Applied Computer Science 2026, vol. 22, no. 1, pp. 99–109
https://doi.org/10.35784/acs_7953

Submitted: 2025-06-19 | Revised: 2025-07-28 | Accepted: 2025-08-11

Keywords: offset printing, quality control, fuzzy logic, Industrial Internet of Things, IIoT

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Models for calculating the integral quality indicator of the offset printing process for the IIOT-system

Abstract

The paper is devoted to the problem of comprehensive quality assessment in offset printing. On the basis of the research conducted, the quality indicators of sheet-fed offset printing with dampening are determined, namely, the print color difference, the fine line width, the color combination accuracy, the "gray balance" and the dot gain. These indicators were divided into two groups: the first group reflects the color reproduction, while the second concerns the reproduction of fine image elements. Based on the principles of fuzzy logic, the evaluation terms "low", "medium", "high" are assigned to the print quality, and a fuzzy knowledge base of the print quality parameters with the fulfillment of the "if-then" condition is formed. Fuzzy logic equations for the calculation of print quality options are constructed, and the defuzzification operation carried out using the "center of gravity" method allows to obtain a quantitative print quality indicator as a result of observing the corresponding modes of the offset printing technological process. The values of the indicators of the parameters of the offset printing quality obtained according to the results of the control and the calculation of the integral indicator serve as data for the reporting of the process in the Industrial Internet of Things system.

1. INTRODUCTION

Dataintelo's analytical analysis shows that the global offset printing market size was valued at US$ 2.72 billion in 2023 and is projected to reach US$ 9.23 billion by 2032, growing at a compound annual growth rate of 13.6% during 2024-2032 (Data Intelo, 2024). The growth trend is confirmed by the report, according to which the global market for offset printing presses continues to grow and amounted to US$ 2.8 billion in 2024 and is projected to grow to US$ 4.01 billion by 2033, demonstrating a CAGR of 3.32% during the period 2025-2033 (Business Research Insights, 2025).

The market growth can be attributed to the introduction of cost-effective solutions for the printing process. Offset printing technology is a cost-effective solution for high-volume printing. The unit cost decreases as the quantity increases, making it a better choice for companies that need to print large quantities. In addition, offset printing technology allows for easy technological adjustments according to the specifics of the job, enabling companies to meet specific requirements and customer demands. It is the use of Industrial IoT systems and artificial intelligence that provides a significant impetus to the development of offset printing. Industrial IoT includes smart sensors in equipment, tools, software platforms, cloud servers, and applications. Smart sensors provide control at every stage of production. These devices continuously send data to an IoT gateway (a communicator between IoT devices and the cloud), which receives the data and sends it to a cloud server for processing and analysis. The software that processes the received data is accessible through smartphone applications, making it easy to access from anywhere in the world.

Such integration has transformed the offset printing market by automating various processes, including prepress, color management and print quality control, thereby increasing efficiency and productivity. In turn, the introduction of digital technologies makes it possible to predict machine malfunctions, facilitate preventive maintenance and reduce downtime, and help optimize ink consumption, thereby reducing waste and contributing to environmental friendliness.

2. LITERATURE REVIEW

Print providers are working hard to optimize and control the quality of technological processes using the latest digital technologies (Urban & Lukaszewicz, 2021). Heidelberg AG offers the Heidelberg Cloud, which provides fast, efficient and comprehensive support for machine operation, increased productivity and, of course, troubleshooting (Heidelberg, 2024). Heidelberg Predictive Monitoring ensures maximum machine availability using a state-of-the-art big data analysis platform with cloud service technology. The goal is to prevent unplanned downtime through continuous monitoring and analysis. Monitoring minimizes unplanned interventions and ensures maximum machine availability: unplanned downtime is reduced by up to 20 percent. Printing press manufacturer Koenig & Bauer GmbH offers its customers Kyana Connect - a secure Industrial Internet of Things (IIoT) gateway between printing presses and the Koenig & Bauer cloud (2025). The service ensures secure processing and transmission of data from press sensors and production orders to the cloud for subsequent analysis. Komori Corporation's KP-Connect Basic service, which enables the company and the printer to receive and share detailed information about press operation, making printing process operations visible in a secure cloud environment. The service enables the creation and delivery of process graphics and the collection of production results based on integrated management for both offset presses and digital printing systems. BOBST Company offers a comprehensive digital platform, BOBST Connect, that enhances and increases the productivity of packaging production. It is designed to make the most of the data generated by the press and increase production efficiency throughout the product value chain. In addition to data analysis, BOBST Connect helps organize and improve the production process, from the receipt of a PDF file to the finished product and its quality report. Global Graphics Software's products and services explore how industrial printing can be improved through Industry 4.0 connectivity. Industry 4.0 emphasizes the integration of digital technologies such as artificial intelligence (AI), robotics, cloud computing, and the Internet of Things (IoT) into traditional manufacturing and industrial practices (Worrall, 2024). For print OEMs, the company offers digital front ends, core SDKs, and enabling technologies that meet the most demanding requirements across a wide range of print applications - including commercial printing, labels and packaging, and industrial inkjet (Hybrid Software HELIX, 2025).

