Analysis of Quality Indicators of Digital Images Obtained by Different Photo-recording Systems

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Abstract

In the publication, a comparative analysis of the quality indicators of photo images obtained by the photo registration systems of an SLR camera and a smartphone is caried out. The authors systematized the quality indicators of digital halftone images and built a cause-and-effect diagram of influencing factors on the specified indicators. Based on the built model of the importance of influencing factors, the priority of the impact on the quality of the digital photo image of the material support of the camera (photosensitive matrix and optics) is determined. Experimental studies conducted by the authors have shown that both types of photo-recording systems have their benefits and weaknesses. The smartphone camera provides great structural characteristics of the photo image, but only due to processing with more advanced software. It has been proven on the basis of objective experimental data that an SLR camera, thanks to the use of a large light-sensitive matrix and high-quality optics, guarantees to obtain a halftone image with a high-quality reproduction of color, brightness, memorable colors and perfect gray balance.

Based on the conducted experimental research and mathematical modelling, it was concluded that there are no proven advantages of any of the investigated photo-recording systems. Devices of both categories have found their niches in the market and continue to develop.

Keywords [1]

Digital photo, quality indicators, SLR camera, mathematical modelling, achromatic colors, color balance, noise, software, factors influencing the quality

1. Introduction

The modern digital photo equipment market is undergoing dynamic changes due to inconstant trends among consumers of products in this segment. Since the release of the first SLR camera in the late 1990s, both the photographic equipment itself and the priorities of its users have undergone transformations. Until recently, there were two classes of digital cameras on the market: SLRs with variable optics (so-called professional) and compact cameras with built-in optics. Today, the latter have practically disappeared from the market, and single-lens reflex cameras (DSLR cameras) have to compete with mirrorless system models and smartphone cameras, which are constantly improving. In 2021, two of the largest manufacturers of cameras, Nikon and Canon, announced the cessation of the production of DSLR camera models and the further development of this technology. The reason for

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such decisions was a significant reduction in 2021 of this segment of cameras on the market both quantitatively (by more than 50%) and in monetary terms (by 31%) [2].

At the same time, cameras in smartphones are also improving. Computational photography in combination with lidar technology makes it possible to form images not only on the basis of optical information but also to calculate various characteristics of the photographed object for the subsequent improvement of data transmission about it. The compactness of the devices, the efficiency in the dissemination of information and the rapid development of digital technologies, which are actively integrated into the software of smartphone cameras, allow some analysts to predict the further narrowing of the market share of digital cameras. There is an assumption that by 2024, the quality indicators of photo images obtained by smartphone cameras will become higher than similar indicators of photo images obtained by digital SLR or system cameras [2].

The purpose of this study was to analyze the relationships between digital photo image quality indicators and technical parameters of photo equipment, determine the priority of individual indicators for the consumer of visual information, as well as a comparative analysis based on objective data on the quality characteristics of digital photo images obtained by photo-recording systems of different technical classes.

Since the photo registration process is very flexible and the characteristics of the photo image are affected by a wide list of factors, there is a need to systematize and prioritize them. This will allow to optimize the process of recording optical information by digital cameras of different technical classes. On the basis of the conducted objective analysis of the quality indicators of digital photo images using the method proposed in the article, it is possible to draw a conclusion regarding the prospects for technical improvement of digital photo technology.

2. Related Works

The photographic process as a whole (film or digital) is very flexible, as many factors influence the final result. The quality of a digital color photographic image is determined by the vast majority of researchers according to a number of indicators — the accuracy of color reproduction, the reproduction of the gradation content of the image as a whole and the elaboration of brightness details in individual tonal ranges, the accuracy of the reproduction of image details, and its sharpness [19].

It is best to implement the photography process in such a way that as few quality indicators as possible are subject to change during post-photographic processing. This applies both to the compositional construction of the photo and the gradation and color content, and especially to the structural characteristics (the presence of noise and sharpness).

At the initial stage of work on the processing of photo images, you should carefully visually evaluate and study the features of the original:

- plot (how it is displayed, for which this photographic image was actually created);
- overall contrast (thethe plot (how is displayed what this photographic image was created f presence and reproduction of brightness details on dark and light backgrounds);
- the color of plot-important details;
- the presence of memorable and achromatic colors;
- location of black and white points.

