Enhancing HMI and Efficiency in Offset Printing: Integrating Eye-Tracking with Simulator-Based Training

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Abstract

This study examines the behaviour of offset-printing operators during the execution of pre-defined tasks within a print-simulation environment, with particular emphasis on aspects of Human–Machine Interaction (HMI). The purpose is to observe and analyse operator responses to two targeted scenarios: identifying a deliberate two-millimetre shift in the printed subject and navigating the press software to locate and modify the corresponding job parameters.

The research was carried out in a controlled laboratory setting using the Sinapse print simulator, which reproduces key operational features of an offset-press control environment. Two groups of participants—experienced and novice operators—completed both tasks, enabling a direct comparison of performance across differing levels of expertise.

Eye-tracking technology was employed to record gaze behaviour during task execution, capturing data on visual attention, fixation patterns, and observation strategies. Complementary screen-recording data documented the full sequence of interaction steps, allowing for detailed analysis of navigation paths and decision-making processes. Brief post-task interviews provided additional qualitative insights regarding user experience, operational challenges and interface related considerations.

The findings highlight specific aspects of software interface design and simulator functionality that may be improved to support more effective HMI. Enhancing these elements is expected to facilitate more accurate task execution, reduce operator-induced errors and strengthen overall efficiency within offset-printing workflows

1. Introduction

This paper presents a systematic framework for evaluating human-machine Interaction (HMI) in the printing industry, focusing on operating offset printing machines using advanced simulation technology. The primary objective is to assess the effectiveness, accuracy, and efficiency of operator training through a print simulator, which accurately replicates the interface of an actual printing press. Additionally, our study investigates potential improvements to the simulator's control console based on participant performance.

Our research adopts a mixed-methods approach, combining quantitative data from eye tracking and performance metrics with qualitative feedback from post-task questionnaires. Participants were divided into two groups: advanced and novice operators. This enables a comparative analysis of how experience and familiarity with the printing machine interface affect operational performance and problem-solving abilities.

The participants in our research were tasked with navigating the printing machine software to adjust job details and detecting a subtle two-millimetre shift in the printed output, providing insights into their operational efficiency and attention to detail. Data collection involved using an eye-tracking system to monitor visual attention and gaze patterns alongside screen recordings to document participant actions. These data were further enriched with qualitative feedback on user experience (UX) and suggestions for control console enhancements.

Our analysis seeks to identify common visual strategies and areas where users encounter difficulties, offering a comprehensive understanding of HMI in offset printing. By integrating these diverse data sources, we aimed to provide actionable recommendations for improving training effectiveness and operational efficiency within the industry. We managed to identify common visual strategies and areas where users encounter difficulties, offering a detailed understanding of HMI in offset printing. By integrating these diverse data sources, our study aims to provide actionable recommendations for improving training effectiveness and operational efficiency within the industry.

A set of key research questions drives this study to evaluate the effectiveness and usability of printing simulators in replicating real-world machine operations and workflows for training purposes. Specifically, the research seeks to determine how well existing simulators emulate the actual functions of printing machines and whether they require improvements in specific areas. Additionally, the study investigates the extent to which employees in the graphic arts industry are aware of the digital transformation of production workflows—such as the shift from manual to automated or software-driven processes—and how comfortable they feel transitioning traditional, hands-on tasks into simulated environments, including those enhanced by eye-tracking technologies. This was particularly relevant for understanding whether offset press operators had previous exposure to or conceptual knowledge of digital workflows (e.g., digital information uploaded to the press about the printing jobs, simulation-based training tools, or automated quality control). Clarifying this link was necessary to interpret their responses to the eye-tracking simulator, as familiarity with such technologies might influence their ease of use, acceptance, and engagement. The study also investigates the common challenges operators face when using simulators to detect and correct print deviations, as well as the potential correlations between ocular physiology (e.g., gaze patterns, cognitive load) and factors such as age, professional experience, and familiarity with control consoles. Furthermore, it examines whether identifiable cognitive or observational patterns can inform improvements in interface design.

The objectives of this research are multifaceted. First, it aims to evaluate the usability and functional effectiveness of the printing simulator used in this study. Second, it seeks to compare the problem-solving performance and capabilities of novice and experienced operators, identifying skill gaps and areas for improvement in training methodologies. Third, the study proposes targeted enhancements to the control consoles of printing machines to optimise them for both training and operational efficiency. Finally, it investigates the specific visual navigation strategies operators employ and their impact on task accuracy and performance. This research bridges gaps in simulator design, training practices, and HMI within the printing industry by addressing these questions and objectives, ultimately fostering more excellent digital adaptation and operational excellence.

2. Literature Review

2.1 Importance of HMI

HMI plays a key role in modern technology, influencing how people interact with machines and systems in various domains. The importance of successful interaction is multifaceted and includes aspects of UX, efficiency, connectivity, security, and adaptability. At its core, HMI seeks to improve UX by making technology more intuitive and accessible. Well-designed interfaces reduce learning difficulty, allowing users to interact with machines more effectively. Whether navigating a smartphone, operating industrial equipment, or using software applications, an intuitive HMI contributes to user satisfaction and proficiency (Lee et al., 2017).

Efficiency and productivity are paramount in industrial and business settings, and HMI is a key factor in optimising operations. For this reason, human factors engineering (HFE) has grown rapidly in recent years in terms of designing interfaces for industrial equipment. The primary goal of HFE is to create user-friendly interfaces that optimise the interaction between operators and machines.

HFE considers factors such as the layout of control panels, information presentation, ergonomic considerations, and safety features. The primary goals are minimising errors, improving operational efficiency, and prioritising usability. Through task analysis, feedback system design, and consideration of different user skill levels, HFE contributes to developing adaptable interfaces that work for a wide range of users, regardless of their experience or physical capabilities (Kumar & Lee, 2022).

Essentially, the role of HFE is to create interfaces that excel in usability and security and provide a positive UX in industrial settings. User-friendly interfaces streamline processes, minimising errors and reducing the time required to perform complex operations. This efficiency not only boosts productivity but also contributes to overall operational excellence.

Real-time decision-making is facilitated by dynamic HMI, allowing users to interact with machines and systems as conditions change. This is particularly critical in areas where rapid decision-making is essential, such as emergency response, financial transactions, or dynamic production processes (Lee et al., 2017).

2.2 Simulators in HMI

Simulators found their place in industrial education in the 1980s, expanding into sectors such as oil and gas, manufacturing, and construction. Used for equipment operation, safety training, and process optimisation, they have become integral elements of workforce development (Schmuck, 2021).