For offset printing technology, there are a number of regulatory documents (International Organization for Standardization, 2013; 2017; International Organization for Standardization, 2022) that allow the use of a number of assessment indicators in accordance with the regulated values. These are, first of all, the optical density of the print, the color difference ΔE, the values of "trapping", contrast, dot gain and fine line width, the accuracy of the color combination, and the "gray" balance. Five main indicators are selected as criteria of image quality obtained as a result of sheet-fed offset printing of control scales:

- The color difference (ΔE). According to the European standard, the value of color difference ΔE should not exceed 3 (International Organization for Standardization, 2013). If this value increases, the eye will see the color difference and the work performed will be of poor quality. Timely monitoring of the color difference indicator ΔE allows to quickly adjust the parameters of the printing technological modes, for example, the ink supply.
- Gray balance. The criterion is the optical density of 80% of the scale area measured using three color filters. The quality of color balance is checked by the elements of the control scale printed with cyan, magenta and yellow inks (usually 75C-64M-64Y - 75 % B, 50C-40M-40Y - 50 % B, 25C-19M-19Y - 25 % B). This area should have a neutral gray color that is visually similar to the 75 %, 50 %, 25 % area printed with black ink. If the color of the control area differs from gray, it indicates an unbalanced ink supply or a deviation from the standard dot gain indicators.
- The dot gain of the halftone elements. One of the important quality indicators is the quality of the transmitted halftones. The dot gain values of 40 and 80 % of the scale areas are selected as parameters;
- Fine line width. The ability to reproduce small details - separately placed strokes, as well as accurately transmit the image of strokes of different sizes: 5; 10; 20; 30; 40; 50; 60 microns. Depending on the printing method, the type of paper and the condition of the printing press, all or only part of the control marks will be reproduced on the imprint. The permissible value is up to 40 microns;
- Accuracy of ink combinations. The maximum permissible deviation between the centers of the cross marks of any two colors should not exceed 0.08 mm - for medium-format printing presses with paper weights greater than 65g/m2 (International Organization for Standardization, 2013).

When quantitatively assessing the quality of a technological process, it is possible to determine both a single quality indicator and a complex indicator characterized by several parameters. The most complete is considered to be the generalized assessment of process quality, which combines the advantages of integral assessment with a thorough analysis of individual process quality indicators.

One of the possible directions of forming an integral indicator is the use of fuzzy logic. The advantage of this approach is the possibility of processing the obtained data both in quantitative form and from the point of view of human reasoning, i.e. assessment from the point of view of acquired practical knowledge. According to the analysis of publications in this direction, results are obtained in the formation of a complex quality indicator of flexographic prints (Repeta & Kukura, 2016). The article (Durnyaket al., 2019) presents a methodology for assessing and predicting the quality of tactile products, especially those designed for visually impaired people. The authors develop a fuzzy logic-based simulation model that translates expert knowledge into a formalized fuzzy knowledge base. The fuzzy inference system processes variables through "if/then" rules, enabling the prediction of the overall quality of tactile products. In the work (Durnyaket al., 2024), the authors proposed a solution to the problem of formation and predictive quality assessment of the design of post-printing processes using the theory of fuzzy control, which is based on sets of linguistic variables and corresponding term sets of values. The paper (Repeta et al., 2024) is devoted to establishing the efficiency of the process of cleaning anilox rollers in a flexographic printing press unit, where the separation of factors is carried out according to the Pareto principle and the process efficiency is established for rollers with different lineatures and with the setting of different degrees of ink viscosity anomaly. The article (Matuszek & Lukaszewicz, 2019) presents an approach to assess the manufacturability of a design using fuzzy logic, taking into account processing requirements, assembly procedures and production organization.