After the initial visual analysis, a number of quality indicators are evaluated on the photo image:

1. Exposure and tonal reproduction: parameters of white and black points, reproduction of brightness details throughout the entire tonal range, tonal reproduction of plot-important objects, overall contrast of the image);

2. Color balance: general color tone of the image, reproduction of memorable colors, color balance in neutral (achromatic) colors;

3. Reproduction of small details and image sharpness;

4. The presence of defects in the image: noise, scratches, etc.

There are certain requirements regarding the sharpness of small details, tonal and color reproduction of artistic originals for polygraphic reproduction. Although these requirements have not yet been formulated in relevant regulatory documents for originals in digital form, any halftone image should have satisfactory tonal reproduction, minimal color separation distortions (normal color balance), clear reproduction of small details [3].

We can distinguish three groups of factors that affect the quality of a digital photographic image:

1. External factors that are correlated with each exposure: distribution of brightness of the shooting object (ability to reflect or absorb certain zones of the light source radiation spectrum), lighting features (power and spectral composition of light source radiation).

2. Factors determined by the characteristics of the camera: the technical class of the lens and matrices of light-sensitive elements determine clarity, noise, dynamic range, optical characteristics (lens aperture), the correct choice of exposure (combination of shutter speed and aperture), type and characteristics of separating media (equipment for recording single-color components of complex radiation), the characteristics of light-sensitive sensors affect the accuracy of color reproduction, color coverage of a photo image. The degree of development of the camera software allows you to more accurately select the parameters of the photograph and improve the characteristics of the photo image during its digitization.

3. Factors caused by image post-processing: contrast, color balance, color saturation, etc. These factors are adjusted after the photography process when processed by a graphic editor or RAW converter. During this technological operation, the disadvantages caused by the factors of the first and second groups are reduced: image clarity is increased, noise suppression algorithms are applied, and tonal manipulations are carried out to redistribute the tonal information captured by the camera; the color management system tries to reduce inaccuracies in color reproduction.

Modern technical and software tools in some models of advanced technical class smartphones allow for achieving high visual quality of digital photos. Some authors [1, 5, 6] claim that the technical level of the smartphone camera allows for getting photos of no worse quality than those obtained by SLR cameras. This means that with small dimensions, mobility and intuitively simple settings of the photography process (in contrast to the somewhat complicated process of shooting with an SLR camera), mobile phones with advanced cameras threaten to push SLR cameras out of the market [8].

The working process of recording an optical signal by light-sensitive sensors of a matrix of semiconductor elements, i.e., the actual process of photo exposure, occurs identically to photo-recording systems of different technical classes: a compact camera, a mirrorless camera, a system mirrorless camera or a camera in a smartphone. In order to obtain a photo image of the subject, it is necessary that the light flow from a light source with a certain distribution of radiation power over the wavelengths of the visible spectrum (a certain spectral composition) – $E_0(\lambda)$ - illuminated the object of photography. The reflected light flux, modulated in terms of power and spectral composition in accordance with the reflection coefficient of the surface of the object - $\rho_0(\lambda)$ – enters the optical system of the lens. The structure of lenses and prisms of the camera's optical system of a camera with the distribution of the transmission coefficient in the wave range of the visible spectrum $\tau_0(\lambda)$ forms an optical image in the plane of the matrix of light-sensitive elements. To ensure the registration of color-separated images, each elementary cell of the matrix of light-sensitive elements is covered with a light filter of one of the colors of additive synthesis (the so-called Bayer array), with transmission coefficients $\tau_{c_1}(\lambda)$, $\tau_{c_2}(\lambda)$, $\tau_{c_3}(\lambda)$ in accordance.

Thus, the integral response of light energy receivers, which forms the quality indicators of the photo image, is described by the following function [11]:

$$r = f(a) = f\left(\int_0^\infty \rho_0(\lambda)\cdot E_1(\lambda)\cdot \tau_0(\lambda)\cdot \tau_c(\lambda)\,d\lambda\right). \quad (1)$$

Based on the obtained dependence, it can be concluded that the technical parameters of the photo-recording system components greatlydetermine the quality indicators of digital photographs. And it is this material support that is significantly different in the design of photo-recording systems of different classes.

