Management and Production Engineering Review
Volume 16 • Number 3 • September 2025 • pp. 1–20
DOI: 10.24425/mper.2025.156144

Managing Productivity in Sheet-fed Offset Printing: An IIoT Comparative Study of a Retrofitted Heidelberg Legacy Printing Press Versus the Latest Model

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Received: 11 September 2024
Accepted: 06 June 2025

Abstract

This paper examines whether retrofitting a 1997 four-color offset press, Heidelberg Speedmaster SM74-4P, with Industrial Internet of Things (IIoT) solutions, preserves its performance compared to a 2021, digitally integrated Heidelberg Speedmaster CX75-4. For this purpose, observational studies with data collection were conducted. The study calculated descriptive statistics and Mann-Whitney U tests for print volume, job set-up time, production speed measures, waste, and overall equipment effectiveness (OEE). The results show that retrofitting an older press achieves comparable print volumes, and even the 1997M press had an average gross throughput that was 9.73% higher and a median that was 22.86% higher than the 2021 press. However, the new press achieves 63.14% higher average run length as well as significantly reduces make-ready time and waste. Despite the benefits that new machines offer due to technical advances, modernizing older machinery through IIoT solutions can therefore be a cost-effective strategy. In the discussed case, adaptation to the requirements of work in the modern IIoT environment by a relatively cheap modernization kit compared to a new machine, allowed for better operational efficiency, thus reducing costs and contributing to the sustainable development of the company without the need to invest in a new machine.

Keywords

IIoT comparative study, managing productivity IIoT, Heidelberg offset presses, IoT towards IIoT evolution, IIoT retrofit.

Introduction

The objective of this article is to conduct a comparative analysis of a retrofitted legacy sheet-fed offset printing press versus its contemporary data-driven counterpart, under similar operational configurations. The central focus is to ascertain the continued productivity and manageability of the legacy press when equipped with Internet of Things (IoT) sensors. This study is underpinned by a comprehensive collection and examination of data from both printing press models, facilitating a detailed evaluation of their key performance metrics. Moreover, it is essential to deduce whether the older, legacy machine, once modernized with data-centric capabilities, retains sufficient productivity to effectively handle order volumes in comparison to the newest model.

Furthermore, the article endeavors to explore the extent to which a non-scalable sheet-fed offset printing press, upon undergoing modernization to incorporate data-driven functionalities, can assist a company in achieving its performance objectives more efficiently. This investigation provides insights into the viability and effectiveness of retrofitting older industrial machinery within the context of evolving technological landscapes, particularly in the realm of Industrial IoT (IIoT) and data-centric operations.

The research outlined in this article addresses several critical gaps in the current literature, particularly within the context of the IIoT as applied to the printing industry.

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These gaps are identified as follows:

- Lack of academic literature on IIoT retrofit in the offset printing sector: There is a noticeable paucity of scholarly research exploring the application and implications of IIoT technologies specifically within the sheet-fed offset printing. This lack of comprehensive academic discourse limits the understanding of IIoT's potential benefits and challenges in this sector.
- Inadequate quantitative analysis of efficiency and productivity gains in the offset printing sector: Current literature does not sufficiently quantify the improvements in efficiency and productivity that can be captured by retrofitting legacy sheet-fed printing machines with IIoT systems, particularly when compared to the latest data-driven printing model. This gap hinders the ability to objectively assess the technological advancements in the printing industry.
- Limited cost-benefit studies utilizing Key Performance Indicators (KPIs) in the offset printing industry: There is a lack of detailed cost-benefit analyses, supported by KPI metrics, evaluating the economic viability of retrofitting traditional sheet fed offset printing presses in the context of productivity management.

Given these research gaps, the detailed objectives of this study are to conduct:

- Investigation of implications of IIoT technologies within the offset printing sector based on industry leader Heidelberger Druckmachinen AG. The aim is to identify the deficiency in the academic literature regarding the deployment of IIoT in this sector. The research entails comprehensive exploration of which IIoT technologies are being integrated into sheet fed offset printing process to gain data comparison to newest machine models. The study will seek to deepen the understanding of IIoT's role and impact in the offset printing industry, contributing to the broader academic discourse on this subject. The objective is pursued through a combination of literature review, with empirical data collection, to provide a well-rounded analysis of IIoT in the context of the printing industry.
- Cost-benefit comparison using case study methodology based on KPI metrics to determine the economic feasibility of traditional sheet fed offset printing press usage with data driven and cloud connected new printing press model.

The phenomenon that makes this research necessary is the ongoing digital transformation of the offset printing industry, which is accompanied by a paradigm shift from product-based to service-based business models on both the supplier and printing company sides (Salwin et al., 2021; Magadán-Díaz & Rivas-García, 2021).

Literature review

IoT background towards industrial dissemination

As in 2015, Eric Schmidt former CEO of Google said, "There will be so many IP addresses, so many devices, sensors, things that you are wearing, things that you are interacting with, that you won't even sense it. It will be part of your presence all the time" (Winter & Ono, 2015), he was reflecting on advanced development of Internet of Things which had a starting point traced back to the early 1980s, when students from Carnegie Mellon University interconnected and devised a method for a vending machine to relay its inventory status via a network. This was achieved through the integration of micro-switches into the machine, enabling it to transmit dat a regarding the availability of beverage cans and their temperature conditions. In 1994, Raji authored a widely read article discussing the potential for integrating networking technology with a range of objects, from domestic appliances to large industrial machinery. This exploration highlighted the prospective fusion of network connectivity with everyday items and industrial equipment, paving the way for what we now understand as the Internet of Things (Raji, 1994). However the term IoT was formally introduced into the technological lexicon in 1999 by Kevin Ashton, who pointed out that "Things can acquire intelligence and be able to communicate by accessing data and information from other parts without any help from humans" (Zivkovic et al., 2020). Since the inception of this Internet of Things definition, IoT has undergone continuous and remarkable evolution. This dynamic progression is largely attributed to a series of revolutionary innovations within the field, each contributing to an expanding and deepening understanding of what IoT encompasses and its potential applications. To better identify the evolution of IoT definitions, it is presented in (Fig. 1).

As long as the IoT evolved, there was a need to distinguish the term by sectors and to draw a map of possible architectures within those sectors (Fig. 2).

To enhance the development of the IoT market, several strategic actions have been proposed by IEEE (Longvinov & Brophy, 2016).

By taking the above into consideration, an initial definition of IIoT was finalized in 2015. According to Dorsemaine (2016), IIoT is a group of infrastructures interconnecting connected objects (i.a. sensors, actuators) and enabling their management, data mining, and access to the data they generate. Connected objects perform specific functions and are designed to

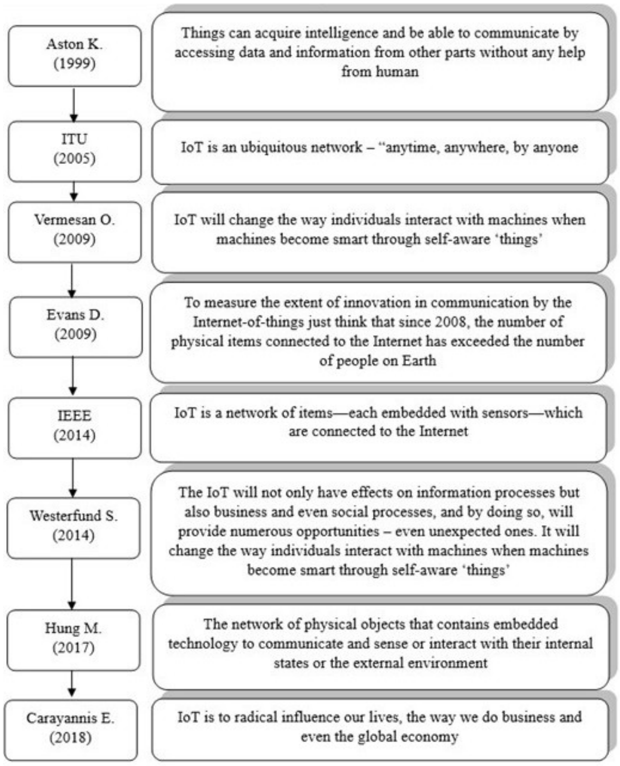

Fig. 1. Evolution of IoT definition concepts, source: own elaboration based on (Aston, 2017; International Telecommunication Union (ITU), 2005; Vermesan, 2009; Evans, 2011; IEEE, 2014; Westerlund et al., 2014; Hung, 2017; Carayannis et al., 2018)

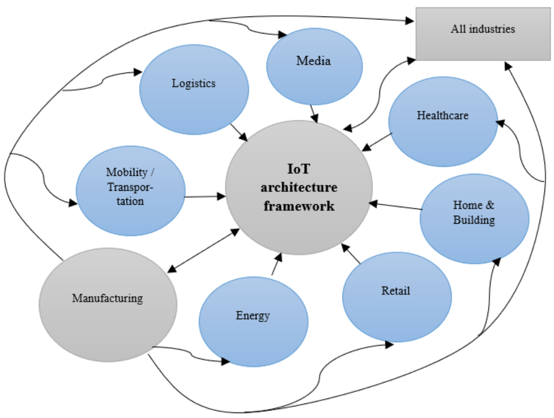

Fig. 2. IoT architecture neuron and the dependency from its stakeholders, source: own elaboration based on IEEE (2015)

communicate with other equipment. In the context described above, the concept of the IoT is generally understood as the expansion of network connectivity and computational power to entities typically not recognized as traditional computing devices.