Simulators have emerged as a key tool in shaping the HMI landscape, particularly in training complex functions. As technological platforms, simulators offer a controlled environment, allowing users to interact with simulated representations of real-world systems or tasks. Through this incremental approach, simulators facilitate skill development while mitigating cognitive overload. Users can systematically improve their proficiency without strain, thus enhancing a more effective learning process (Reedy, 2015). A recent shift in advanced service models is integrating digitally enhanced advanced services (DEAS), which use innovative digital technologies like gamification to educate users. This approach focuses on delivering outcomes to customers rather than just products, and simulators serve as an essential tool for improving the understanding of complex maintenance and operational scenarios (Khan, Charissis, & Harrison, 2022).

An important aspect of impact lies in managing cognitive load. Simulators are controlled environments where users can engage with tasks and scenarios without risks. This controlled condition leads to structured progression in task complexity, allowing users to focus on specific aspects of a task. Through this incremental approach, simulators facilitate skill development while mitigating cognitive overload. Users can systematically improve their proficiency without strain, thus enhancing a more effective learning process (Reedy, 2015).

In addition, simulators play a critical role in forming and improving mental models, which are cognitive representations of how a system or task works. By providing an immersive and repetitive experience, simulators contribute to the development of strong mental models. Users can deepen their understanding of the simulated system's complexities, relationships, and dependencies. The procedural knowledge gained through these interactions is internalised, enhancing users' ability to predict and respond effectively to different scenarios. (Tremblay et al., 2023).

2.3 The role of simulators in industrial automation and production

Automation and technological advancements have permeated every aspect of the graphic arts industry, from the initial client communication to the final production of the desired print or digital media. This trend aligns with the principles of Industry 4.0, which is reshaping the manufacturing sector, including the printing industry. Known as the "Fourth Industrial Revolution," Industry 4.0 represents a significant global movement integrating automation and data exchange in industrial processes (Gamprellis et al., 2021).

Simulators play a crucial role in industrial automation, enhancing various aspects of the process and significantly improving system efficiency, safety, and reliability. In the context of Industry 4.0, simulators are integral for developing and optimising complex, smart production systems. They excel particularly in training and skill development by offering a safe, controlled environment where operators can refine their skills in operating and troubleshooting automation systems (Cat® Simulator Systems, 2024). This approach minimises the risk of equipment failure and production downtime. As Industry 4.0 advances, simulation technology has become fundamental in optimising decision-making, designing and operating smart production systems, and evaluating the risks, costs, and implementation barriers associated with these systems. Simulators now help companies navigate their journey toward Industry 4.0 by providing insights into operational performance impacts and the overall roadmap for integration (de Paula Ferreira et al., 2020).

Simulators are instrumental in reducing downtime and production costs, particularly within modern asset maintenance and management. In increasingly automated and integrated production environments, where high asset availability is critical, simulators allow operators to model and refine processes before implementing changes in the actual production setting. This proactive approach minimises disruptions and potential economic losses by enabling thorough testing of control systems and automation software. The capability of simulators to model complex systems, including various maintenance sub-systems such as asset utilisation, failure, scheduling, staffing, and inventory, supports performance improvement and enhances overall system reliability. By simulating these processes, organisations can identify and resolve potential issues before they affect actual operations, ensuring smoother and more reliable operation of automated systems. (Marcano, Haugenb, Sannerud, & Komulainen, 2019) Simulation techniques also play a key role in assessing condition-based maintenance (CBM) and other maintenance strategies, contributing to more thorough maintenance systems (Alabdulkarim et al., 2013).

Simulators are also crucial during the design and prototyping phases of automation systems. Engineers utilise simulators to evaluate various control strategies, assess the impact of different parameters, and refine designs before implementing them physically. This iterative approach promotes the development of more efficient and cost-effective automation solutions. A notable example is the digital twin concept, where a digital replica of the physical system is created. This "twin" is subjected to various conditions and scenarios through parameterisation to ensure the system's optimal performance before it is applied in the real world (Malik et al., 2022).

2.4 Eye-tracking systems and their applications

Eye-tracking technology has become increasingly accessible and advanced, with modern systems capable of precisely tracking eye movements. These systems are employed in various fields, including psychology, neuroscience, marketing, virtual reality, and gaming. Integrating AI and machine learning has further enhanced the analytical capabilities of eye-tracking systems, enabling more profound insights into human behaviour and cognition (Borgianni et al., 2018).

Eye-tracking systems utilise sophisticated technologies to track and analyse a person's eye movements. These systems combine specialised hardware and software to record and interpret complex eye movement patterns, providing valuable information about human behaviour and cognitive processes (Carter & Luke, 2020). Eye-tracking systems, in particular, work by recording and analysing eye movements using infrared cameras that detect light reflected from the eye. Light sources create reflections in the cornea and pupil, known as corneal and pupillary reflections, which help determine eye position and orientation (Carter & Luke, 2020).

Calibration is essential before using the equipment. Users focus on specific points, allowing the system to record eye movements. This process accounts for individual variations in anatomy and gaze behaviour. The recorded images undergo real-time processing using sophisticated algorithms that identify features such as the pupil's centre and corneal reflections. The system then calculates the point in the user's field of view where they are looking, with accuracy being crucial for reliable results (Harezlak et al., 2014).

The system extracts data representing the user's gaze points over time, including metrics such as fixation duration (the time spent focusing on a point) and saccadic movements (rapid eye movements between fixations), among other gaze behaviour parameters (Carter & Luke, 2020).

The integration of Eye-Tracking systems into various applications depends on the intended use. In human-computer interaction (HCI), these systems can control a computer screen's cursor or enable hands-free interaction in virtual reality environments. The data is analysed in research settings to gain insights into cognitive processes, attention mechanisms, and user behaviour.

In the industrial sector, a primary application of eye-tracking systems is HMI. By monitoring users' gaze patterns, these systems facilitate the ergonomic design of machines and their control interfaces while identifying where users experience difficulty during operation (Borgianni et al., 2018).

Eye tracking is crucial in understanding consumer behaviour in market research and advertising. Companies can optimise product packaging, store layouts, and digital advertisements to enhance consumer engagement and drive sales by analysing where people focus their attention and how long they fixate on specific items. This application also extends to website and user interface design, allowing developers to create more user-friendly and visually appealing digital experiences (Zheng et al., 2022).