SLR cameras have significant technical advantages: matrix size from 24×36 mm (in individual models even more) and larger lenses with the possibility of optical zoom and selection of the aperture number. In contrast, smartphones are equipped with light-sensitive matrices of significantly smaller size: average models with matrices 1/3 inch diagonally, and individual manufacturers (Samsung and Xiaomi) adapt the design features of smartphone cases to larger dimensions of the matrix - up to

1/1.33 inch. The latest iPhone camera models have a 1/2.55-inch sensor. And this is practically the limit of the possibilities of increasing the size of light-sensitive matrices in smartphones [20].

The size of the matrix determines the size of its elementary cell - the size of a single pixel. For small matrices in smartphones, this value ranges from 1.4 to 2.44 micrometres for flagship models, and 0.8 micrometres for mid-range models. When increasing the resolution of the matrix of light-sensitive elements to 64 megapixels and more, the pixel size does not exceed 0.8 microns in all smartphone models [1, 2]. In comparison, the pixel size of a full-frame SLR camera is 8.4 microns. This provides significantly lower noise generation, the greater output of photoreaction, wider dynamic range and higher light sensitivity of the matrix, both threshold and integral. Smartphone manufacturers are trying to solve this problem using pixel binning technology when information from four adjacent cells (2×2) is recorded as one elementary area of the image.

The optics in the smartphone camera also differ from the optics of SLR cameras primarily in terms of design. This is mainly a combination of two or more cameras, with different focal lengths and subsequent image processing by software (stacking) [19]. The smartphone camera software itself, in combination with a powerful processor, is the strength of the so-called mobile photography, as it allows the use of computational photography technologies and, in particular, stacking (the combination of a large number of photos taken by different cameras and with different shooting parameters into one image).

Due to the development of software capabilities and the mobility of the device itself, cameras in smartphones are conquering and practically absorbing the niche of amateur photography. Therefore, in many publications, SLR cameras are predicted to lose their positions in the market quickly.

However, the analyzed publications [3, 6, 9] do not provide an objective analysis of the main quality indicators of digital photos obtained by a smartphone camera but perform a subjective analysis based on the visual evaluation of the photo by the viewer. It is known that such expert analysis can be done by a group of qualified experts and only under standardized viewing conditions (appropriate level and spectral composition of lighting, viewing angle, etc.) and on calibrated viewing devices. But even under such conditions of implementation of quality indicators evaluation, the obtained results are subjective, since it is known that only instrumental methods of quality evaluation are considered objective. The expert method of determining the values of product quality indicators is used only when certain quality indicators cannot be determined by other, more objective methods [12, 13].

Thus, in connection with the small number of publications covering this problem based on the analysis of objective data, this study proposes to evaluate the quality indicators of photo images obtained by photo-recording systems of different technical classes (SLR camera and smartphone camera).

3. Information model for determining the importance of factors affecting the quality of a digital photo image

Let us consider the factors that significantly affect the quality parameters of a digital photo image. Today, there is no regulatory documentation that would regulate these indicators, which can be explained by the wide variety of methods of obtaining them and the constant improvement of technologies. The main indicators of the quality of a digital color tone image are:

1. Tone reproduction (exposure);
2. Color balance (reproduction of memorable colors and gray balance);
3. Reproduction of small details and clarity (sharpness) of the image;
4. The presence of defects in the image (noise, etc.).

Each indicator of the quality of a digital photographic image is established at the stage of exposure and depends on many factors: the hardware of the camera, its software, as well as external factors (the power and spectral composition of the radiation at which the exposure is carried out, the reflective properties of the shooting object and their dependence on wavelengths of light source radiation), which dynamically change during each exposure.

In order to systematize all factors influencing the quality of a digital photo image, let's build a diagram of the causal relationship of influencing factors (Fig. 1).