The goal of this work is to develop a comprehensive apparatus for calculating the integral quality indicator (IQI), which is the result of strict compliance with the requirements of the offset printing process modes.

3. METHODS

Fuzzy logic is known for the fact that the interpretation of the influence of a certain parameter or factor uses the concept of linguistic variable and logical rules that reproduce the principles of human reasoning. The founder of the principle of fuzzy logic is Lotfi Zadeh, and the principles themselves were implemented in his works. Lotfi Zadeh (1975) laid the foundations of the direction of fuzzy logic and introduced the concept of some universal set for a certain problem area.

The fuzzy logic method includes the following sequence of operations:

- For defining a universal term-set of values and corresponding linguistic terms for describing linguistic variables. The term set represents real numbers whose limits characterize the influence of a particular linguistic variable;
- Obtaining membership functions for the studied linguistic variables;
- Developing a knowledge base using the "if-then" rule;
- Construct and solve fuzzy logic equations;
- Defuzzifying a fuzzy set, for example, according to the center of gravity (CoG) principle (Yager & Zadeh, 2012; Ross, 2010).

The defuzzification operation according to the principle of the "center of gravity" for the determination of the integral quality indicator of the offset printing process quality is carried out according to the formula (Yager & Zadeh, 2012; Saatchi, 2024):

$$P = \frac{\sum_{i=1}^{m} u_i \cdot \mu(u_i)}{\sum_{i=1}^{m} \mu(u_i)} \tag{1}$$

where: P – the final crisp value after defuzzification;
u – output variable;
$\mu(u_i)$ – degree of membership (between 0 and 1) of the value u_i.

Fuzzy logic is particularly well-suited for calculating the integral quality indicator of the printing process because it effectively handles uncertainty and subjectivity. It allows expert knowledge to be embedded through intuitive if/then rules, enabling transparent and interpretable decision making. Unlike data-driven approaches, fuzzy systems do not rely on large data sets, making them ideal for industrial environments with limited or inconsistent data. In addition, fuzzy logic facilitates the aggregation of multiple quality parameters - often expressed in different units and scales - into a single, coherent output.

To obtain the integral quality indicator of the process, the harmonic mean method was applied:

$$Q = \frac{n}{\sum_{i=1}^{n} \frac{1}{x_i}} \tag{2}$$

where: Q – the harmonic mean value as the integral quality indicator in our case;
x_i – every one of the n values;
n – the number of values.

The harmonic mean is an aggregation technique that emphasizes the balance between multiple input values. It is particularly sensitive to small values, meaning that even a single small input can significantly lower the overall result. This characteristic makes it particularly suitable for quality control applications where all contributing factors must perform adequately to ensure high overall quality.

4. CONSTRUCTION OF LOGICAL AND BASIC MODELS FOR QUALITY CONTROL IN OFFSET PRINTING

On the basis of the analysis, the quality indicators of offset printing are identified and grouped, i.e. the indicators that determine the accuracy of color reproduction and the indicators that determine the ability to reproduce small elements of the printed image. Accordingly, the quality of offset printing is defined as

$$Q = f(X, Y) \tag{3}$$

where: Q – is the quality of the offset printing process;
X – are indicators responsible for the color reproduction quality;
Y – are indicators responsible for the small element reproduction quality.

$$X = f(x_1, x_2, x_{3(40)}, x_{3(80)}) \tag{4}$$

x_1 – is the indicator of the color difference on imprint;
x_2 – is the indicator of the «gray balance»;
$x_{3(40)}$ – is the indicator of the dot gain at 40 % of the scale area;
$x_{3(80)}$ – is the indicator of the dot gain at 80 % of the scale area.

$$Y = f(y_1, y_2) \tag{5}$$

y_1 – is the indicator of the ink combination accuracy;
y_2 – is the indicator of the fine line width.

In accordance with the results of expert assessments and experimental studies, a scheme of logical formation of an integral evaluation of the quality of offset printing is formed (Fig. 1).