2.5 Basic concepts in eye-tracking metrics

Data reliability in eye tracking refers to the difference between the actual gaze position and the position recorded by the system, highlighting how closely the recorded data matches the actual eye movements. Factors influencing reliability include calibration quality, camera resolution, and system stability (Andersson, Nyström, & Holmqvist, 2010). High accuracy and reliable data are crucial in tasks requiring precise eye movement analysis, such as clinical assessments. Validity refers to the consistency of the recorded data, indicating how reliably the eye tracker captures the same eye movement under identical conditions. This is typically calculated using the sampling points' root mean square (RMS). A highly valid system produces similar results repeatedly when tracking the same eye moved, demonstrating low variability or error in the measurements. Validity is critical for obtaining consistent data, especially in research where subtle differences in eye movements must be accurately detected and analysed.

Fixation refers to the period during which the eyes focus on a visual target. Visual perception stabilises during fixation, allowing the eyes to gather visual information. However, the eyes cannot capture high-quality information from the visual field in a single fixation, necessitating frequent eye movements. Consequently, most fixations are relatively brief. The duration of fixations can vary based on factors such as the nature of the visual stimuli, the purpose and complexity of the task, and the individual's skill and attention level, generally ranging from 180 to 330 milliseconds (Carter & Luke, 2020). Saccadic movements are rapid, ballistic shifts of the eye from one fixation point to the next, during which visual input is momentarily suppressed (Rolfs, 2015). The speed and duration of saccadic movements are directly related to the distance travelled. These movements can vary in magnitude and duration depending on the task. For example, a typical reading saccade is small (around 2° rotation). It lasts about 30 milliseconds, whereas saccadic movements during scene perception are usually more significant (approximately 5° rotation) and last 40 to 50 milliseconds (Carter & Luke, 2020).

Metrics, including data reliability, validity, fixation, and saccadic movements, provide eye-tracking insights into human visual behaviour and cognitive processes. Understanding these concepts is essential for various applications, from clinical assessments to research in cognitive psychology, ensuring that the data collected is accurate and consistent for effective analysis.

2.6 HMI in the offset printing method

HMI in the printing industry is crucial for optimising the efficiency and quality of printing processes. This interaction involves a broad spectrum of activities, from printing machines' initial setup and operation to ongoing maintenance and quality control. Operators engage with various types of printing equipment, using control panels, touchscreens, and software interfaces to configure and monitor machine settings.

In offset printing, HMI is particularly intricate due to the complexity of the technology involved. The production process begins with preparing the printing machine, with a number of manual preparations (for example semi-automatically placement of the printing plates on the plate cylinders, adjustment of the inking units etc.). Critical tasks also include configuring the paper feed and aligning the printing plates to ensure the quality of the printed output.

During the printing process, operators must continuously monitor machine readings and make necessary adjustments to maintain the process within specified parameters. To ensure consistent output, they oversee the printing machine in real time, fine-tuning ink-water ratios, pressure settings, and paper feed mechanisms.

Regular maintenance is also vital in offset printing. Operators clean the inking rollers, inspect and replace consumables and lubricate moving parts to prevent mechanical failures. Expert troubleshooting is required to diagnose and resolve problems quickly, minimising production downtime when mechanical or software issues arise.

Quality control during printing involves detailed inspection of printed sheets for defects such as ink smudges, misalignment of colours, or colour inconsistencies. Operators make the necessary adjustments to ensure the final product meets stringent quality standards. This level of HMI in offset printing highlights the critical role of skilled operators in managing sophisticated machinery and achieving consistent, high-quality production.

3. Research Methodology

3.1 Ethical Considerations

This research was conducted within the framework of a Master's thesis and, according to the institutional regulations, did not require approval from a formal Research Ethics Board. The Director of the Hellenic Graphic-Media Research Lab – GRAPHMEDLAB provided oversight and guidelines regarding ethical procedures. All participants received full information about the purpose of the study, the handling and storage of their personal data, and their rights—including the right to request immediate deletion of their data at any stage. In accordance with the laboratory's security policy, all eye-tracking recordings were collected on an isolated, non-networked computer system. Access to the recorded data is strictly controlled and requires explicit authorisation from the GRAPHMEDLAB Director, granted only with the written consent of the individuals whose biometric data are involved.

3.2 Eye-tracking system and simulator setup

We employed the advanced Sinapse print simulator to replicate the control console of Heidelberg's offset presses. This simulator provides an immersive and realistic environment that mirrors printing press operations offering access to a press capable of printing up to 4 colours top and bottom side, producing 16 pages folded. The central console is a control system with different screens, each controlling different simulator functions. Our research explored how eye-tracking systems can enhance UX and HMI within the printing industry.

Two distinct groups of offset press operators participated in our research: novice and experienced. The first group consisted of experienced operators (five operators), including graduate students of the Graphic Arts Technology Department who work in the printing industry and professionals with many years of experience in offset printing. The second group included novice operators (four operators), including undergraduate students of the Graphic Arts Technology Department, or operators who were relatively new to the industry with no prior experience in related professions. A preliminary survey ensured that all participants met the required essential criteria.

Participants engaged in tasks designed to evaluate their interaction with the simulator. They focused on detecting a deliberate 2 mm shift in the placement of the print subject relative to its correct position on the substrate and navigating the printing machine software to identify and adjust job specifications. An eye-tracking system monitored and recorded the operators' eye movements throughout the tasks, capturing detailed data on their interaction with the simulator interface. This provided insights into their focus points, gaze patterns, and interaction sequences.

After completing the tasks, participants underwent a brief interview using questions designed to assess their problem-solving experiences and broader perspectives on the graphic arts industry. The questions were structured to accommodate both novice and experienced operators.

Figure 1 illustrates the setup, which featured a dual-screen computer configuration to enable the operation of the simulator and the simultaneous recording of screen and eye-tracking data. The first screen displayed the simulator applications in front of the participant. The second screen, placed sideways to the participant, displayed the system’s monitoring and recording software.

Figure 1: Installed iris tracking system

Before using the system, each user must calibrate individually to obtain specific eye measurements (Figure 2). A five (5) point calibration was chosen, with a fixed data collection frequency of 60 Hz. All calibrations were achieved on the first attempt without the need for recalibration.

Figure 2: Calibration process of the eye tracker

We employed the Gazepoint control system as the eye-tracking system, known for its high precision in biometric data recording (Figure 3). The eye tracker was positioned at a 45° angle and approximately 65 cm from the participant's face, with adjustments made for users wearing glasses to minimise reflective interference. Our study was conducted in the Hellenic Graphic-Media Research Lab – GRAPHMEDLAB, where the eye-tracking system and the simulator were installed. The laboratory offered a controlled environment with consistent artificial lighting, provided by cool-coloured fluorescent lamps and supplemented by natural light. The ambient temperature was maintained at a constant 25°C to ensure a comfortable setting for all participants and to support the integrity of the study.

