploy sensor networks and advanced analytics for real-time condition monitoring
Collaborative Robotics (Cobots)	Enhances productivity and worker safety by automating repetitive or hazardous tasks	Integrate cobots equipped with advanced sensors and vision systems into shared workspaces
Digital Twins (DTs)	Facilitates real-time monitoring, predictive analytics, and informed decision-making	Develop comprehensive DT models accurately reflecting physical assets and workflows
Cybersecurity	Protects sensitive data and maintains operational integrity	Implement robust cybersecurity measures and continuous risk assessments
Workforce Training and Development	Ensures workforce readiness and adaptation to new technologies	Provide continuous training, skill enhancement programs, and hands-on workshops
Regulatory Compliance	Ensures adherence to global and local standards and regulations	Stay updated with international regulatory frameworks and establish clear internal compliance practices

7. Conclusion

Research specifically illuminated critical individual, organizational, technological, and environmental factors influencing IIoT adoption, highlighting the complex ecosystem required to ensure successful technological integration in industrial printing.

In addition, this research underscored several key considerations that impact the effective deployment of Digital Twins (DTs) in the printing industry. High capital investments, the necessity for consistently reliable data, intricate workflow processes, and the complexity of managing numerous variables inherent in physical assets were identified as significant barriers. Addressing these challenges strategically will be essential for achieving the full potential of DTs, particularly in enhancing productivity, efficiency, and predictive maintenance capabilities.

The investigation further revealed critical challenges specifically associated with the implementation of Industry 5.0 technologies, including technological integration complexities, ethical and sociological concerns surrounding human-machine collaboration (HMC), workforce education deficiencies, skill gaps, and regulatory ambiguities. Unlike Industry 4.0, which primarily focused on automation, efficiency, and data-driven decision-making, Industry 5.0 emphasizes a human-centric approach, incorporating ethical, societal, and sustainability concerns alongside technological advancement. This shift towards human-centricity offers new opportunities for creating safer, more inclusive, and creatively engaging work environments in the printing industry.

Industry 4.0 largely promoted a vision of fully automated, highly efficient, and interconnected systems, often marginalizing the role of human input. In contrast, Industry 5.0 integrates advanced technology with human creativity and cognitive skills, positioning employees not merely as operators but as active collaborators and innovators. Within the printing industry, this transition can significantly enhance operational flexibility and creative problem-solving capacities, facilitating faster adaptation to market demands and customization needs.

Nevertheless, despite the identified benefits and promising future, the current study acknowledges certain methodological limitations. Being conceptual rather than exploratory or descriptive in nature, the research findings might lack empirical depth and comprehensive validation. Therefore, future research is recommended to employ empirical methods such as surveys, case studies, and longitudinal analyses to gain deeper insights, validate the conceptual frameworks presented, and extend the generalizability of these findings.

Future research should also further explore comparative analyses between Industry 4.0 and 5.0 frameworks, particularly emphasizing empirical validation of human-machine interactions in practical printing industry environments. Such studies could provide clearer insights into optimal strategies for technological and human-centric integration, fostering a balanced, sustainable, and innovative industrial landscape.

Ultimately, the findings of this investigation suggest that embracing Industry 5.0, characterized by its holistic, human-centric perspective, can profoundly transform the automated printing industry. By addressing the identified challenges and leveraging the unique strengths of both technology and human expertise, Industry 5.0 can drive unprecedented levels of innovation, sustainability, and competitiveness in the printing industry sector.

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