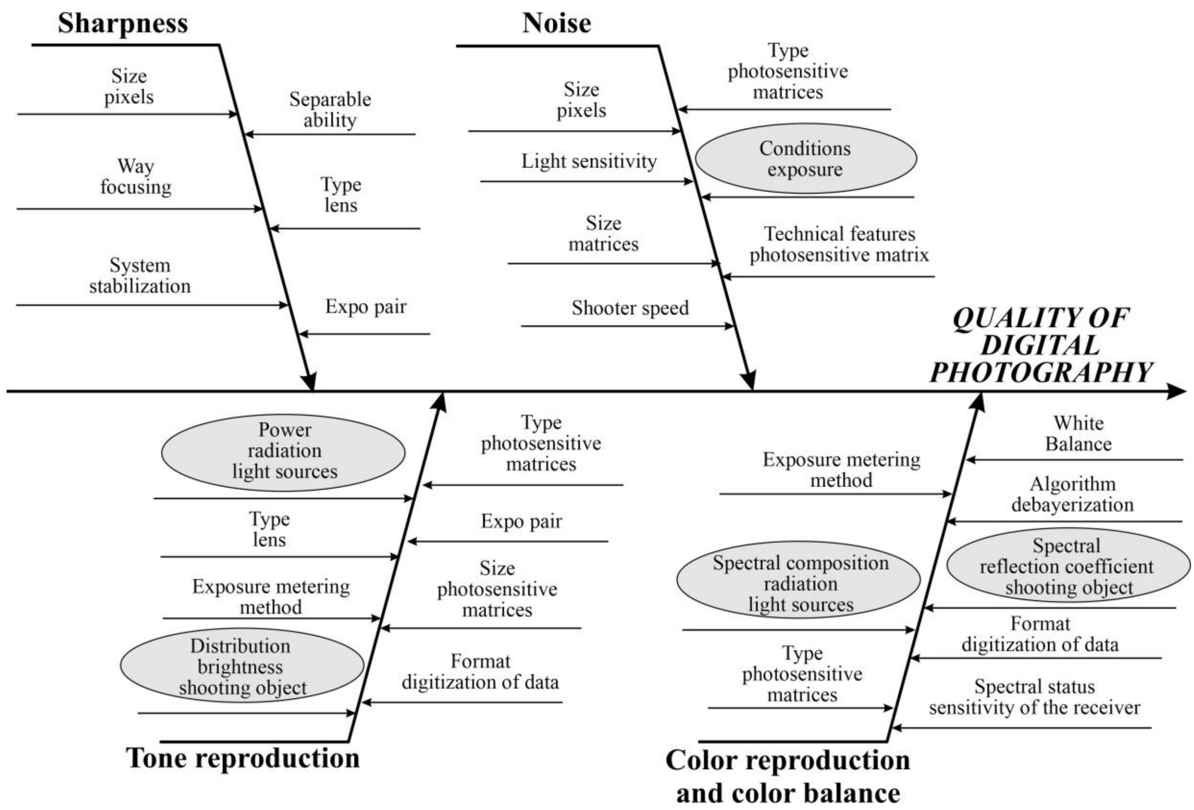


Figure 1: Diagram of the cause-and-effect relationship of influencing factors on the quality indicators of a digital photo image

The presented diagram demonstrates that the four main quality indicators are influenced by a number of factors. Some of them are the so-called external factors that either cannot be influenced or the influence is limited. These are the characteristics of the light flux, as well as the brightness and color characteristics of the shooting object. The listed factors on the diagram are marked separately and we will exclude them from the further analysis of the priority of factors.

We will consider the procedure for realizing the quality of creating a digital photo image as some function, the arguments of which will be the above factors.

$$P = F\left(s_1, s_2, s_3, s_4, s_5, s_6, s_7, s_8, s_9, s_{10}, s_{11}\right) \quad (2)$$

where s_1 – camera software (CSW); s_2 – expo pair (EXP); s_3 – method of focusing (MF); s_4 – a type of lens (TL); s_5 – stabilization system (STS); s_6 – exposure method (EXM); s_7 – a type of photosensitive matrix (TPM); s_8 – pixel size and resolution (PER), s_9 – light sensitivity (LS); s_{10} – white balance (WB); s_{11} – digitization format (DFT).

In terms of terminology and essence, the identified factors are classified as linguistic variables, which in the tasks of the process of creating a digital photo image can be parameters that affect its final quality. To do this, we will build an initial graphic model (orientated graph), taking into account expert judgments regarding the pairwise influence (connections) between the factors (Fig. 2).