3.3 Data analysis and insights

3.3.1 Statistical foundations of correlation analysis in eye-tracking research

In statistical analysis, correlation measures the degree of association between two or more variables, offering insights into patterns and dependencies within datasets. Among the most widely used metrics in correlation analysis is Pearson's correlation coefficient, a parametric measure that quantifies the strength and direction of the linear relationship between two continuous variables. The formula for Pearson's correlation coefficient is given by (Asuero et. al, 2006):

$$r = \frac{\sum \left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right)}{\sqrt{\sum \left(X_i - \overline{X}\right)^2 \sum \left(Y_i - \overline{Y}\right)^2}}$$

where X_i and Y_i are individual data points, and $\bar{X}$ and $\bar{Y}$ are their respective means. This measure assumes normality in data distribution and is particularly sensitive to outliers, making data preprocessing an essential step in correlation analysis.

The Pearson correlation table presents the Pearson correlation coefficients (r) for each variable pair and ranges from -1 to 1:

r = 1: Perfect positive linear correlation.
r = -1: Perfect negative linear correlation.
r = 0: No linear correlation.

Correlation strength is interpreted as:

0 to ± 0.3: Weak correlation.
±0.3 to ±0.7: Moderate correlation.
±0.7 to ±1: Strong correlation.

For Pearson's correlation coefficient to be valid, certain assumptions must be met:

- **Linearity:** The relationship between the variables should be approximately linear. If the data exhibit a curved pattern, alternative correlation measures such as Spearman's rank correlation might be more appropriate.|

- **Normality:** Both variables should be approximately normally distributed, especially for small sample sizes. In cases of non-normality, transformations such as log or square root transformations may be applied.
- **Homoscedasticity:** The variance of one variable should remain constant across the values of the other variable. Heteroscedasticity (non-constant variance) may distort correlation estimates.
- **No significant outliers:** Outliers can disproportionately affect Pearson's correlation, leading to misleading results. Robust statistical methods or outlier removal techniques may be necessary to mitigate their impact.

A broader perspective on correlation structures can be obtained through the correlation matrix, a symmetric matrix that displays pairwise correlation coefficients among multiple variables in a dataset. This matrix facilitates multivariate analysis by highlighting interdependencies between variables, allowing for deeper exploration of complex relationships. It serves as a foundation for dimensionality reduction techniques, feature selection in machine learning, and exploratory data analysis in empirical research. The correlation matrix is computed as:

$$R = \begin{bmatrix} 1 & \cdots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & 1 \end{bmatrix}$$

where each r_{ij} represents the Pearson correlation coefficient between variables X_j. This matrix is extensively used in disciplines such as psychology, economics, and engineering, providing a quantitative basis for inferring relationships and guiding predictive modelling.

In this study, Pearson's correlation and correlation matrices were employed to analyze gaze fixation metrics and their associations with demographic factors and operational experience. These statistical tools provided insights into how print simulator and expertise influenced gaze behaviour in an industrial printing environment. Specifically, the correlation analysis helped determine:

- Whether fixation duration correlates with operator experience, indicating the impact of training on visual processing efficiency.
- The relationship between saccadic movements and problem-solving efficiency, shedding light on how experienced and novice users scan interface elements.
- The connection between pupil dilation and cognitive load helps to assess mental effort during specific tasks.

3.3.2 Descriptive Statistics of Eye-Tracking Metrics

Table 1 presents the descriptive statistics for the principal eye-tracking variables examined in this study, including fixation onset, fixation duration, pupil diameter, saccadic characteristics, and blink behaviour. The metrics exhibit substantial variability, which is expected in visually demanding tasks where cognitive load, attentional allocation, and individual perceptual strategies differ across participants. The large spread observed in fixation-related and saccadic measures reflects the heterogeneity of visual search patterns during interaction with the offset printing console, while pupil- and blink-based measures demonstrate sensitivity to physiological and cognitive fluctuations throughout task execution. These descriptive distributions characterise the underlying data utilised in the subsequent statistical analyses and provide a quantitative foundation for interpreting the relationships observed among the recorded visual-attention indicators.

Table 1: Descriptive Statistics of Key Eye-Tracking Metrics

Metric	N	Mean	SD	Min	Max
Fixation Onset (FPOGS)	11096	35.748.183,53	26.442.300,33	130.070,4	105.000.000
Fixation Duration (FPOGD)	11096	35.762,45	20.697,90	153,0	131.000
Left Pupil Diamter (LPMM)	11096	6.471.273,62	6.294.126	415.786,2	6.294.126
Right Pupil Diameter (RPMM)	11096	3.868.439,65	3.791.208	423.019,8	3.791.208
Saccade Magnitude (SACCADE_MAG)	11096	38.285.850	679.740.200	1,0	679.740.200
Saccade Direction (SACCADE_DIR)	11096	27.230.400	35.997.200	0	35.997.200
Blink Count (BKID)	11096	6,36	89,55	0	610
Blink Duration (BKDUR)	11096	5.802,22	1.457,50	0	144.586

3.3.3 Statistical analysis of iris tracking data and demographic correlations

This section presents the research findings derived from iris tracking of participants during task-solving, followed by subsequent interviews. Data analysis was performed using SPSS, employing the Chi-Square test of independence and Pearson's correlation to examine potential relationships and dependencies.
A statistical analysis of participants' demographic data was also conducted. Examining the correlation between demographic factors—age and total years of experience—and iris tracking data offers more profound insights into how different worker groups interact with offset printing machines. These findings can inform the development of personalized, more effective training programmes and targeted ergonomic adjustments.

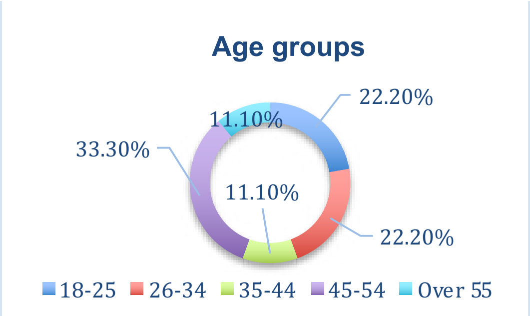

Figure 3: Age groups of participants

Figure 3 shows the distribution of survey participants based on age groups. The 18-25 age group represents 22.2% of the total participants, and the 26-34 age group represents 22.2% of the total. The 35-44 age group and the 55 and older age group are the smallest, making up 11.1% of the total. The largest age group in the survey is the 45-54 age group, which corresponds to 33.3% of the total.