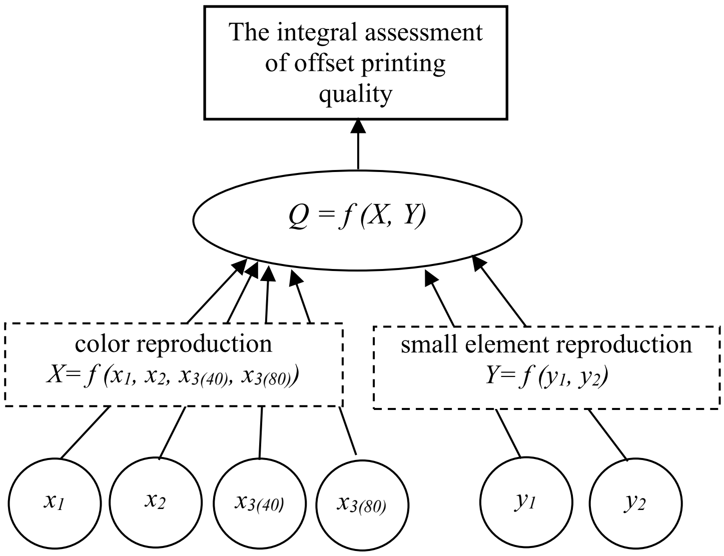

Fig. 1. The model of logical formation of an integral assessment of offset printing quality

Accordingly, Figure 2 presents an IIoT model for the offset pressroom.

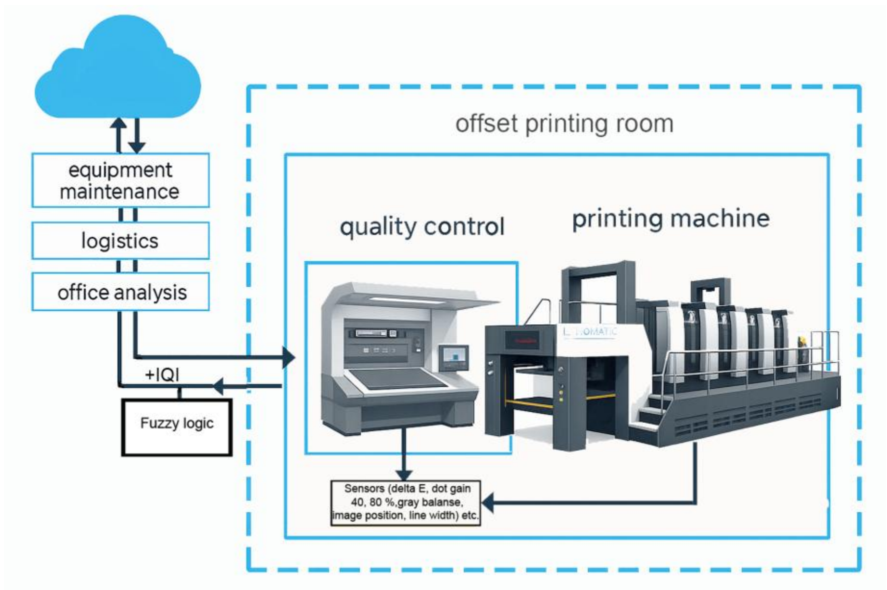

Fig. 2. IIoT model for the offset printing room

The IIoT model presented illustrates an intelligent offset printing system that uses fuzzy logic, cloud computing, and real-time sensor data to maintain high-quality print output and streamline operations. Sensors collect real-time data from both the press and the quality control system. These sensors monitor key parameters such as colour difference (ΔE), dot gain at 40% and 80% of scale, image positioning and fine line width. Data from the sensors is sent to a fuzzy logic module. This module interprets complex, imprecise data (such as varying print quality) and makes decisions based on a set of fuzzy rules. Based on this, the system can suggest or automatically implement adjustments to the printing process. In parallel, data related to the organization of the technological process is also processed. The cloud services handle: equipment maintenance - prediction and scheduling of maintenance needs; optimization of material supply and inventory based on real-time production data; office analytics - generation of reports and analyses for management and process improvement. The fuzzy logic output and operational data are sent to the cloud for higher-level processing and decision making. Adjustments based on quality control feedback are sent back to the press in real time, ensuring continuous improvement and process stability.

This model embodies the principles of Industry 4.0 by integrating sensor networks, intelligent control (fuzzy logic), and cloud-based analytics to ultimately improve print quality, reduce downtime, and optimize resource utilization.

5. RESULTS

The linguistic variables that ensure the quality of offset printing and the terms of their evaluation are presented as a system of qualitative concepts and are listed in Table 1.