This encompasses objects, devices, sensors, and various items, transforming them into "intelligent objects". These entities are characterized by their ability to autonomously produce, share, and utilize data with minimal human intervention. They are frequently connected to distant facilities for data gathering, analysis, and managing these data to gain efficiency. Moreover, the concept of the IIoT extends beyond the mere application of IoT solutions in the industrial sector. It encompasses a network of interconnected and collaborative instruments and devices from the realms of Information Technology (IT) and Operational Technology (OT). The synergy within a network of elements such as industrial control systems (ICS), various sensors, computers, mobile devices, and computerized production management systems facilitates the collection, analysis, processing, and exchange of vast amounts of data among them (Sisinni, 2018).

A key topic within IIoT is retrofit, where existing industrial machines are upgraded with IoT technologies. This practice allows for the integration of modern sensor and connectivity technologies into legacy systems, thus extending their lifecycle, enhancing data collection capabilities, and improving overall performance without the need for new manufacturing system investments. Taking into consideration retrofitting, there is a need to distinguish consumer IoT (CIoT) and IIoT (Sisinni, 2018), where retrofitting in IIoT exemplifies a strategic approach in adopting IoT solutions, addressing the challenges of integrating new technologies with existing infrastructures (Tab. 1). This not only underscores the adaptability and scalability of IoT technologies but also highlights the diverse applications and potential of IoT across different domains.

The integration of retrofitted machines in the whole IIoT production environment enhances the efficiency of production itself as well as processes that support effective production management. The dynamic development of the Industrial Internet of Things is made possible through advanced technologies such as cloud computing, edge computing, big dat a analytics, artificial intelligence, and machine learning (Chigilipalli et al., 2023).

Progress in these areas allows for the widespread application of IoT in manufacturing, regardless of the type of operations conducted. One practical application of the IoT concept that has gained popularity in recent years is the predictive approach to maintenance management, known as Predictive Maintenance. The goal of predictive maintenance is to reduce the costs associated with servicing and repairing machines and equipment, as well as the costs related to production downtime. Various sensors (temperature, vibration, humidity), integrated into a network and utilizing an

Table 1
Comparison between Consumer IoT and Industrial IoT

Feature	**CIoT**	**IIoT**
Impact	Revolution	Evolution
Retrofit	Limited	Widespread
Service Model	Human-centered	Machine-oriented
Current Status	New devices and standards	Existing devices and standards
Connectivity	Ad-Hoc (infrastructure is not tolerated; nodes can be mobile)	Structured (nodes are fixed; centralized network management)
Criticality	Not stringent (excluding medical applications)	Mission critical (timing, reliability, security, privacy)
Data Volume	Low/Medium to High	High to Very High
Interoperability	Limited, often proprietary systems	High, with industry-standard protocols
Latency	Tolerable delays	Low latency required for real-time processing
Scalability	Designed for consumer-scale deployment	Designed for large-scale industrial deployment
Integration	Standalone devices or systems	Integrated into enterprise systems and processes
Security	Important but often secondary to ease of use	Paramount, with rigorous standards and regulations
Lifespan	Shorter lifecycle, frequent updates	Longer lifecycle, with focus on durability and stability
Cost Sensitivity	Price sensitive, targeting mass market	Investment driven by ROI, long-term cost savings
Maintenance	User-managed or through service providers	Often requires specialized support teams
Upgrade Path	Rapid evolution, with frequent need for hardware upgrades	Gradual evolution, with a focus on software updates and modular upgrades
Data Analytics	User data for service improvement and marketing	Operational data for efficiency and optimization
Autonomy	Limited, often requiring user interaction or control	High, data analytics with/without system making decisions

Source: Own elaboration based on (Sisini et al., 2018)

IoT platform, provide a wealth of data on machine operation. This data, when analyzed with appropriate tools, enables highly accurate predictions of potential failures and automated notification to maintenance departments, allowing for service just before a failure occurs while considering the current state of the machine (Meissner, 2021).

Understanding the IIoT and OEE importance in sheet fed offset printing

In a key example of the early use of IoT technologies, Kevin Ashton pointed out Heidelberger Druckmaschinen AG (Heidelberg), a German manufacturer of sheet-fed offset printing presses (hereinafter referred to as printing press), as a forerunner in using predictive maintenance and sensors for quick response to machine failures. Originally, the company would send maintenance workers in vehicles to fix the printing press. However, when the internet became widely available, Heidelberg saw an opportunity. They realized they could use the same sensors, which were previously only for checking machines, to connect directly to the internet. This connection meant they could identify and respond to machine problems much faster, without always needing to send out maintenance teams. This pioneer decision made in 1992, was in fact the first move to predictive maintenance. Further, Heidelberg pioneered the integration of dialogue connections in its printing presses. This innovation allowed clients experiencing operational issues to connect the printing press to a phone line, enabling the transmission of diagnostic data to the maintenance team for analysis and troubleshooting. The success of this approach catalyzed a broader adoption of IoT within Heidelberg strategy. The company integrated thousands of IIoT-enabled sensors, shifting much of its business model toward data dependency. Furthermore, Heidelberg expanded its operations to include a consultancy division. This new branch specialized in the analysis of data collected from various clients, providing comparative insights and recommendations for optimizing machine usage. Ashton underscored Heidelberg's exemplary use of IIoT not merely as a data collection tool for its own profitability, but as a strategic means to enhance customer service and improve client business operations. This case exemplifies the transformative impact of the IIoT in streamlining manufacturing processes and maximizing production efficiency, as evidenced by Heidelberg's evolution of printing presses (Ashton, 2017).

Considering the aforementioned context, Heidelberger Druckmaschinen AG exemplifies a case where practical implementation surpasses theoretical postulations, particularly in the realms of predictive maintenance and the IIoT. This company's proactive approach and tangible applications in these areas serve as a benchmark, demonstrating an advanced understanding and execution of concepts that are often discussed primarily in theoretical terms. Heidelberg's initiatives in predictive maintenance and IIoT adoption not only align with but also advance the discourse in these fields, showcasing real-world applications and benefits of these technologies. Their actions stand as a testament to the practical viability and strategic importance of integrating advanced technological solutions in industrial operations. Considering the technological advancement of Heidelberg and its subsidiaries over the years, the company has drawn up a visible approach towards IoT/IIoT (well before the concepts of IoT were formally defined). We can currently observe that Artificial Intelligence (AI) started to be used as an autonomous system to support IIoT. To understand the path of remarkable inventions a table has been drawn based on classification, year and type of development (Tab. 2).

Heidelberg understood well that effective planning is crucial for managing the entire lifecycle of their printing press production and the need to connect it to the entire facility. This includes everything from the initial creation to the eventual phase-out. There are two types of planning involved where IIoT is the key to achieve:

1. Systematic Planning: This approach considers every stage of the printing facility's lifecycle. It's a comprehensive method that accounts for all aspects and phases of the production process (performance peak);
2. Situational Planning: This type of planning is more reactive and occurs in response to changes during operation (quality assurance).

However, having a good facility layout and planning is not enough on its own. To truly achieve the desired outcomes, these plans must be closely integrated with internationally recognized best practices in production process planning and management with suitable KPIs (Moses et al. 2018). The methodology for calculating KPIs is rooted in the DMAIC cycle, a concept introduced by W.E. Deming in the early 1950s. Measuring: This step consists of measuring the process and establishing and verifying a measurement system to gather necessary data. Analyzing: At this stage, the data collected is analyzed to pinpoint the key factors that impact the critical quality characteristic defined earlier. Improving: This phase focuses on implementing measures to adjust the identified elements to their required values. Controlling: Moreover, the first and most significant KPI, Overall Equipment Efficiency (OEE), was introduced by Seiichi Nakajima in 1988. Initially applied at Nippondenso, a supplier for Toyota, OEE later became a foundational aspect of the continuous improvement strategy within the Toyot a production system. In 2014, the International Organization for Standardization (ISO) released the ISO22400 standard, titled „Automation systems and integration - KPIs for manufacturing operations management". This standard aimed to establish a comprehensive set of KPIs for managing manufacturing operations. Within its normative sections, amendments, and technical reports, a total of 41 KPIs were specified, including the renowned Overall Equipment Effectiveness (OEE) (Schiraldi, 2020).

To monitor and improve the production process, Heidelberg began focusing on measuring OEE when the CIP3 workflow was introduced in 1999. The CIP3 workflow enabled Heidelberg to move machines into an IIoT environment, where OEE plays an important role in understanding equipment performance and identifying areas for improvement. In 2001 R.C. Hansen pointed out that OEE is a powerful tool for increased profits through autonomous processes which encompass a range of automated tasks, including color selection and measurement, plate fabrication and replacement, job selection, job transitioning, and quality control (Hansen, 2001).