Regarding experience in graphic arts: To examine how years of experience influence attitudes toward technological advancements.

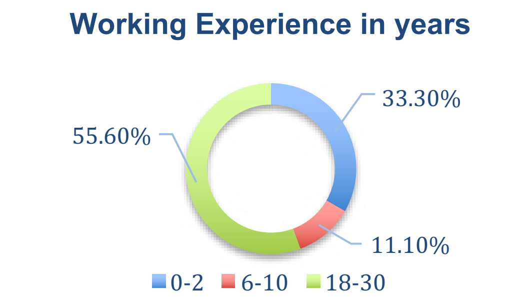

Figure 4: Working experience in yours of participants

Figure 4 illustrates the distribution of participants based on their work experience. A majority of the sample (55.6%) reported between 18 and 30 years of experience. Another 11.1% reported exactly 10 years of experience, while 33.3% had up to 1 year of experience. Notably, no participants in this sample reported work experience between 1 and 9 years or between 11 and 17 years. This gap may reflect the current composition of the workforce, where experienced professionals and newly hired operators are more prevalent than those in mid-career stages. Work experience is directly proportional to age, particularly for individuals over 40, whereas beginner operators typically do not exceed 1 year of experience.

Regarding experience with control consoles: To assess whether prior console experience correlates with ease of simulator use and problem-solving efficiency.

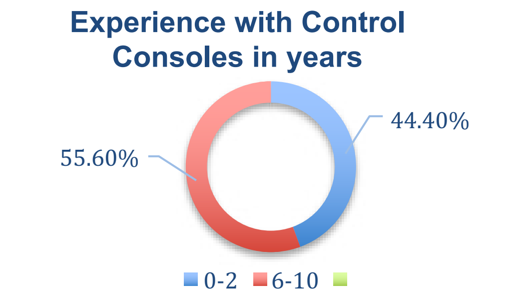

Figure 5: Experience with control consoles in years of participants

Figure 5 represents the distribution of participants based on their experience in a console environment. 55.6% of the sample has more than 11 years of experience working with consoles, while 44.4% represents the beginner group, with no more than 1 year of experience in a console environment. Experienced operators appeared to have been introduced to electronic control consoles at the onset of rapid technological advancements and automation in offset printing machines. This suggests that the greek market responded quickly to acquiring technologically advanced equipment for the graphic arts industry. However, this does not necessarily imply that the workforce adapted at the same pace.

Three hypotheses were tested:

- Age influences responses, with older workers expected to resist new technologies while younger workers show greater adaptability.
- Years of experience in graphic arts correlate with responses, as longer-tenured workers may have started their careers during earli-

er technological stages.
- Prior experience with control consoles correlates with simulator ease and problem-solving speed, suggesting that familiarity with consoles enhances performance in simulated environments.

Inductive statistical methods were applied to infer population parameters from the sample. Hypothesis testing was conducted by evaluating the null hypothesis (H_0) against the alternative hypothesis (H_1) at a significance level of $\alpha = 0.05$. The p-value determined whether H_0 should be rejected, with lower p-values providing more substantial evidence against H_0.

Table 2: Correlation between age and question "Do you consider that the simulator, as a troubleshooting basis, can guide someone adequately?"

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	9.000[a]	4	0.061

Table 2 presents the Pearson Chi-Square test, which yields a value of 9.000 with 4 degrees of freedom and an asymptotic significance (p-value) of 0.061. This p-value suggests a borderline absence of a significant correlation between age and the responses. However, since the p-value is influenced by sample size, a larger sample could likely have revealed a significant relationship between age and the perceived adequacy of the simulator as a troubleshooting tool.

Table 3: Correlation between years of experience in graphic arts and the question, "Do you consider the simulator, as a troubleshooting basis, can guide someone adequately?"

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	1.406[a]	2	0.495

Table 3 presents the results of the Pearson Chi-Square test, showing a chi-square value of 1.406 with 2 degrees of freedom and a p-value of 0.495. The high p-value indicates a low degree of correlation, suggesting that the relationship between the examined variables is not statistically significant.

Table 4: Correlation of prior experience with control consoles and the question, "Do you consider that the simulator, as a troubleshooting basis, can guide someone adequately?"

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	0.900[a]	1	0.343

Table 4 presents the results of the Pearson Chi-Square test, which yields a value of 0.900 with 1 degree of freedom. The p-value is 0.343, indicating that the result is not statistically significant at conventional thresholds.

3.3.4 Gaze fixation analysis and correlation of eye-tracking metrics

The analysis of gaze fixations provided valuable insights into where operators focused their attention, highlighting critical points on the control console that required significant focus. By examining saccades, or the rapid eye movements between points, we aimed to under-

stand how operators shifted their gaze across different interface areas. Heatmaps, which visually illustrated areas of concentrated gaze, revealed key interaction points where operators directed most of their attention. Specific Areas of Interest (AOI) were defined for tasks such as starting the machine, correcting print alignment, and adjusting job specifications.
Several metrics obtained from the eye-tracking system were analyzed for our research:

- Time (TIME): The duration measured from the start of recording for each participant.
- Fixation Start (FPOGS): The start moment of gaze fixation.
- Fixation Duration (FPOGD): The duration of each fixation in seconds.
- Pupil Diameter (LPMM, RPMM): The right and left pupils' diameters are measured in millimetres.
- Saccade Magnitude (SACCADE_MAG): The magnitude of saccadic movement between fixations.
- Saccade Direction (SACCADE_DIR): The direction of saccadic movement, measured in degrees.
- Blink Count (BKID): The number of blinks per participant.
- Blink Duration (BDUR): The duration of each blink.
- Overall Experience (SYNOLIKI EMPEIRIA): The total experience of the participants.
- Platform Experience (EMPEIRIA PLATFORMA): The experience specific to operating offset machine control consoles.

Normality testing was performed using the Shapiro–Wilk test for all continuous eye-tracking variables. As shown in Table 5, all variables exhibited statistically significant deviations from normality ($p < 0.001$), with Shapiro–Wilk statistics substantially below 1 across all metrics. These results confirm that the underlying distributions of fixation measures, pupil-diameter values, saccadic movements, and blink-related metrics are non-normal. Pearson's correlation was applied descriptively to summarise linear associations among the continuous variables.

Table 5: Correlation between age and question "Do you consider that the simulator, as a troubleshooting basis, can guide someone adequately?"