Tab. 1. Linguistic variables that ensure the quality of offset printing method

Variable	Name of a linguistic variable	Universal set	Linguistic term
x1	color differences	0-5 c. u.	insignificant, average, large
x2	gray balance	72-80 %	small, average, large
x3(40)	dot gain at 40 % of the scale area	1-25 %	low, average, large
x3(80)	dot gain at 80 % of the scale area	1-25 %	low, average, large
y1	image positioning	0-0,12 mm	high, average, low
y2	fine line width	5-40 µm	low, average, high

Let's form the fuzzy sets of membership functions for the variable “color difference”. According to the requirements and data of Table 1, the level of color difference is determined by the universal set: u_1= 1 un.; u_2= 2 un.; u_3 = 3 un. ; u_4= 4 un.; u_5= 5 un. A set of fuzzy terms $U(x_1)$ = <insignificant*, average, large*> is used for linguistic evaluation of the factor.

The values of the variable in the form of fuzzy sets are as follows:

$$large=\left(\frac{1}{1};\frac{0,89}{2};\frac{0,78}{3};\frac{0,22}{4};\frac{0,11}{5}\right),\ \text{un};$$

$$average=\left(\frac{0,11}{1};\frac{0,78}{2};\frac{1}{3};\frac{0,78}{4};\frac{0,11}{5}\right),\text{un};$$

$$insignificant=\left(\frac{1}{1};\frac{0,22}{2};\frac{0,78}{3};\frac{0,89}{4};\frac{1}{5}\right),\text{un.}$$

The following linguistic variables are described using fuzzy sets and their respective membership functions. Thus, the linguistic variable x_2 “gray balance” on the universal set $U(x_2)$ = [72; 74; 76; 78; 80] % is identified with the following values of fuzzy sets:

$$small=\left(\frac{1}{72};\frac{0,88}{74};\frac{0,55}{76};\frac{0,33}{78};\frac{0,11}{80}\right),\%;$$

$$average=\left(\frac{0,11}{72};\frac{0,55}{74};\frac{1}{76};\frac{0,55}{78};\frac{0,11}{80}\right),\%;$$

$$large=\left(\frac{0,11}{72};\frac{0,33}{74};\frac{0,55}{76};\frac{0,88}{78};\frac{1}{80}\right),\%.$$

For the linguistic variables $x3_{(40)}$, $x\ 3_{(80)}$ “dot gain at 40 and 80 % of the scale range” on the universal set $U(x_{3(40)})$ and $U(x_{3(80)})$ = [1; 6; 12; 18; 25] % , the following fuzzy set is formed:

$$low=\left(\frac{1}{1};\frac{0,75}{6};\frac{0,5}{12};\frac{0,25}{18};\frac{0,125}{25}\right),\%;$$

$$average = \left(\frac{0,125}{1};\frac{0,5}{6};\frac{1}{12};\frac{0,5}{18};\frac{0,125}{25}\right), \%;$$

$$large = \left(\frac{0,125}{1};\frac{0,25}{6};\frac{0,5}{12};\frac{0,75}{18};\frac{1}{25}\right), \%.$$

For the linguistic variable y_1 “image positioning” on the universal set $U(y_1)$ = [0; 0.4; 0.6; 0.8; 0.12] mm is identified with the following values of fuzzy sets:

$$high = \left(\frac{1}{0};\frac{0,89}{0,4};\frac{0,78}{0,6};\frac{0,22}{0,8};\frac{0,11}{0,12}\right), \text{mm};$$

$$average = \left(\frac{1}{0};\frac{0,78}{0,4};\frac{1}{0,6};\frac{0,78}{0,8};\frac{0,11}{0,12}\right), \text{mm};$$

$$low = \left(\frac{0,11}{0};\frac{0,22}{0,4};\frac{0,78}{0,6};\frac{0,89}{0,8};\frac{1}{0,12}\right), \text{mm}.$$

Let us form fuzzy sets from the membership functions of the following linguistic variables. Thus, the linguistic variable y_2 “fine line width” on the universal set $U(y_2)$ = [5; 10; 20; 30; 40] µm is identified with the following values of fuzzy sets:

$$high = \left(\frac{1}{5};\frac{0,88}{10};\frac{0,55}{20};\frac{0,33}{30};\frac{0,11}{40}\right), \mu\text{m};$$

$$average = \left(\frac{0,11}{5};\frac{0,55}{10};\frac{1}{15};\frac{0,55}{20};\frac{0,11}{40}\right), \mu\text{m};$$

$$low = \left(\frac{0,11}{5};\frac{0,33}{10};\frac{0,55}{15};\frac{0,88}{20};\frac{1}{40}\right), \mu\text{m}.$$

We form the fuzzy knowledge base on the color reproduction quality (Table 2).