These processes operate independently of human oversight, contingent upon the fulfillment of certain predefined conditions. The incorporation of sensors and cameras into Heidelberg printing presses was a crucial move toward quality assurance (CIP 3 and Autoplate loading system). These technological integrations

Table 2
Heidelberger Druckmachinen AG development towards IoT/IIoT systems towards AI support

Year	Development	IoT / IIoT / AI
1978	Chromaskop (Dr. Hell)	
1979	Harris Telecolor	
1980	First control console CPC I (Heidelberg)	
1985	First high resolution PostScript RIP 1 with RT screening/halftoning method (Dr. Hell)	
1987	Chromacom Proof Recorder (Dr. Hell)	
1990	RIP 30 with a screening filter	IoT
1990	Speedmaster CP Tronic control Console	
1992	RIP 60 with I.S Technology (Linotype-Hell)	IoT
1992	Predictive maintenance via phone line (Heidelberg)	IoT
1994	Control console CPC 1.03 (Heidelberg)	IoT
1995	Computer-to-Press digital imaging Quickmaster DI (Heidelberg)	IoT
1995	Control console CPC 1.04 with CP-Tronic (Heidelberg)	IoT
1997	Heidelberg FMR Delta RIP (Linotype-Hell)	
1998	CPC Prepress Interface	IoT
1999	CIP 3 Workflow / Autoplate changing	IIoT
2001	Ecocool drying, trapping solutions	
2008	Prinect Press Center with Wallscreen and IntelliStart	IIoT
2010	Prinect Inspection Control	IIoT
2012	Prinect Performance Benchmarking	IIoT
2017	Prinect Press Center XL 2.0 with XL Wallscreen and IntelliStart	IIoT
2018	Heidelberg Assistant – URL portal to connect to machines	IIoT
2020	Prinect Press Center 3.0	IIoT
2020	Push to stop / Intellistart 3.0	IIoT
2021	Plate to Unit Speedmaster XL106	IIoT
2021	Preset 2.0 / AI supported IIoT	AI / IIoT

Source: Own elaboration based on: (Hamilton, 1993)

are designed to prevent the progression of blank pages (doubling effect), to autonomously discard substandard prints, and to obviate the occurrence of double paper feeds in sheet-fed printers, thereby demonstrating an intelligent approach to error elimination. These technological enhancements facilitate the production of substantial volumes with elevated precision, markedly reducing the necessity for human interaction in the printing process. Further development of Heidelberg printing presses is now supported by Artificial Intelligence (AI) with Preset 2.0 and the intelligent assistance systems Intellistart 3, Wash Assistant, Powder Assistant, and Color Assistant, where manual interventions are reduced to a minimum and the competitiveness of print shops is increased (Heidelberger Druckmaschinen AG official website).

In the systematic literature review (SLR) there is a lack of information about the focus on the integration of IoT/IIoT in the offset printing sector. Table 3 summarizes the findings based on a search conducted across multiple academic databases including SCOPUS, Web of Science, and EBSCO. The search criteria used for this SLR encompassed a combination of keywords: "Internet of Things" AND "IoT" AND "offset printing", "Industrial Internet of Things" AND "IIoT" AND "offset printing", "retrofit" AND "sheet fed offset", and "IIoT" AND "retrofit" AND "sheet fed offset printing". The results were based on the search terms: the title, the abstract, or as keywords. From SCOPUS, while no articles were identified with the terms directly in the title, 10 were found with terms in the abstract, and 2 in the keywords. Similarly, in the Web of Science, 10 articles had the search terms in the abstract and none in the keywords, while articles with terms in the title amounted to 10. EBSCO yielded no articles across all categories. After identifying the articles, duplicates were eliminated, resulting in a total of 8 unique articles. These were further scrutinized to verify whether the abstracts were relevant to the leading research subject of IIoT retrofit in offset printing. However, none of the abstracts sufficiently focused on this subject as the primary topic of research. The results of the literature review are presented (Tab. 3).

Table 3
The results of Systematic Literature Review on IoT Retrofit in offset printing sector (literature review in IOT)

	Number of identified articles		
Selection criteria: "Internet of Things" AND "IoT" AND "offset printing" OR "Industrial Internet of Things" AND "IIoT" AND "offset printing" OR "retrofit" AND "sheet fed offset" OR "IIoT" AND "retrofit" AND "sheet fed offset printing"	*SCOPUS*	*Web of Science*	*EBSCO*
Impact	0	10	0
Retrofit	10	10	0
Service Model	2	0	0
In total: elimination of duplicates	8		
Verification of abstracts in terms of the leading subject of research – IoT retrofit offset printing	0		

Source: Own elaboration

Materials & Methods

The study compared typical offset printing machines manufactured by a large and well-established producer. Since manufacturers offer differentiated pricing based on market conditions, machine configuration, and the scope of accompanying services, the exact prices are not publicly disclosed. However, the new machine used for comparison was estimated to be valued within a range of €900,000 to €1.2 million.

Similarly, the prices of older machines vary depending on the market. In the context of this study, the retrofitted machine had an estimated market value ranging from €35,000 to €65,000. It should be noted, however, that from the user's perspective, this value may differ depending on the level of wear and depreciation (i.e., the book value of the unit).

The total cost of the retrofit was approximately €100,000, although, depending on specific market pricing for individual components and services, this figure may range from €90,000 to €120,000. The printing press comparison and retrofit towards data driven IIoT environment. Based on the adopted research methodology and empirical dat a comparing the modernization (IIoT retrofit) of Heidelberg legacy printing machine vs. cost of the latest model, a research framework was developed and is presented in Figure 3.

OEE is a metric that is inherently individualistic and heavily dependent on the nature of a client's order portfolio in the printing sector. Nevertheless, the studied print house has a high frequency of short-run orders typically on both compared machines and experiences a greater number of setups (Make Ready), which inherently reduces the production time available and, consequently, diminishes the OEE. In contrast, a printing facility handling a larger number of extended-run orders will encounter fewer setups (Make Ready). To understand the complexity of calculating the printing press OEE, it is necessary to explain its components in contrast to the data obtained from the legacy printing press before retrofit (Tab. 4).

In general, a higher OEE is indicative of superior performance. However, the maximum achievable value of OEE is constrained by the existing operational structure, particularly by the types of orders being processed and the efficiency with which they are executed. This variation is also why OEE comparisons across different facilities can be misleading. If one intends to conduct an OEE comparison, it is imperative to ensure that the equipment being compared is employed in printing similar types of orders. This precaution is necessary to account for the variability introduced by differing operational structures and order types. The studied company has generally similar jobs to print which are mainly CMYK (4 colours), were the performance of both machines is comparable (Tab. 5).

The legacy printing press Heidelberg SM 74-4P from 1997 is not connected to any network. The stand-alone core of the printing press is the CPC 1.04 control panel, which can store up to 50 print jobs by saving them to a memory card. It works closely with the CP-Tronic board and software which gathers and controls numeric data from basic sensors. From the main display control panel we can as per picture no. 1 according to numbers:

Table 4
Description of data components to calculate OEE of sheet-fed offset press

Category	Subcategory	Description	Legacy printing press
Standstill and Other Time	Effective Other Time	The active phase of other time, involving preparatory actions for the next job, i.e. plate preparation, loading materials, and configuring print parameters.	Not calculated
	Standstill Time	The idle phase within other time when the machine is not actively engaged in printing. This includes periods of waiting for materials, maintenance, or other delays.	Not calculated
	Standstill Fine Tuning Time	Time allocated for fine adjustments and calibrations during machine downtime.	Not calculated
	Standstill Production Time	Downtime that occurs during the production phase, not directly linked to active printing.	Not calculated
	Standstill Other Time	Organizational or maintenance-related downtime, not associated with the direct printing process.	Not calculated
Make Ready Time	Basic Make-Ready Time	The initial setup time for a new printing job, including CTP (computer to plate) plates, ink refilling, printing blanket changes, paper quality adjustments, and other preparatory activities. Strongly influenced by internal logistics.	Manual count
	Fine Tuning Time	The period starting from the printing of the first setup sheet to the beginning of good sheet counts, including color and registration adjustments and downtime	Not calculated
	Effective and Standstill Times	Division of each process stage into active (effective time) and inactive (standstill time) periods, offering insights into where time is being lost in contrary to operating time.	Not calculated
Waste Metrics	Run Waste average	The average amount of material wasted per run. Monitoring this average helps in identifying trends and potential areas for process improvement to reduce waste.	Manual count
	Run waste from make ready to run processes	Total waste accumulated from Make-Ready (M) and Run (R) processes. It is essential to minimize this figure to enhance cost-efficiency and sustainability of the printing operations.	Manual count
Net Productivity	Net impressions, gross impressions, average run length, speed	Measuring the ratio of good-quality printed sheets to machine operating time, expressed in sheets per hour (gross impressions vs. net impressions). High net productivity reflects better performance but it is related to average run length and good production speed.	Automated count