The output graph of Fig. 2 will be used to rank the factors by the importance of influence on the researched process, the result of which will be a multi-level model of quality factors of creating a digital photo image. For the synthesis of the linguistic model, we will use the tools of matrix theory and system analysis [8].

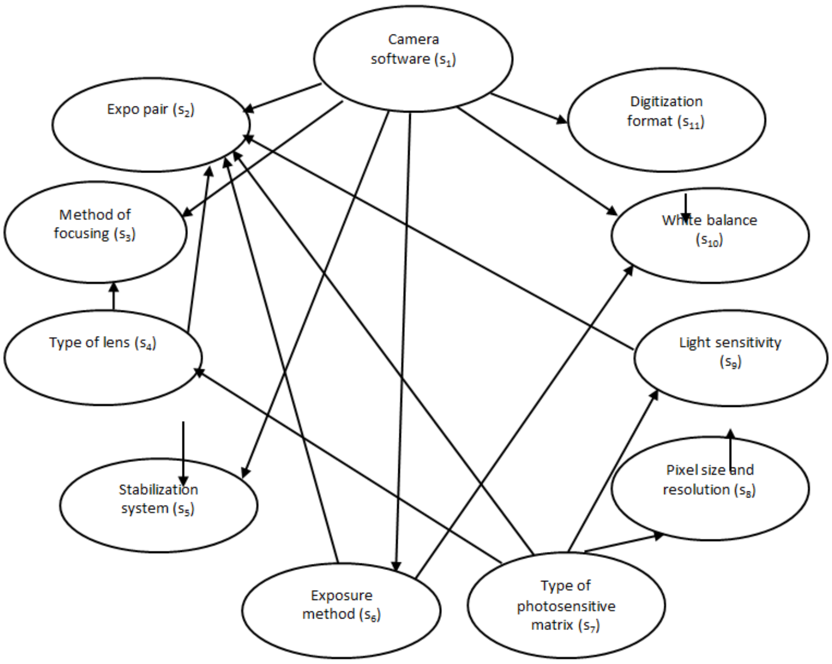


Figure 2. Initial graph of relationships between influencing factors on the quality of creating a digital photo image

To synthesize the model of process quality assurance factors, we will use the method [8], which distinguishes between their types by assigning different expert weights to each of them. The essence of the proposed method of ranking factors that affect the quality of the implementation of arbitrary technological processes will be considered using the example of the analysis of relationships between factors related to the quality of a digital photo image.

It is expedient to carry out further research on the basis of taking such definitions and statements into account.

Definition 1. Each technological process related to the formation of a digital photo image contains a certain set of factors or parameters that determine the completeness and quality of its implementation.

Let $P=\{p_1, p_2,..., p_m\}$ – an arbitrary set of technological processes; $M=\{x_{1_m}, x_{2_m},..., x_{n_m}\}$ – a number of factors affecting quality m- the process, where n_m – the number of factors m- the process. We will also consider, that

$$Q(x_k)\equiv\bigcup_{j=1}^{n}\omega(x_{j_k}),\quad (k=1,2,...,m) \tag{3}$$

where: $Q(x_k)$ – a numerical indicator of the quality function m- the process; $\omega(x_{j_k})$ – numerical weight index of the input j-м factor of additional quality in k-th technological process. Then the definition can be given as follows:

$$(\exists p)\ (\forall x)\ Q(x_k);\ p\in P;\ x\in M \tag{4}$$

Definition 2. The rank of the factor or priority in terms of its impact on the technological process is determined by the weighting factor. Among the set of factors of the technological process, there will be at least one that dominates over other factors, that is, the priority of which is decisive.

Adhering to the terminology adopted above, we obtain: for the set $W=\{w_{1_m}, w_{2_m},..., w_{n_m}\}$ the weight of the factors of the technological process under the condition that $B(w)\equiv\max\{w_{1_m}, w_{2_m},..., w_{n_m}\}$, we will have:

$$(\forall p)\,(\exists w)\,B(w);\ p\in P;\ w\in W \tag{5}$$

Statement 1. The presence of connections (influences and dependencies) between factors creates a prerequisite for building their formalized representation in the form of an oriented graph.