Tab. 2. Knowledge matrix for addiction (4)

IF				THEN
Color differences	**Gray balance**	**Dot gain (40%)**	**Dot gain (80%)**	**Quality x**
large	small	average	large	low
large	average	large	large	
average	average	average	average	medium
insignificant	average	low	average	
insignificant	large	low	low	high
average	average	low	low	

Let's form logical equations that reflect the knowledge base about the fulfillment of the “if-then” condition for color reproduction quality:

$$\mu low = \mu lar(x1) \wedge \mu sl(x2) \wedge \mu av(x3(40)) \wedge \mu lar(x3(80)) \vee$$
$$\mu lar(x1) \wedge \mu av(x2) \wedge \mu lar(x3(40)) \wedge \mu lar(x3(80));$$

$$\mu med = \mu av(x1) \wedge \mu av(x2) \wedge \mu av(x3(40)) \wedge \mu av(x3(80)) \vee$$
$$\mu ins(x1) \wedge \mu av(x2) \wedge \mu low(x3(40)) \wedge \mu av(x3(80)); \quad (6)$$

$$\mu high = \mu ins(x1) \wedge \mu lar(x2) \wedge \mu low(x3(40)) \wedge \mu lar(x3(80)) \vee$$
$$\mu av(x1) \wedge \mu av(x2) \wedge \mu low(x3(40)) \wedge \mu low(x3(80)).$$

The abbreviation $\wedge$ and $\vee$ are the operations for determining the minimum and maximum in logic equations.

Substituting degrees of membership into a system of fuzzy logic equations provides one of the options for calculating color reproduction quality:

$$\mu low = 0{,}22 \wedge 0{,}88 \wedge 0{,}5 \wedge 0{,}75 \vee 0{,}22 \wedge 0{,}55 \wedge 0{,}75 \wedge 0{,}75 = 0{,}22$$

$$\mu med = 0{,}78 \wedge 0{,}75 \wedge 0{,}5 \wedge 0{,}5 \vee 0{,}89 \wedge 0{,}75 \wedge 0{,}75 \wedge 0{,}5 = 0{,}5$$

$$\mu high = 0{,}89 \wedge 0{,}88 \wedge 0{,}75 \wedge 0{,}75 \vee 0{,}78 \wedge 0{,}55 \wedge 0{,}75 \wedge 0{,}75 = 0{,}75$$

We form the fuzzy knowledge base on the small element reproduction quality (Table 3).

Tab. 3. Knowledge matrix for addiction (5)

IF		**THEN**
Image positioning	**Fine line width**	**Quality Y**
low	low	low
average	low	
average	average	medium
high	low	
high	high	high
high	average	

Let's form logical equations that are a reflection of the knowledge base on the fulfilment of the “If-Then” condition for small element reproduction quality:

$$\mu low = \mu low\ (y1) \wedge \mu low\ (y2) \vee \mu av\ (y1) \wedge \mu low\ (y2);$$

$$\mu med = \mu av\ (y1) \wedge \mu av\ (y2) \vee \mu high\ (y1) \wedge \mu low\ (y2); \qquad (7)$$

$$\mu high = \mu high\ (y1) \wedge \mu high\ (y2) \vee \mu high\ (y1) \wedge \mu lav\ (y2).$$

$$\mu low = 0{,}22 \wedge 0{,}33 \vee 0{,}78 \wedge 0{,}78 = 0{,}33$$

$$\mu med = 0{,}78 \wedge 0{,}55 \vee 0{,}89 \wedge 0{,}33 = 0{,}55$$

$$\mu high = 0{,}89 \wedge 0{,}88 \vee 0{,}89 \wedge 0{,}55 = 0{,}55$$

To calculate according to formula (1), the conditional limits for the variable P are determined, i.e. 1-100 un. Accordingly, we obtain the following quality indicators for our two groups of factors:

$$X = \frac{1 \cdot 0{,}22 + 50 \cdot 0{,}5 + 100 \cdot 0{,}75}{0{,}22 + 0{,}5 + 0{,}75} = 68{,}18 un.$$

$$Y = \frac{1 \cdot 0{,}33 + 50 \cdot 0{,}55 + 100 \cdot 0{,}55}{0{,}33 + 0{,}55 + 0{,}55} = 57{,}9 un.$$