Source: Own elaboration

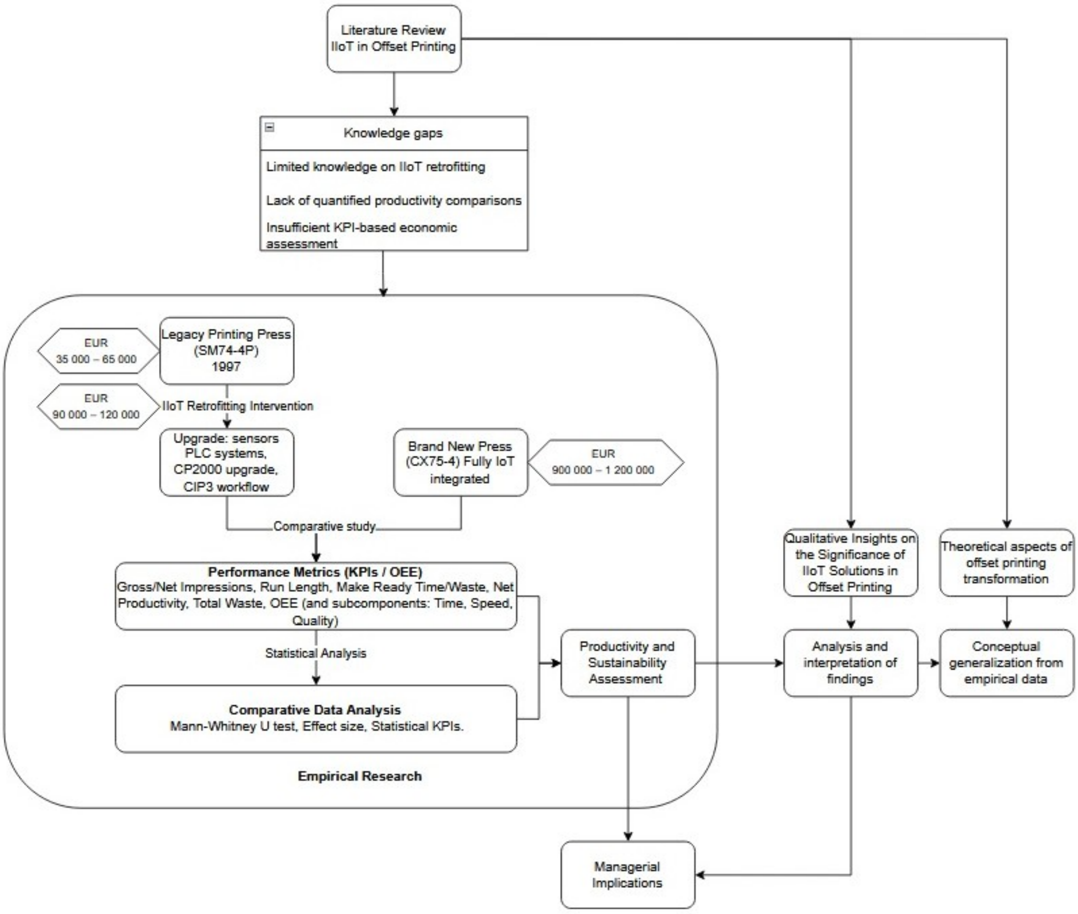

Fig. 3. Research framework, source: own elaboration

Table 5
Specification of the studied printing presses

Criteria	Heidelberg Speedmaster SM74-4P	Heidelberg Speedmaster CX 75-4
Build year	1997	2021
Printing units	4 colours – CMYK	4 colours – CMYK
No. of printed sheets until end of 2023	125 million	11 million
Max. Sheet Size	520 × 740 mm	530 × 750 mm
Min. Sheet Size	210 × 280 mm	280 × 350 mm
Sheet Thickness	0.04 mm – 0.60 mm	0.03 mm – 0.60 mm
Max. Print speed	15 000 s/ph	15 000 s/ph
Control center	CPC 1.04	Press Center 3.0
Machine production manager	CP-Tronic	Prinect Production Manager

Source: Own elaboration based on: (Heidelberg, 2025)

3. Command with control buttons; Enter/Delete, 4. Data transfer, make job preparation, do positioning, control ink shut-off, 5. Switch to different printing unit or view globally, 7. Learn about production run, malfunction, service, ink fountain properties, 12. All operations done via centralized display (Fig. 4).

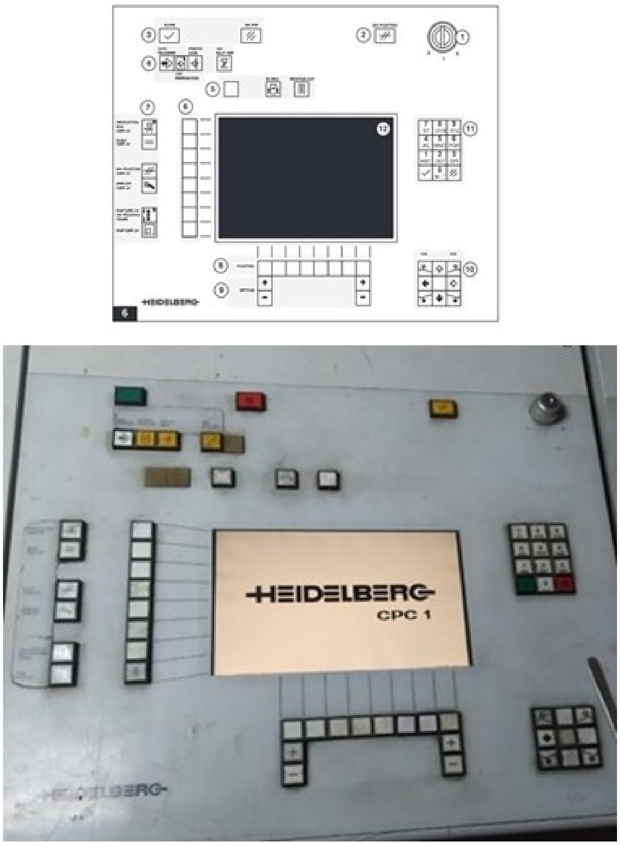

Fig. 4. CPC 1.04 control panel, the only IoT gathering point for information analyses on SM74-4P 1997, source: own elaboration based on (Heidelberg, 1997)

Enhancements towards IIoT retrofit

One of the most important enhancements introduced by the upgrade is the built-in support for various paper type presets (i.a. Gloss Coated, Matt Coated, and Uncoated). This feature enables a wide range of paper calibrations to be directly entered into the new software settings. The calibrations can be fine-tuned for the specific paper type in use before being transferred to the memory card. This also provides the opportunity for precise OEE measurement between the machines under study. Furthermore, the newly integrated CPU is equipped with a Programmable Logic Controller (PLC) monitor. This system is now seamlessly connected via Ethernet to cloud-based services with an unlimited upload of jobs (see Fig. 5) The CPC 1.04 has been upgraded to CP2000 Center system with CIP3 workflow (Fig. 5).

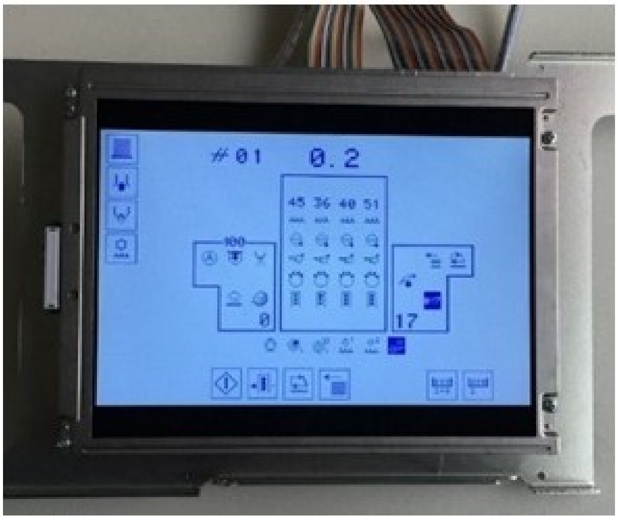

Fig. 5. New central controlling system for CPC control panel, source: own elaboration

To further enhance monitoring capabilities, CT sensors were installed to measure the power consumption and calculate press availability and operating times by analyzing voltage spikes. These sensors, connected via Ethernet, support the impression counter sensor on the press, which calculates the number of sheets per job. In conjunction with the CT sensor, it can measure the average run length. The combination of these data points, including how many jobs are printed daily or monthly, generates crucial information about make-ready times, all delivered in real-time via a wireless connection to the cloud.

Sensed Data from Retrofitted Equipment

The retrofit also introduced a broad spectrum of sensed data capabilities:

- Variable speed drive cards and microprocessors have been integrated to enhance control over machine operations, offering more precise adjustments and feedback.
- TV monitor with combined spectrophotometer device to ensure repeatability of the job printed before and exact color match shown on a TV screen
- Temperature and humidity sensors ensure that the press environment is maintained within optimal parameters, preserving paper quality and consistency of prints.
- The impression counter sensor aids in tracking production volume and operational efficiency.

- Photocells and stack height sensors are employed for sheet doubling checks, reducing the risk of print errors and paper wastage.
- New connections to upgraded sensors for chemistry, spray powder, and ink control sensor bars allow for better control over the printing process, enhancing print quality and consistency.
- Mechanical sensors, either replaced or connected to the new system, improve the detection of mechanical faults, thus reducing downtime.
- Finally, cabling connected to IIoT middleware solutions ensures that all data from these sensors are seamlessly integrated and communicated to the cloud for real-time monitoring and analysis linked with all software related to the retrofit.

The general architecture of changes in the context of retrofitting represents a systematic and comprehensive approach to upgrading existing industrial machinery and systems. This framework is designed to incorporate cutting-edge technologies into older equipment, enhancing functionality, efficiency, and connectivity. By integrating modern sensors, control units, and connectivity solutions, it is also possible to extend the operational life and performance of legacy systems. This not only optimizes production processes but also aligns with sustainable practices by reducing the need for new resources (Fig. 6).