Variable	Shapiro-Wilk Statistic	p-value
FPOGS	0.9301	2.23×10^{-43}
FPOGD	0.7671	1.67×10^{-64}
LPMM	0.6181	1.97×10^{-74}
RPMM	0.4242	3.14×10^{-83}
SACCADE_MAG	0.5922	8.35×10^{-76}
SACCADE_DIR	0.9529	2.18×10^{-37}
BKID	0.2108	2.49×10^{-90}
BKDUR	0.0046	9.59×10^{-96}

The data were analysed using the Pearson correlation method instead of the chi-square test. The Chi-Square test yielded a p-value of 0, indicating that the x^2 value was so immense that the probability of observing this result (assuming variable independence) was extremely low. Consequently, the independence hypothesis was rejected, confirming a statistically significant correlation among the four variables. However, since the chi-square test

does not specify the nature or direction of the correlation, the Pearson correlation coefficient was employed.
The following hypotheses guided the iris-tracking research:

Pupil size and fixations: Examines the correlation between pupil size and fixations during problem identification and solution search, focusing on visual attention and cognitive effort.

Saccadic movements and fixations: Investigates the relationship between saccadic movements and fixations to identify patterns of visual control and observation in the printing area.

Final fixation and pupil dilation: Tests whether the last fixation before entering the AOI is accompanied by pupil dilation, potentially serving as a human-computer interaction checkpoint.

Fixations, saccades, and overall experience: Explores how overall experience correlates with fixations and saccadic movements, hypothesising that experienced participants navigate consoles more efficiently.

Fixations, saccades, and console experience: Assesses whether prior experience with control consoles facilitates more straightforward navigation and menu recognition.

Age and blinks: Investigates whether simulator operation induces fatigue concerning age.

Table 6 represents the correlation between pupil size and fixation metrics during the problem identification phase. A moderate positive correlation of 0.599 between left and right pupil size indicates synchronized pupil dilation likely driven by shared cognitive or physiological processes. A weak positive correlation of 0.109 between left pupil size and fixation onset and 0.143 between right pupil size and fixation onset suggests that larger pupils may be linked to earlier fixations, potentially reflecting cognitive load. However, the relationship between pupil size and fixation duration is minimal, with weak negative correlations of -0.033 for left pupil size and -0.015 for right pupil size. Additionally, a weak negative correlation of -0.081 is observed between fixation onset and fixation duration, implying that earlier fixations tend to be slightly shorter. While pupil dilation may indicate cognitive engagement, it does not significantly impact fixation timing or duration.

Table 6: Correlation matrix of pupil size and fixation metrics during problem identification

Metric	LPMM	RPMM	FPOGS	FPOGD
LPMM	1			
RPMM	0.599	1		
FPOGS	0.109	0.143	1	
FPOGD	-0.033	-0.015	-0.081	1

Table 7 represents the correlation between pupil size and fixation metrics during the problem-solving phase, analyzing how changes in pupil dilation relate to eye movement patterns. A moderate positive correlation of 0.523 between left and right pupil size suggests synchronized pupil dilation, likely influenced by shared cognitive and physiological mechanisms. Compared to the problem identification phase, this correlation is slightly weaker, possibly reflecting differences in cognitive load.

Weak positive correlations of 0.062 and 0.089 between pupil size and fixation onset indicate minimal influence of pupil dilation on the timing of fixation initiation. Similarly, weak negative correlations of -0.054 and -0.067 between pupil size and fixation duration suggest that as pupil size increases, fixation duration may slightly decrease. A weak negative correlation of -0.098 between fixation onset and duration implies that earlier fixations tend to be shorter. While pupil dilation appears to reflect cognitive engagement, its impact on fixation behaviour during problem-solving remains limited.

Table 7: Correlation between pupil size and fixation metrics during problem-solving

Metric	LPMM	RPMM	FPOGS	FPOGD
LPMM	1			
RPMM	0.523	1		
FPOGS	0.062	0.089	1	
FPOGD	-0.054	-0.067	-0.098	1

Table 8 illustrates the connection between saccadic movement characteristics and fixation metrics. The findings show weak correlations between saccade magnitude and direction, with no significant effect of saccade size on direction. A slight positive correlation between saccade magnitude and fixation onset suggests that larger saccades may be linked to earlier fixation initiation.

However, saccade direction has little to no impact on fixation onset and duration. The study concludes that while saccadic magnitude has some weak associations with fixation metrics, saccade direction has minimal influence on fixation timing and duration. Overall, saccadic movements are related to attentional shifts but do not strongly affect fixation characteristics.

Table 8: Correlation between saccadic movement characteristics and fixation metrics

Metric	SACCADE_MAG	SACCADE_DIR	FPOGS	FPOGD
SACCADE_MAG	1			
SACCADE_DIR	-0.083	1		
FPOGS	0.078	-0.039	1	
FPOGD	-0.130	-0.028	-0.059	1

Table 9 represents the analysis of whether the last fixation before users enter the AOI is accompanied by pupil dilation. The correlation matrix for saccadic movements and fixation data reveals weak relationships between the variables. A moderate negative correlation of -0.130 is found between saccadic magnitude and fixation duration, suggesting that more significant saccadic movements are weakly associated with shorter fixations. The correlation between saccadic magnitude and fixation onset is weakly positive (0.078), indicating a slight influence on when fixations begin. However, the correlation between saccadic direction and fixation onset (-0.039) and fixation duration (-0.028) is weak, suggesting minimal impact. Overall, the findings highlight that saccadic movements subtly influence fixation characteristics, but other factors likely play a more significant role in determining fixation behaviour.

Table 9: Correlation of the last fixation before AOI entry and its association with iris dilation

Metric	SACCADE_MAG	SACCADE_DIR	FPOGS	FPOGD
SACCADE_MAG	1			
SACCADE_DIR	0.499	1		
FPOGS	0.006	0.023	1	
FPOGD	-0.042	-0.037	-0.080	1

Table 10: Correlation matrix of saccadic movement metrics, fixation data, and overall experience

Metric	SACCADE_MAG	SACCADE_DIR	FPOGS	FPOGD	SINOLIKIEMPEIRIA
SACCADE_MAG	1				
SACCADE_DIR	0.001	1			
FPOGS	-0.029	0	1		
FPOGD	-0.191	0.013	0.015	1	
SINOLIKIEMPEIRIA	0.180	0.013	-0.038	0.153	1

Table 10 presents the correlation matrix for saccadic movement metrics, fixation data, and overall experience (SINOLIKI EMPEIRIA). It shows a weak positive correlation between saccadic magnitude and overall experience (0.180), indicating that more experienced individuals may make slightly larger saccadic movements. The relationship between saccadic direction and other variables is minimal, with no meaningful correlation to fixation onset or saccadic magnitude. There is a weak negative correlation between saccadic magnitude and fixation duration (-0.191), suggesting larger saccades are weakly linked to shorter fixations. A weak negative correlation between overall experience and fixation duration (-0.153) implies that more experienced individuals may have slightly shorter fixations. Overall, the correlations are generally weak, indicating that other factors likely influence fixation behaviours more significantly.