Let us calculate a special case of the integral quality indicator of the offset printing process:

$$Q = \frac{2 \cdot 68{,}18 \cdot 57{,}9}{68{,}18 + 57{,}9} = 173{,}7 un.$$

To verify the knowledge base and to synthesize a model of the influence of indicators, a system for developing fuzzy control systems - Fuzzy Logic Toolbox system of the Matlab technological computing environment and Mamdani principle is used (Izquierdo &Izquierdo, 2018). For the defuzzification stage, the "Center of Gravity" method was used, which allows precise transformation of fuzzy output values into crisp results (Rotshtein & Shtovba, 2002). Figure 3 illustrates the resulting fuzzy inference models, which capture the complex relationships between input factors that influence printing process quality.

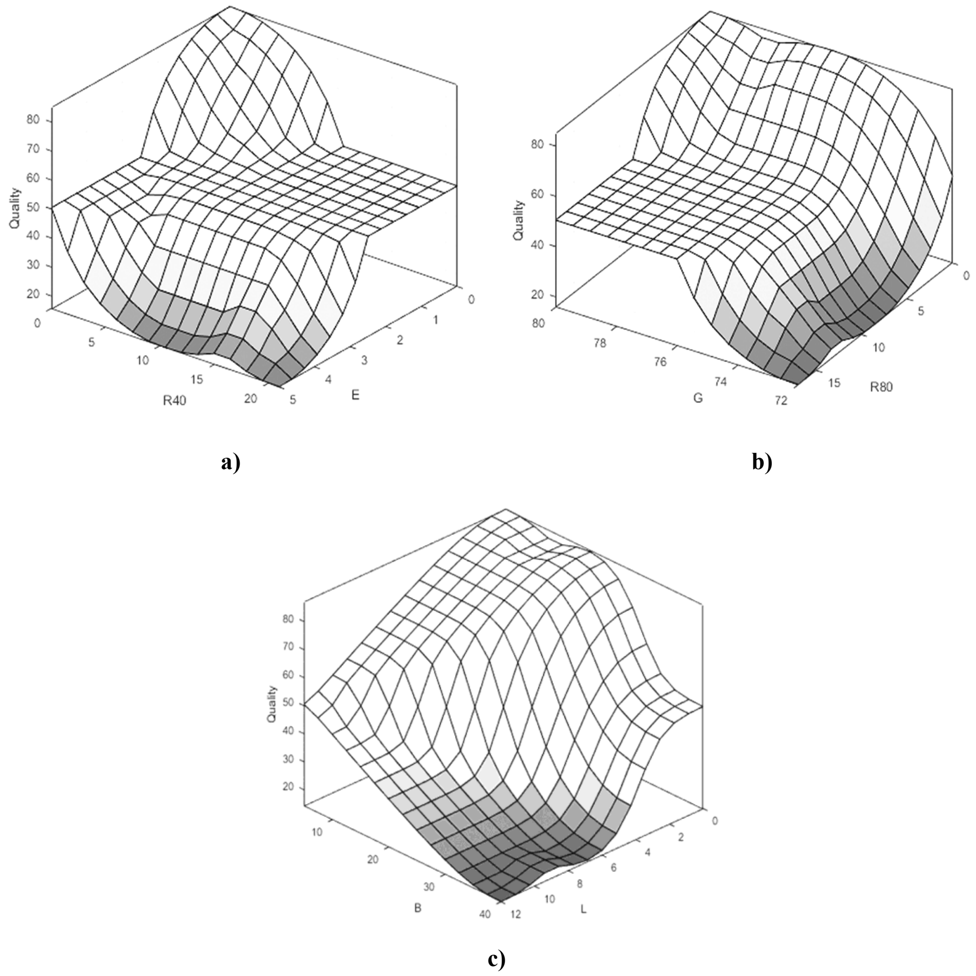

Fig. 3. Models of the factor influence on the printing quality: a) – color differences (E) and Dot gain (R $_{40\%}$); b) – gray balance G and dot gain (R $_{80\%}$); c) – image positioning (L) and fine line width (B)

Table 4 shows several calculation options for the integral quality indicator of the offset printing process.