Results

Data comparison

The research was conducted over a span from March 2022 until December 2023 at a printing house with a general commercial printing profile, located in a European Union country. The study involved data collection from fitted sensors in a legacy sheet-fed offset press, specifically the Heidelberg Speedmaster SM74-4P from 1997, as well as from a press center computer

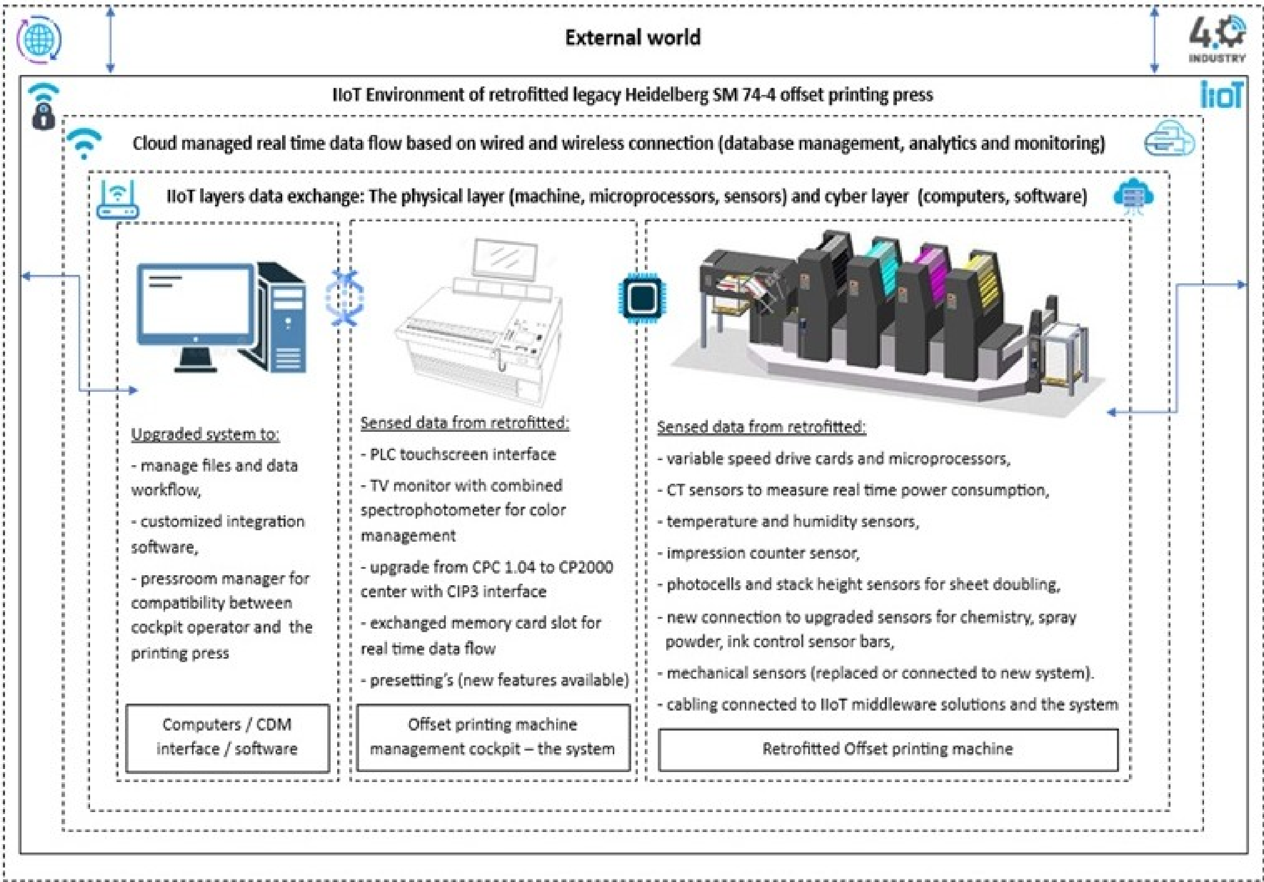

Fig. 6. Retrofitted sheetfed offset printing machine Heidelberg SM74-4 towards managing productivity in a drawn environment, source: own elaboration

connected to a newly installed machine, the Heidelberg Speedmaster CX75-4 from 2021 (Fig. 7). Both machines were configured to print in CMYK, four-color artwork. The method of research entailed collecting and aggregating data into monthly reports generated from the IIoT systems of both the modernized and newly installed offset printing machines. This dat a was then analyzed through statistical methods based on KPIs to compare performance.

Fig. 7. Retrofitted Heidelberg Speedmaster SM74-4 from 1997 (below) and newest CX75-4 Heidelberg model as from 2021 (above), source: own elaboration

The comparison of performance values for the modernized machine includes measurements based on data collected over 20 months of continuous operation from a legacy machine retrofitted with IIoT sensors (Table 6), as well as data from the newest machine (presented in Table 7).

Data were compared using descriptive statistics (mean, median, standard deviation) and inter-group comparison for independent samples using the Mann-Whitney U test with the calculation of the Effect Size.

Results of comparative study

As a next step, it is necessary to provide the differences in performance between machines.

In terms of a number of parameters, both machines turned out to be comparable on average, with minor variations that did not exceed a 10% difference there were the following measures: Gross Impressions, Net Impressions, Good Production Speed, and Net Output. The new machine shows much higher averages in terms of Run Length (63.14%), Operating time (59.66%), Make Ready Waste (216.60%), Net Productivity (42.70%), Run Waste % (37.67%), Run Waste (avg.) (44.87%), Total Waste (M/R + Run) (431.18%), and all OEE metrics (OEE, OEE 10000, OEE Quality, OEE Speed, OEE Time) ranging from 18.71% to 42.70%. The modernized machine had higher average values for Make Ready (119.26%) and Make Ready Time (34.97%). This task is accomplished in (Tab. 8).

In the analysis of the modernized 1997 press versus the brand new 2021 press using Mann-Whitney U test, several operational metrics demonstrated statistically significant differences, which include Run Length, Make Ready, Operating Time, Make Ready Waste, Make Ready Time, Other Time, Good Production Speed, Net Productivity, Run Waste %, Total Waste, OEE, OEE 10000, OEE Quality, OEE Speed, and OEE Time. In contrast, Gross Impressions, Net Impressions, Net Output, and Run Waste (avg.) 1997 did not show statistically significant differences (Tab. 9).

The legacy press (1997M) has an average output (gross impressions) that is 9.73% higher than the newest (2021), with a median that is 22.86% higher. Mann-Whitney U test results ($p = 0.174$, Effect Size = 0.255) indicate that although the legacy press shows higher outputs both in average and median terms, this difference is not statistically significant, indicating comparable capabilities in total print production (Fig. 8).

Considering that the statistical test used takes into account the difference in means, while the difference is greater in the case of the median, it may be true that the older machine is more efficient.

Net impressions, including only the acceptable prints after quality line checks, show the newest press having 10.50% higher average and a slight increase (0.21%) in median outputs are not statistically significant ($p = 0.799$, Effect Size = 0.050), suggesting that both presses are nearly equivalent in producing quality prints, despite the newest press showing a slightly higher output.

In terms of the average number of prints in a continuous run without stopping, the brand new press machine has a 63.14% higher average run length and a 55.24% higher median.

Moreover, there is a statistically significant ($p < 0.001$) and substantial (Effect Size = 0.895) improvement in the run length for the brand new press, indicating that newer technology offers better performance in sustaining longer continuous operations, even if the older one is equipped with IIoT solutions. The newest

Table 6
Production efficiency values of the legacy machine modernized with IIoT technology