Table 11 presents the correlation matrix for various metrics related to saccadic movements, fixation data, and platform experience. The metrics include saccadic magnitude (SACCADE_MAG), saccadic direction (SACCADE_DIR), fixation onset (FPOGS), fixation duration (FPOGD), and platform experience (EMPEIRIA PLATFORMA). The results show that saccadic magnitude has a weak positive correlation of 0.133 with platform experience. This suggests that individuals with greater platform experience may exhibit slightly larger saccadic movements, although the effect is minimal. The correlation between saccadic magnitude and fixation duration is negative, -0.191, indicating that more significant saccadic movements are weakly associated with shorter fixation durations. The correlations between saccadic direction and all other metrics, including fixation onset and duration, are negligible, with values close to zero, suggesting that the direction of saccadic movements has little impact on these fixation behaviours. The correlation between fixation onset and fixation duration is also very weak, 0.015, indicating that these two aspects of eye movements are mainly independent. Overall, the table highlights that while there are some minor associations between the metrics, the overall relationships are weak, indicating that other factors may play a more significant role in influencing these behaviours.

Table 11: Correlation matrix of saccadic movements, fixation data, and platform experience

Metric	SAC-CADE_MAG	SAC-CADE_DIR	FPOGS	FPOGD	EM-PEI-RIA PLAT-FOR-MA
SAC-CADE_MAG	1				
SAC-CADE_DIR	0.001	1			
FPOGS	-0.029	0	1		
FPOGD	-0.191	-0.004	0.015	1	
EM-PEIRIA PLAT-FORMA	0.133	0.004	0.001	-0.114	1

Table 12 represents the relationship between age and blink-related metrics, specifically blink frequency and blink duration. The findings reveal a weak negative correlation of -0.066 between age and blink frequency, suggesting that older individuals tend to blink slightly less often, though the effect is minimal. Conversely, a weak positive correlation of 0.020 between age and blink duration indicates that older participants may have slightly longer blinks, but this relationship is also negligible. The correlation between blink frequency and duration is nearly zero at -0.004, showing no meaningful connection between the two. Overall, the results suggest that age has a minor influence on blinking behaviour, with other factors such as cognitive load, fatigue, or environmental conditions likely playing a more significant role.

Table12: Correlation matrix of age and blink-related metrics

Metric	AGE	BKID	BK-DUR
AGE	1		
BKID	-0.06596539437	1	
BKDUR	0.01956453927	-0.004002350334	1

4. Evaluation

The analysis of eye-tracking data during problem identification and problem-solving phases revealed different patterns of pupil size and fixation duration among users. During problem identification, a positive correlation between pupil size and fixation duration suggested that larger pupils, indicative of higher cognitive load, were associated with longer fixations, reflecting a thorough inspection strategy. Conversely, a negative correlation indicated that larger pupils were linked to shorter fixations, implying a rapid scanning strategy.

In the problem-solving phase, a positive correlation between pupil size and fixation duration indicated ongoing cognitive effort and detailed focus, with participants engaging in prolonged analysis to address issues. Conversely, a negative correlation suggested that larger pupils were associated with shorter fixations, reflecting a more efficient problem-solving approach. Experienced operators, in particular, processed information quickly and made swift decisions, resulting in brief but intense fixations.

In our study, we explored the relationship between overall experience and eye movements. Experienced operators tended to make larger saccadic movements, enabling efficient information gathering. The positive correlation between saccade direction and experience indicated that seasoned operators had more strategic eye movements, focusing on critical areas. The negative correlation between the number of fixations and overall experience suggested that experienced operators required fewer fixations to gather information, demonstrating efficient visual processing. Additionally, experienced operators typically had shorter fixation durations, indicating quick extraction of relevant information.

We observed a weak positive correlation between age and the duration of involuntary blinks, with older participants generally exhibiting longer blink durations. This finding contrasts with existing literature, which reports shorter blink durations with age. The discrepancy may be attributed to increased cognitive load or fatigue experienced by older participants, affecting their visual processing efficiency and blink duration. Additionally, changes in motor control and reflexes due to ageing might influence blink duration and stability, potentially resulting in less precise motor control.

5. Conclusions

The responses revealed several noteworthy trends that could inspire future research with a larger participant pool to validate and strengthen the findings through additional correlations. A key finding was the collective agreement that the simulator is an effective tool for helping new employees grasp the fundamentals of offset printing. Both novice and experienced participants supported incorporating digital training as a preliminary step, allowing trainees to familiarise themselves with machine operations through simulation. Notably, many participants suggested using Virtual Reality (VR) and simulators with iris-tracking technology to replicate manual tasks, enabling trainees to perform operations using hand controllers in a simulated environment.

These insights highlight the potential for integrating advanced digital tools into offset machine operator training, reducing risks such as accidents, material waste, and unproductive downtime. The majority also agreed that simulators could be effective troubleshooting guides, emphasising the need for a digital database of problem-solving scenarios. This would benefit both experienced operators, who could tackle complex tasks in a simulated setting, and new employees, who could quickly gain exposure to a wide range of issues without waiting for real-world problems to arise.

Additionally, participants expressed a positive attitude toward having the machine verify job specifications instead of relying on traditional physical production folders. This reflects a broader trend toward digital transformation, with active participation from younger, tech-savvy employees and experienced operators who recognise the efficiency gains from automation and machine interconnectivity. This marks a significant shift from 5-10 years ago when industry workers were more resistant to digital tools and information management. Today, experienced operators consider checking job specifications a routine part of their workflow, advocating for widespread adoption. Despite these advancements, the nature of producing a "living" product like paper, which does not always conform to strict specifications, necessitates continued reliance on physical quality checks. Participants emphasised the importance of verifying printed products against prior samples or proofs, demonstrating enduring trust in product-based quality control over purely digital information.

Our study, leveraging the Sinapse print simulator and eye-tracking technology, provided valuable insights into HMI within offset printing. Our findings indicate that experienced operators demonstrated superior accuracy in detecting print shifts and adjusting job specifications compared to novice operators. This highlights the significant role of hands-on experience and familiarity with printing machines in achieving high operational efficiency. The eye-tracking system effectively captured detailed data on eye movements, offering deep insights into how operators engaged with the simulator interface. The observed patterns in gaze behaviour, such as fixation duration and saccadic movements, are crucial for designing more intuitive and user-friendly interfaces.