Tab. 4. Calculating the integral quality indicator of the offset printing process

No	Color differences	Gray balance	Dot gain (40%)	Dot gain (80%)	Quality *X*	Image positioning	Fine line width	Quality *Y*	Integral quality indicator *Q*
1	1	72	1	10	50,4	0,06	22,5	50,5	151,5
2	3,4	74	1	10	57,3	0,007	22,5	82,4	247,2
3	3,5	75	12	11	39,5	0	7,1	85,1	255,3
4	2,6	77	16	15,5	41,9	0,12	40	15,8	47,4
5	1,8	79	1,7	4,3	62,5	0.09	30,6	43,6	130,8

The modeling results show the adequacy of the developed knowledge base and the possibility of its use for an integrated quality assessment of the offset printing process for the purpose of statistical analysis and data generation for the IIoT system.

6. DISCUSSIONS

The modeling results confirm the practical feasibility of applying fuzzy logic to the evaluation and control of offset printing quality. The use of linguistic variables such as color difference, gray balance, dot gain, image positioning, and fine line width allowed the transformation of expert knowledge into a formalized fuzzy knowledge base. These fuzzy rules, structured according to the "If-Then" rule, reflect real-world outcomes and subjective judgments that are difficult to express using conventional mathematical models. The fuzzy inference system demonstrates the ability to handle uncertainty in data obtained from sensors as well as subjective judgments. It ensures a smooth transition from vague or imprecise descriptors ("low", "medium", "high") to quantitative quality indicators, thus bridging technical parameters with human-centered evaluation. Table 4 shows how changes in factor values within the two groups of quality indicators affect the overall quality of the offset printing process.

The use of the harmonic mean method has the advantage of being sensitive to small values, which means that even a single small input can significantly reduce the overall result. This makes it particularly suitable for quality control applications where all contributing factors must function properly to ensure high overall quality. This result is clearly illustrated by point 4 in the calculations shown in Table 4, where a sharp decrease in the process quality indicator to 47.4 units is observed. Other calculations show a significantly higher integral quality indicator, in particular with $X = 39.5$ and $Y = 85.1$ units, the maximum value of 255.3 units was obtained.

The integration of the fuzzy inference module into an IIoT architecture highlights the synergy between intelligent control and cloud-based analytics. Real-time data collected from printing presses and quality control systems is efficiently processed to provide dynamic feedback and optimize production processes. The proposed model is particularly relevant for industrial environments characterized by variability in materials, conditions, or manual adjustments, where classical logic may not reflect the full complexity of the actual printing process.

7. CONCLUSIONS

Thus, the development of offset printing technology, as well as other printing technologies, is intensified by the introduction of information technologies, accordingly, it is necessary to apply scientific approaches to assess the quality of the printing process using numerical data, which are sometimes characterized by fuzziness and are based on practical experience. Based on the analysis of the technological process, the quality indicators were divided into two main groups.

The first group includes parameters that define the quality of color reproduction, while the second group includes indicators that characterize the ability to reproduce fine elements of the printed image. The first group includes linguistic variables such as color difference, gray balance and dot gain values at 40% and 80% of the control scale area. The second group includes color registration accuracy and fine line width. Accordingly, a graphical multi-level fuzzy inference model was developed to represent the hierarchical relationship of the integral quality indicator in the offset printing process. For each group, a set of linguistic variables with corresponding terms was defined. This approach allowed a quantitative assessment of quality using fuzzy logic. The analysis of offset prints, based on expert linguistic knowledge, enabled the formulation of fuzzy logic equations describing the influence of input variables on the overall print quality, thus providing a comprehensive evaluation of the technological process. The use of the harmonic mean method offers the advantage of increased sensitivity to low values, allowing the detection of cases where even a single weak parameter can significantly reduce the overall quality. This makes the method particularly suitable for scenarios where all contributing factors must perform at an adequate level. The results of the developed model and the constructed fuzzy knowledge base, using the "If-Then" rule, were validated through the Fuzzy Logic Toolbox software environment with "Center of Gravity" defuzzification. The calculations provided illustrate how the integral quality indicator varies in response to the values of the linguistic variables within the two categorized groups, allowing the operator to better understand the impact of individual factors on the quality of the offset printing process. The IIoT model itself demonstrates the principles of integrating sensor networks, intelligent control (including fuzzy logic), and cloud-based analytics to contribute to improved print quality, reduced downtime, and optimized resource utilization.

Conflicts of Interest

The authors declare no conflict of interest.

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