Year Month	Gross Impressions	Net Impressions	Run Length (avg)	Make Ready	Operating time	Press Availability (avg)	Make Ready Waste (avg)	Make Ready Time (avg)	Other Time (avg)	Good Prod. Speed (avg)	Net Output (avg)	Net Productivity (avg)	Run Waste %	Run Waste (avg)	Total Waste (M/R + Run)	OEE	OEE 10000	OEE Quality	OEE Speed	OEE Time
1	250942	182906	1016	180	7	31	355	0.016	0.012	8484	5075	1159	0.022	23	68036	0.08	0.17	0.73	0.56	0.19
2	277337	206396	1134	182	7	30	372	0.017	0.015	8754	5709	1173	0.015	18	70941	0.08	0.17	0.74	0.57	0.18
3	400324	314191	1475	213	11	31	376	0.019	0.021	8840	5751	1230	0.019	28	86133	0.08	0.17	0.78	0.58	0.18
4	375032	301607	1516	199	8	30	343	0.015	0.016	8687	6052	1528	0.017	26	73425	0.10	0.20	0.80	0.57	0.22
5	265255	201270	1131	178	8	31	345	0.017	0.018	8684	5836	1109	0.013	15	63985	0.07	0.17	0.76	0.56	0.17
6	308578	248145	1266	196	7	31	295	0.013	0.014	8447	5659	1450	0.010	13	60433	0.10	0.19	0.80	0.55	0.22
7	300212	230992	1111	208	8	30	318	0.017	0.015	8389	6004	1151	0.013	15	69220	0.08	0.17	0.77	0.54	0.18
8	423280	333186	1424	234	11	31	370	0.019	0.016	8596	6100	1318	0.010	15	90094	0.09	0.17	0.79	0.56	0.20
9	326614	250689	1341	187	7	30	392	0.016	0.013	9058	6604	1480	0.010	14	75925	0.10	0.20	0.77	0.59	0.22
10	363570	257063	1201	214	16	31	467	0.029	0.035	8268	5047	669	0.025	30	106507	0.04	0.11	0.71	0.53	0.12
11	295082	236378	1545	153	9	28	352	0.022	0.028	8877	6315	1069	0.020	32	58704	0.07	0.16	0.80	0.58	0.15
12	228751	167776	1075	156	10	31	356	0.021	0.037	8474	5576	680	0.031	35	60975	0.05	0.14	0.73	0.56	0.11
13	337364	273495	1266	216	10	31	278	0.015	0.020	8849	6156	1199	0.014	18	63869	0.08	0.18	0.81	0.57	0.17
14	472059	379194	1656	229	10	30	370	0.018	0.016	8739	5739	1516	0.021	36	92865	0.10	0.18	0.80	0.58	0.22
15	448670	363705	1568	232	10	31	345	0.016	0.015	8986	6373	1593	0.013	21	84965	0.11	0.20	0.81	0.59	0.22
16	379029	303235	1274	238	8	30	294	0.015	0.012	9067	6650	1490	0.019	25	75794	0.10	0.20	0.80	0.60	0.21
17	424570	344732	1567	220	10	31	344	0.016	0.018	9191	6855	1512	0.012	19	79838	0.10	0.21	0.81	0.60	0.21
18	279683	214578	1047	205	7	31	307	0.014	0.012	9156	6580	1322	0.010	11	65105	0.09	0.19	0.77	0.60	0.19
19	313457	236352	1390	170	8	30	431	0.021	0.019	8680	6176	1164	0.016	22	77105	0.08	0.16	0.75	0.57	0.18
20	527462	407460	1430	285	12	31	399	0.019	0.014	8562	5869	1369	0.015	22	120002	0.09	0.18	0.77	0.56	0.21
Average	355841	277279	1365	203	10	30	366	0.019	0.020	8676	5905	1234	0.016	23	78563	0.08	0.17	0.78	0.57	0.19
SD	78383	65412	219	34	2	1	51	0.004	0.008	288	538	242	0.005	7	16187	0.02	0.02	0.03	0.02	0.03
Median	331989	256911	1407	207	9	31	363	0.017	0.017	8682	5937	1190	0.015	22	74610	0.08	0.17	0.78	0.56	0.19
SUM	8540192	6654685	32767	4872	229	730	8791	0.444	0.469	208218	141729	29615	0.392	542	1885507	1.97	4.12	18.64	13.58	4.47

Source: Own elaboration based on data collected from the studied company

Table 7
Production efficiency values of the new machine

Year Month	Gross Impressions	Net Impressions	Run Length (avg)	Make Ready	Operating time	Press Availability (avg)	Make Ready Waste (avg)	Make Ready Time (avg)	Other Time (avg)	Good Prod. Speed (avg)	Net Output (avg)	Net Productivity (avg)	Run Waste %	Run Waste (avg)	Total Waste (M/R + Run)	OEE	OEE 10000	OEE Quality	OEE Speed	OEE Time
1	34 614	32 648	989	33	20:37:48	720:00:00	53	0:06:48	0:21:22	9 929	6 352	1 583	0.7%	7	1 966	10.6%	27.7%	94.3%	65.7%	17.0%
2	275 037	268 632	3 018	89	144:45:36	744:00:00	47	0:07:28	1:01:34	9 538	6 343	1 856	0.8%	25	6 405	12.4%	23.3%	97.7%	63.7%	19.9%
3	163 375	158 247	1 954	81	55:09:00	720:00:00	49	0:12:34	0:11:26	9 520	6 953	2 869	0.8%	15	5 128	19.1%	32.3%	96.9%	63.4%	31.1%
4	122 603	121 042	2 882	42	67:33:36	744:00:00	29	0:36:50	0:32:23	9 495	6 334	1 792	0.3%	8	1 561	11.9%	23.2%	98.7%	63.0%	19.2%
5	237 695	222 320	3 269	68	124:26:24	720:00:00	105	0:18:48	0:51:14	8 691	4 933	1 787	3.6%	121	15 375	11.9%	18.9%	93.5%	59.1%	21.6%
6	282 192	265 706	2 920	91	101:35:24	744:00:00	135	0:15:41	0:19:25	9 038	5 495	2 615	1.6%	47	16 486	17.4%	24.8%	94.2%	60.1%	30.8%
7	186 187	171 852	3 997	43	171:01:48	720:00:00	199	0:48:09	2:08:22	8 418	3 860	1 005	3.3%	135	14 335	6.7%	11.3%	92.3%	57.4%	12.7%
8	265 415	249 216	1 860	134	119:13:48	744:00:00	95	0:08:00	0:28:03	9 143	6 438	2 090	1.3%	25	16 199	13.9%	28.0%	93.9%	61.3%	24.2%
9	211 256	199 262	3 321	60	77:46:12	672:00:00	183	0:11:55	0:39:20	9 356	7 514	2 562	0.5%	17	11 994	17.1%	28.4%	94.3%	62.1%	29.2%
10	160 875	149 874	2 584	58	97:13:12	744:00:00	130	0:23:23	0:43:13	8 520	4 564	1 542	2.2%	59	11 001	10.3%	17.1%	93.2%	57.2%	19.3%
11	406 126	393 005	4 466	88	226:28:12	744:00:00	113	0:17:00	1:26:25	8 907	5 255	1 735	0.8%	36	13 121	11.6%	17.5%	96.8%	59.3%	20.2%
12	129 175	126 778	4 372	29	52:18:00	744:00:00	57	0:08:31	0:31:00	8 772	3 819	2 424	0.6%	26	2 397	16.2%	19.9%	98.1%	58.6%	28.1%
13	494 377	468 657	2 893	162	243:19:48	720:00:00	139	0:12:51	0:49:07	9 112	6 163	1 926	0.7%	20	25 720	12.8%	22.9%	94.8%	60.6%	22.3%
14	82 172	80 601	8 956	9	28:56:24	744:00:00	160	0:22:28	1:15:28	9 163	5 656	2 785	0.2%	14	1 571	18.6%	19.3%	98.1%	60.7%	31.2%
15	344 716	335 462	7 137	47	192:03:00	720:00:00	151	0:43:14	1:43:04	8 456	4 331	1 747	0.6%	46	9 254	11.6%	13.7%	97.3%	56.4%	21.2%
16	464 667	448 132	4 573	98	199:21:36	744:00:00	149	0:31:43	0:42:24	8 855	5 722	2 248	0.4%	20	16 535	15.0%	19.8%	96.4%	58.7%	26.4%
17	475 741	454 276	3 468	131	196:41:24	720:00:00	117	0:14:14	0:41:05	8 701	5 983	2 310	1.3%	47	21 465	15.4%	23.6%	95.5%	58.3%	27.6%
18	576 430	545 279	2 996	182	279:12:00	744:00:00	127	0:31:46	0:23:47	8 830	4 926	1 953	1.4%	44	31 151	13.0%	20.9%	94.6%	59.1%	23.3%
19	641 818	617 313	5 716	108	221:22:48	672:00:00	163	0:19:04	0:35:25	8 744	5 007	2 788	1.1%	64	24 505	18.6%	22.1%	96.2%	58.5%	33.0%
20	940 767	889 336	2 955	301	314:16:48	744:00:00	130	0:13:15	0:18:19	8 557	5 705	2 830	1.4%	41	51 431	18.9%	26.4%	94.5%	57.2%	34.9%
Average	222901	211751	1839	67	4	1	48	0	0	415	989	516	0	34	12061	0	0	0	0	0
SD	270226	257461	3143.5	84.5	5.608	31	128.63	0.0113	0.02792	8881.05	5680.73	2021.60	0.00816	30.7931	13728	0.1347	0.2248	0.9514	0.5919	0.2376
Median	6495238	6197638	74326	1854	2933:22:48	14568:00	2329.96	6:43:41	15:42:26	179744	111352	42446	23.59%	816.629	297600	282.97%	441.07%	1911.31%	1200.46%	493.25%

Source: Own elaboration based on data collected from the studied company

Table 8
Performance comparison of two machines (new machine as reference)