The realism offered by the Sinapse print simulator, which closely replicates Heidelberg's control console, proved highly beneficial for training and assessment. Its ability to mimic real-world scenarios accurately allowed for a meaningful evaluation of operator skills and identifying areas that require improvement. The challenges operators encounter during tasks, such as detecting subtle print shifts and navigating the software interface, underscore the ongoing need for simulator design and user interface improvements. Participant feedback emphasised the importance of refining these tools to enhance their effectiveness for training and overall usability.

Furthermore, the integration of eye-tracking technology was central to this study, providing critical insights into operator visual behaviour during simulator-based tasks. Metrics such as fixation duration, saccadic movements, and pupil dilation were systematically analysed to assess cognitive load, decision-making strategies, and interface usability. These findings underscore the value of eye-tracking as a diagnostic and design tool, reinforcing its essential role in enhancing HMI within the offset printing context.

Despite differences in platforms and usage environments, the challenges in UX design for mobile applications and HMI for offset printing share common objectives: ensuring smooth, intuitive, and efficient interaction. While mobile applications face constraints such as limited screen size and the need for features that support user mobility (Vonitsanos et al., 2022), HMI systems in printing demand precision and effective management of complex interfaces. Techniques such as eye tracking and simulations provide the capability to monitor users' visual focus and behaviour, enabling the identification of critical improvement areas and the implementation of targeted adjustments that enhance the user experience in both mobile applications and printing HMI systems.

Our research underscores the necessity of targeted training programmes that cater to the specific needs of both novice and experienced operators. Providing comprehensive training and support resources is essential to bridging performance gaps and enhancing overall efficiency in offset printing operations. Overall, our study highlights the critical role of HMI in optimising offset printing processes and underscores the potential for simulation technology to advance training and operational efficiency significantly in the graphic arts industry.

6. Future research

This study highlights several promising directions for future research to enhance HMI and operational efficiency in the printing and packaging industry. Expanding the research to more extensive and diverse participant pools—considering different geographic regions, experience levels, and printing environments—could validate the current findings and uncover new trends.

Future research should also explore advanced eye-tracking metrics, such as pupil dilation and gaze patterns, to assess cognitive load and engagement during tasks. Incorporating AR for real-time information overlays and AI for adaptive learning and predictive maintenance could further refine operator training and machine performance. Longitudinal studies tracking the adoption of digital tools over time could provide valuable insights into workforce adaptation and long-term benefits.

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Appendix A: Follow-up Interview Questions:

Question 1: Do you think that the use of the simulator makes it easier for a new employee to understand the basic principles of the method? Optional justification.

YES		NO	
COMMENTS:			

Question 2: Have you seen/worked in person on an offset printing machine? If so, is the illustration of operations indicative of the actual environment?

YES		NO	

Question 3: Do you feel that the simulator, as a troubleshooting basis, can guide someone competently?

YES		NO	

Question 4: How could the manual maintenance tasks required be assigned to the simulator?

COMMENTS:

Question 5: At the time of set-up, is it within your scope of duties to read the technical specification of the job? If you are not working, is it considered to be within your scope of duties?

YES		NO	

Question 6: Is it helpful to digitally upload the job to the machine (save specification and settings)? Optional justification.

YES		NO	
COMMENTS:			

Question 7: How easy was it for you to identify the printing problem without a physical print sample? (1 very difficult - 5 very easy).

1		2		3		4		5	

Question 8: If you were/are working in a real printing environment, the working method you would use would be to first identify differences between printed sheet and sample or check if any differences are due to the machine settings after the job has been uploaded (e.g. measures, inking, etc.)?

Checking Samples:		Checking settings on the press:	

Question 9: Where would you check the specifications of the work? Hard copy production folder or from the press?

Hard Copy Production folder:		Press:	

Appendix B: AOIs Used in the study

AOI 1: Specification panel

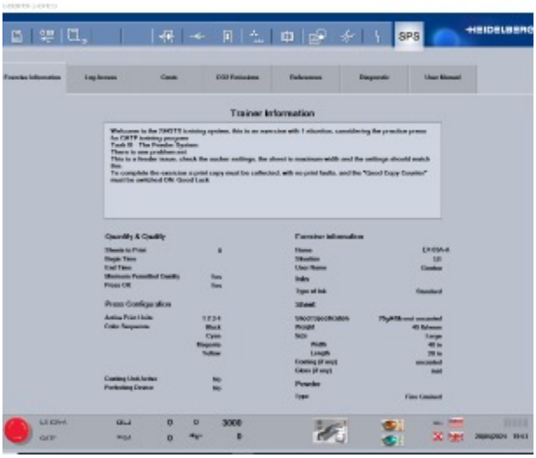

Figure 6: AOI 1 for Specifications Panel

This particular screen is the one participants must identify, as it contains the job specifications they are expected to locate and prepare for the print task. The information displayed on this screen is critical for the correct printing press setup. If the job details are incomplete or the screen is not easily accessible to operators, there is a significant risk of incorrect machine preparation, leading to production errors.
It is common for experienced operators to rely on their personal expertise, printed samples, or reference standards when preparing the machine, often overlooking the digital information available through the job entries loaded into the system.

AOI 2: Detection of an intentional shift of two (2) millimetres of all four colours of the subject to be printed.

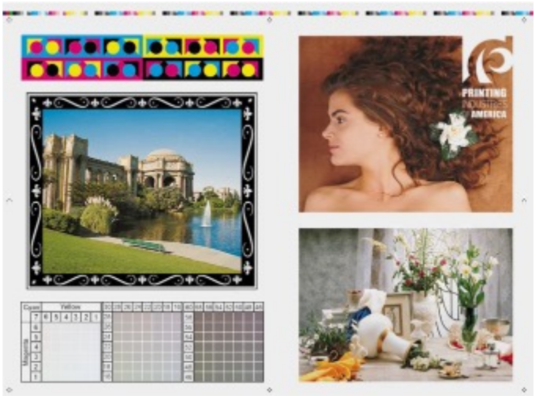

Fig. 7: Detection of an intentional shift of two (2) millimetres of all four subject colours to be printed.

The second area of interest involved the detection of an intentional two-millimeter misregistration of all four process colours in the printed subject. Operators were required to examine the printed output and compare it with the corresponding digital proof, to identify the colour misalignment.

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