	Average			SD		Median			Total			Minimal		Maximal	
	1997M	**2021**	**Difference**	**1997M**	**2021**	**1997M**	**2021**	**Difference**	**1997M**	**2021**	**Difference**	**1997M**	**2021**	**1997M**	**2021**
Gross Impressions	356368.30	324761.90	–0.10	118272.27	217896.58	331989.00	270226.00	–0.23	7127366.00	6495238.00	–0.10	228751.00	34614.00	527462.00	940767.00
Net Impressions	277329.15	309881.90	0.11	88113.98	208070.65	256910.50	257461.00	0.00	5546583.00	6197638.00	0.11	167776.00	32648.00	407460.00	889336.00
Run Length (avg)	1369.85	3716.30	0.63	542.90	1891.20	1407.00	3143.50	0.55	27397.00	74326.00	0.63	1047.00	989.00	3018.00	8956.00
Make Ready	203.25	92.70	–1.19	69.86	73.77	206.50	84.50	–1.44	4065.00	1854.00	–1.19	135.00	9.00	285.00	301.00
Operating time	9.76	6.11	–0.60	3.73	3.41	9.36	5.61	–0.67	195.14	122.22	–0.60	6.77	0.86	16.01	13.09
Press Availability (avg)	30.35	30.35	0.00	0.93	0.98	31.00	31.00	0.00	607.00	607.00	0.00	28.00	28.00	31.00	31.00
Make Ready Waste (avg)	368.83	116.50	–2.17	145.38	65.83	371.28	128.63	–1.89	7376.62	2329.96	–2.17	278.06	29.29	488.63	198.77
Make Ready Time (avg)	0.02	0.01	–0.35	0.01	0.01	0.02	0.01	–0.66	0.38	0.28	–0.35	0.01	0.00	0.03	0.03
Other Time (avg)	0.02	0.03	0.38	0.01	0.02	0.02	0.03	0.37	0.41	0.65	0.38	0.01	0.01	0.04	0.09
Good Prod. Speed (avg)	8655.99	8987.24	0.04	494.58	270.44	8638.33	8881.06	0.03	173119.73	179744.76	0.04	8178.26	8417.58	9929.27	9929.27
Net Output (avg)	5911.19	5567.63	–0.06	568.40	945.96	6027.99	5680.74	–0.06	118223.71	111352.55	–0.06	4950.69	3818.61	6952.86	7513.65
Net Productivity (avg)	1215.99	2122.30	0.43	472.72	549.18	1189.52	2021.61	0.41	24319.84	42446.08	0.43	669.17	1004.81	2869.39	2869.39
Run Waste %	0.02	0.01	–0.38	0.01	0.01	0.02	0.01	–0.85	0.32	0.24	–0.38	0.01	0.00	0.03	0.04
Run Waste (avg) 1997	22.51	40.83	0.45	8.23	34.26	22.01	30.79	0.29	450.20	816.63	0.45	10.75	6.58	34.78	134.60
Total Waste (M/R + Run)	79039.15	14880.00	–4.31	35448.27	18833.64	74609.50	13728.00	–4.43	1580783.00	297600.00	–4.31	58704.00	1561.00	120002.00	51431.00
OEE	0.08	0.14	0.43	0.03	0.04	0.08	0.13	0.41	1.62	2.83	0.43	0.04	0.07	0.19	0.19
OEE 10000	0.17	0.22	0.23	0.05	0.05	0.17	0.22	0.24	3.39	4.41	0.23	0.11	0.11	0.32	0.32
OEE Quality	0.78	0.96	0.19	0.08	0.05	0.78	0.95	0.18	15.54	19.11	0.19	0.71	0.92	0.98	0.99
OEE Speed	0.56	0.60	0.06	0.04	0.02	0.56	0.59	0.05	11.28	12.00	0.06	0.53	0.56	0.66	0.66
OEE Time	0.18	0.25	0.25	0.04	0.06	0.18	0.24	0.23	3.68	4.93	0.25	0.11	0.13	0.31	0.35

Source: Own elaboration based on data collected from the studied company

Table 9
Mann-Whitney U test with mean difference and effect size based on

Criterions	Parameters	p-value	Mean difference	Effect size
Gross Impressions	149	0.174	77163,00	0.255
Net Impressions	190	0.799	14045,00	0.05
Run Length (avg.)	21	< 0.001	–1836.1036	0.895
Make Ready	28.5	< 0.001	122.55375	0.8575
Operating time	81	< 0.001	3.924	0.595
Make Ready Waste (avg.)	0	< 0.001	247.7255	1
Make Ready Time (avg.)	106.5	0.012	0.00656	0.4675
Other Time (avg.)	122	0.036	–0.00799	0.39
Good Prod. Speed (avg.)	108	0.012	–297.431	0.46
Net Output (avg.)	153	0.211	302.9805	0.235
Net Productivity (avg.)	20	< 0.001	–867.5965	0.9
Run Waste %	99.5	0.007	0.00596	0.5025
Run Waste (avg.) 1997	137	0.091	–10.8245	0.315
Total Waste (M/R + Run)	0	< 0.001	61609,00	1
OEE	19.05	< 0.001	–0.05798	0.9025
OEE 10000	71.5	< 0.001	–0.05093	0.6425
OEE Quality	0	< 0.001	–0.17599	1
OEE Speed	54.5	< 0.001	–0.0345	0.7275
OEE Time	68.5	< 0.001	–0.05901	0.6575

Source: Own elaboration based on data collected from the studied company

printing press demonstrates a dramatic reduction in setup time, with 119.26% decrease in average setup time and a 144.38% decrease in median setup time, significantly ($p < 0.001$) excelling in reducing preparation time, greatly enhancing operational efficiency (Effect Size = 0.8575).

Operating time for the newest press is reduced by 59.66% on average and 66.89% at the median compared to the legacy press. The difference is significant ($p < 0.001$), with a noticeable Effect Size (0.595).

The newest press shows a 216.60% decrease in average make-ready waste and a 188.64% decrease in median waste, while the mean difference is statistically significant ($p < 0.001$) and with maximum effect size (1.000).

For Make Ready Time calculated for the 2021 press, it is increased by 34.97% in average and 66.24% in median compared to the legacy one, and the difference is statistically significant ($p = 0.012$, Effect Size = 0.4675), suggesting longer setup times which, while notable, have a moderate impact on overall operational efficiency. This could potentially suggest that adapting an old press to the standards of the modern IIoT leads to even better automation than a modern machine with good parameters in that regard.

There is an escalation in non-production time for the 2021 press, showing a 38.05% increase in average and a 37.32% increase in median. This increase is statistically significant ($p = 0.036$, Effect Size = 0.3900), indicating more time spent on maintenance or setup. This is another variable suggesting that legacy press is less time-consuming to use. This would mean that more advanced technologies have been implemented by the manufacturer in such a way that they are more complicated to operate, while this effect is not present when modernizing a machine based on old technologies.

In case of Good Production Speed the newest machine from 2021 exhibits a slight improvement in production speed with a 3.69% increase in average and a 2.73% increase in median. These changes are statistically significant ($p = 0.012$, Effect Size = 0.4600), suggesting faster operational capabilities without compromising the quality or efficiency of the prints produced.

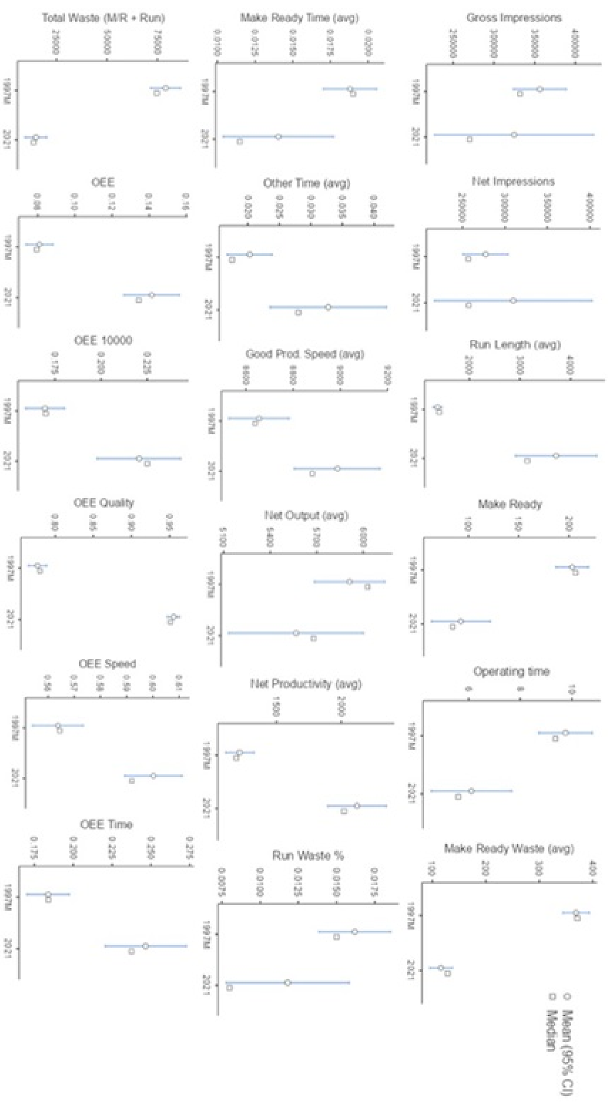

Fig. 8. Statistical comparison of parameters used in the comparative study.
Source: own elaboration (Jamovi Software)

There are small differences here which generally indicate that both machines are comparable. Comparing the Net Output, there is a decrease of 6.17% in average and 6.11% in median for the 2021 press, however, these differences are not statistically significant ($p = 0.211$, Effect Size = 0.2350), indicating that both presses are comparable.

Net Productivity has markedly increased in the 2021 press, with a 42.70% rise in both average and median productivity. This significant improvement ($p < 0.001$, Effect Size = 0.9000) indicates the advanced efficiency of the new press in utilizing its outputs effectively.

The newest press shows a reduction in waste percentage during runs, with a 37.67% decrease in average and an 85.47% decrease in median. These changes are significant again ($p = 0.007$, Effect Size = 0.5025), illustrating better waste management in the newer model.

Total Waste (M/R + Run) radically decreased (Fig. 8) for the 2021 press, with a reduction of 431.18% in average and 443.48% in median. This improvement is significant ($p < 0.001$, Effect Size = 1.000), underscoring a major enhancement in waste efficiency, which was not compensated by the modernization of the old machine.

The OEE for 2021 press has improved in both average (42.70%) and median (41.16%). This significant enhancement ($p < 0.001$, Effect Size = 0.9025) reflects a substantial increase in the effectiveness of the newer press, combining aspects of availability, performance, and quality. There is currently a need to check the individual components of this indicator.

The OEE 10000, which scales the overall equipment effectiveness by a factor of 10,000 for enhanced precision, demonstrates a 23.07% improvement in average OEE and a 24.28% improvement in median OEE for the 2021 press. Statistical analysis confirms the improvement as significant ($p < 0.001$) with an effect size of 0.6425.

In terms of quality, the 2021 press shows an 18.71% improvement in average quality rates (Tab. 8) and an 18.04% improvement in median rates, with maximum effect size (1.000) and significant p-values (p <0.001), suggesting that the brand new press is substantially more reliable in producing quality prints without defects, enhancing its credibility for high-quality output.

The speed efficiency of the 2021 press also shows significant enhancements, with a 6.05% improvement in average speed efficiency and a 4.65% improvement in median efficiency. The Mann-Whitney U test results ($p < 0.001$, Effect Size = 0.7275) indicate a notable increase in the actual operating speed compared to the ideal speed, demonstrating faster production capabilities that do not compromise quality or increase downtime, Though the differences are not large, both machines are in fact comparable.

Lastly, the effective utilization of operational time has also improved significantly in the 2021 press, with a 25.43% better average time utilization and a 22.54% improvement in the median. The significant statistical results ($p < 0.001$, Effect Size = 0.6575) mean that use of operational time is more efficient in the case of the brand new machine.

Discussion

Comparative study of productivity between a retrofitted Heidelberg Speedmaster SM74-4P legacy printing press incorporating IIoT technologies into the older press, and the latest Heidelberg Speedmaster

CX75-4 model was conducted, including KPIs and OEE parameters over a period of 20 months. The results indicate that while the new model generally outperforms the retrofitted machine in several aspects, the legacy press, once modernized, still holds significant productivity potential.

A comparative analysis of a retrofitted older sheet-fed offset press with its modern data-driven counterpart, under similar operating configurations, was conducted to determine the continued productivity and manageability of the older machine equipped with IIoT sensors. In fact, the results were somewhat ambiguous in this respect. Considering all production parameters, it turned out that the newer machine could outperform the older retrofitted machine during short periods of time. In the analyzed data, there were months when the significantly higher value of the newer machine led to much better results, but at the cost of producing more waste and spending more time on non-printing maintenance. The older machine generally had lower peak performance. On the surface, this difference could be explained by reliability issues, since it can be assumed that even after the implementation of IIoT sensors, the overall material and technical issues related to the operation of almost thirty-year-old systems remain unchanged. This difference could only be eliminated by a zero-hour upgrade, which would restore the condition of the components to the condition they were when the unit originally left the original production line.

Generally, companies with legacy press equipment can consider retrofitting as a viable option to enhance productivity without the substantial investment required for new machines. In this regard, the findings suggest that retrofitting can extend the lifecycle of existing machines, allowing companies to allocate resources more effectively and avoid large capital expenditures. By extending the usability of older machines, modernization clearly supports sustainability initiatives and reduces environmental impact.

The introduction identified the following knowledge gaps: a lack of literature on IIoT retrofits in offset printing, a lack of quantitative analysis of efficiency and productivity gains, and a lack of cost-benefit analyses based on KPIs.

The presented results contribute to addressing this situation and partially shed light on the potential to close these gaps.

As the result of the empirical findings, the study provides a particularly significant practical contribution. While a single empirical study does not substantially expand theoretical academic literature, it offers a concrete case study of IIoT retrofits in a printing company using Heidelberg machines, helping to address the gap.

In this form, the findings are not in conflict with the existing body of literature, but rather expand upon the perspectives presented therein.

Digital retrofitting offers the potential to extend the life of existing manual systems by equipping them with cyber-physical capabilities (Azzouz et al., 2022). Previous studies, however, have primarily focused on functionality rather than the performance of the equipment.

The modernization of older offset printing machines through retrofitting has been proposed by Meissner (2021) as an alternative to purchasing new equipment, suggesting potential benefits, albeit without empirical data. This study is the first to demonstrate that modernization using IoT not only brings qualitatively understood advantages, but also yields quantitative results, bringing the performance of an older printing press closer to that of a new one.

As Urban and Łukaszewicz (2021) rightly observed, modern offset printing requires automated supervision and the reduction of human error – an aspect that proves to be crucial in light of the performance indicators obtained for the retrofitted machine. In particular, consistent with the assumptions of Urban and Łukaszewicz (2021), the conducted research confirms the importance of real-time data monitoring as a means of enhancing production control.

A deeper analysis of the relationship between the study's findings and the existing body of literature should consider not only machine performance, but also the structural transformations occurring across the entire industry. In practice, decisions are rarely as binary as simply purchasing new equipment or retaining an outdated fleet. From the perspective of production management and engineering in the offset printing industry, such decisions are increasingly shaped by shifts in the business models of machine manufacturers.

This phenomenon is aptly described by Salwin et al. (2021) in the context of a paradigm shift among equipment suppliers – from a product-based to a service-based model. In this model, the machine is not always sold as a tangible asset, and the manufacturer's role extends far beyond supplying hardware. It encompasses a comprehensive commercial service that includes support, consultancy, and data analytics. From the perspective proposed by Salwin et al., the findings of this study illustrate that digital transformation within the offset printing sector can occur bottom-up, without being entirely dependent on manufacturers. On the contrary, key qualitative improvements linked to digitalization – particularly those enhancing production efficiency – can take place independently of suppliers' business models.

On the other hand, if the results are interpreted through the lens of Salwin et al. (2021), they also suggest that retrofit-generated data could be leveraged not only operationally but commercially as well – for instance, as part of a new service offering from the machine manufacturer. In a service-oriented model, even legacy equipment already owned by the client may be treated as a valuable asset. If modernization proves significantly more cost-effective than delivering a brand-new machine – and if the goal of the service is to maximize digital transformation benefits – then such upgrades could yield much higher margins. A compelling example might be a hybrid approach where select older machines are modernized and integrated with new factory equipment, achieving a production setup comparable in performance to a totally new machine fleet.

A very similar transformation – a shift from a product delivery model (printed materials, packaging) to a service delivery model – is also taking place on the side of offset printing companies. This trend is aptly recognized in the literature by Magadán-Díaz and Rivas-García (2021), who highlight the emergence of hybrid business models. In such models, competitive pressure drives printing companies toward shorter delivery times, lower costs, and greater personalization, along with investments in digitization, automation, and the development of additional services – even extending into the publishing sector through self-publishing and online sales. However, the adaptation of these models remains partial and uneven.

When confronting the study's findings with these broader changes, it becomes clear that as business model transformation increasingly aims to maximize flexibility, order fulfillment speed, and the benefits of operating in a digital environment, machine fleet modernization aligns with – and indeed facilitates – these same objectives. Moreover, it does so with a significantly lower entry barrier than a full-scale transformation of the business model.

The study has several general limitations. It was conducted over 20 months at a single printing facility, while only a broader study across multiple facilities, and – possibly a longer duration could provide more generalizable results. The data were collected from sensors retrofitted into the legacy machine and the built-in systems of the new machine. Differences in sensor quality and data collection methods could always introduce biases. This limitation applies to all studies in principle, in which a small number of machines is compared (in this case two) may cause systematic errors. This risk can be mitigated (if the sensors are set up correctly) by maximizing the sample size, i.e. by including a much larger number of machines. The study assumes similar operational conditions for both machines, but variations in job complexity, operator expertise, and maintenance schedules could affect performance metrics.

The cost implications of retrofitting versus purchasing new equipment were not deeply analyzed. The costs of modernizing machines and buying new machines are the secrets of the manufacturers. It can only be said in general terms that the total cost of buying and modernizing an older machine was many times lower than the cost of buying a brand new press. Nevertheless, this does not provide a basis for conducting a complete cost-effect analysis for modernization compared to purchase, which would allow for drawing more far-reaching conclusions, as a detailed cost-benefit analysis including long-term maintenance and operational costs could provide more insights.

The cost implications of modernization versus purchasing new equipment have not been analyzed in depth, because the costs of modernizing machines and purchasing new machines are not disclosed by the manufacturers. Only approximate data have been provided, based on which it can be assumed that the total cost of purchasing and modernizing an older machine was many times lower than the cost of purchasing a completely new press.

Conclusions

IIoT is an area that allows for extensive modifications giving new life to old industrial machines, which, equipped with new sensors and effectors, can partially match the performance of much more expensive new machines, which contributes to potential financial and environmental savings. In the case of offset printing, which is a generic technology in principle, this is a huge opportunity to increase the competitiveness of companies, especially in the bridging period before switching to digital printing. However, it should be borne in mind that even extensive modernization does not compensate all the advantages of brand new machines.

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