Statement 2. The initial ranks of the factors are established by considering and analyzing the types and quantities of connections between them in the original graphical model built on the basis of expert judgment.

Statement 3. The synthesized multilevel model reflects only preferences between factors, provided they are compared within the original graph.

Statement 4. Establishing the final weight values of the factors that determine their rank and the degree of influence on the technological process is possible based on the construction and processing of the matrix of pairwise comparisons and the calculation of the normalized components of the main eigenvector of the matrix.

Definition 3. Among the set of factors, arranged in descending order of their normalized weight values, there are none that are absolutely identical in terms of the degree of influence on the technological process.

Provided that $D(w)\equiv w_j > w_{j+1}$ for $(j=1,2,...,n-1)$ the following entry will be correct:

$$(\forall w)\,D(w);\ w\in W \tag{6}$$

Following statements 1-4, the synthesis of the model of the priority influence of factors on the technological process is realized through the identification of factors characteristic of this process, the construction, analysis and processing of the original graphic model, in which the relationships between factors are established on the basis of expert judgments. The number and conditional weight of factors according to various types of connections between them ultimately determine the priority of their influence on the process.

The proposed mathematical model is based on numerical indicators that relate to the number of influences and dependencies between factors and their corresponding weighting coefficients. At the same time, we will distinguish between direct influences, calling them 1st-order influences, and indirect— 2nd-order influences. Dependencies will also be distinguished by similarly setting the 1st and 2nd orders of importance for them.

To calculate the total weight values of the direct and indirect effects of factors and their integral dependence on other factors, we will introduce appropriate notations. Let - the number of influences or dependencies for j-the factor ($j=1,...,n$); w_i – the weight of the -the type.

At the same time, we will distinguish the following types of connections between factors, which will depend on the value of the index of the type of connection, i.e.: $i=1$ – effects of the 1st order; $i=2$ – effects of the 2nd order; $i=3$ – dependencies of the 1st order; $i=4$ – dependencies of the 2nd order.

For calculations, we set some conditional values for the weighting factors in relation to the types of dependencies. We will assume that for the effects of both types the weights will be positive, i.e $w_1>0$, $w_2=w_1/2$, respectively, for dependencies - negative, namely: $w_3<0$, The integral weights of the factors based on the sums of the weights of all types of connections are denoted by S_{ij}.

Finally, we will get the following formula for calculations:

$$S_{ij}=\sum_{i=1}^{4}\sum_{j=1}^{n}k_{ij}w_i \tag{7}$$

,

where n – conditional number of the technological process factor.

If a certain type of connection is missing for some factor, then it is obvious that the value corresponding to it is missing in expression (7) will be zero. The given formula serves as a basis for obtaining weight values - the grounds for ranking factors, taking into account various types of connections between them.

Since according to the given initial conditions $w_3<0$ i $w_4<0$, then the corresponding partial sums will also have a negative value: $S_{3j}<0$ i $S_{4j}<0$. To bring the weight values of the factors "to the origin of the coordinates", that is, to obtain positive values, it is necessary to conditionally move the histogram of the integral graphic display of all types of connections upwards, that is, to introduce a correction, which is established on the basis of the following ratio:

$$\Delta_j = \max|S_{3j}| + \max|S_{4j}|, \ \ (j = 1, 2, ..., n), \qquad (8)$$

Taking into account (8), the final calculation formula for obtaining the final weighted values of the factors will have the following form:

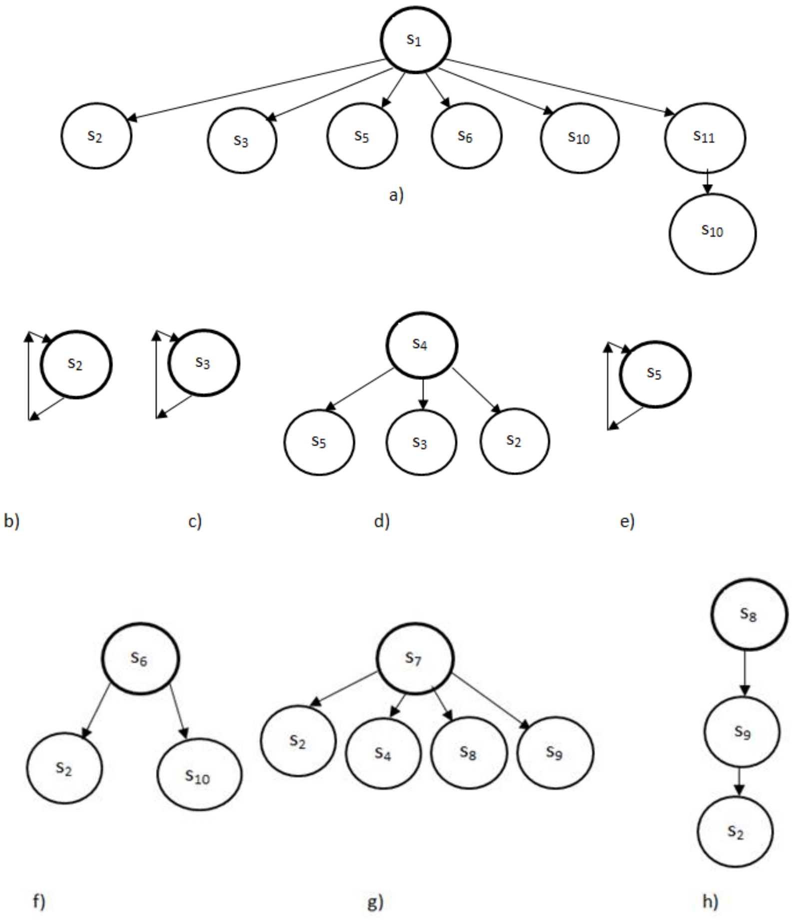
$$S_{Fj} = \sum_{i=1}^{4} \sum_{j=1}^{n} \left(k_{ij} w_i + \Delta_j \right), \qquad (9)$$

Magnitudes S_{Fj} serve as a basis for ranking the weights, i.e. establishing the levels of the factors of the technological process, which enable the synthesis of the resulting model of the priority influence of the factors on the researched process. On the basis of this model and the scale of the relative importance of objects, a matrix of pairwise comparisons is built, the processing of which leads to an optimized model of ensuring the quality of the technological process.

For further explanation, we will use the original graph of connections between factors (see Fig. 2). Based on it, we build hierarchical trees of connections with other factors for each of the factors, taking into account direct and indirect influences.

The graphs in fig. 3 is used to build a modified diagram of relationships between factors, creating table 1 in which, in addition to the number of the factor, the directions of direct influence of each of the factors and the paths of dependence on other factors are given. We will calculate the total weighted values of the direct and indirect effects of factors and their integral dependence on other factors, taking into account the designations and conditions introduced above.

Options b), c), e), j) means no influence of factors: s_2, s_3, s_5 та s_{10} on other factors, that is, their connections have the form of a loop.



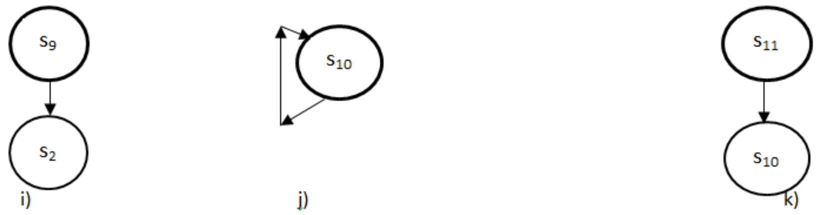


Figure 3. Graphs of multi-level hierarchical relationships for factors. In the implementation process of creating a digital photo image: a) - k)

For calculations, we will accept the following conditional values for weighting factors in conventional units: $w_1 = 10$, $w_2 = 5$, $w_3 = -10$, $w_4 = -5$.

As a result, for the original graph of Fig. 2, taking into account (7), we obtain an expression for calculating the intermediate total values of factor weights:

$$S_{ij} = \sum_{i=1}^{4} \sum_{j=1}^{8} k_{ij} w_i \quad , \qquad (10)$$

Table 1

The scheme for presenting relationships between factors has been modified

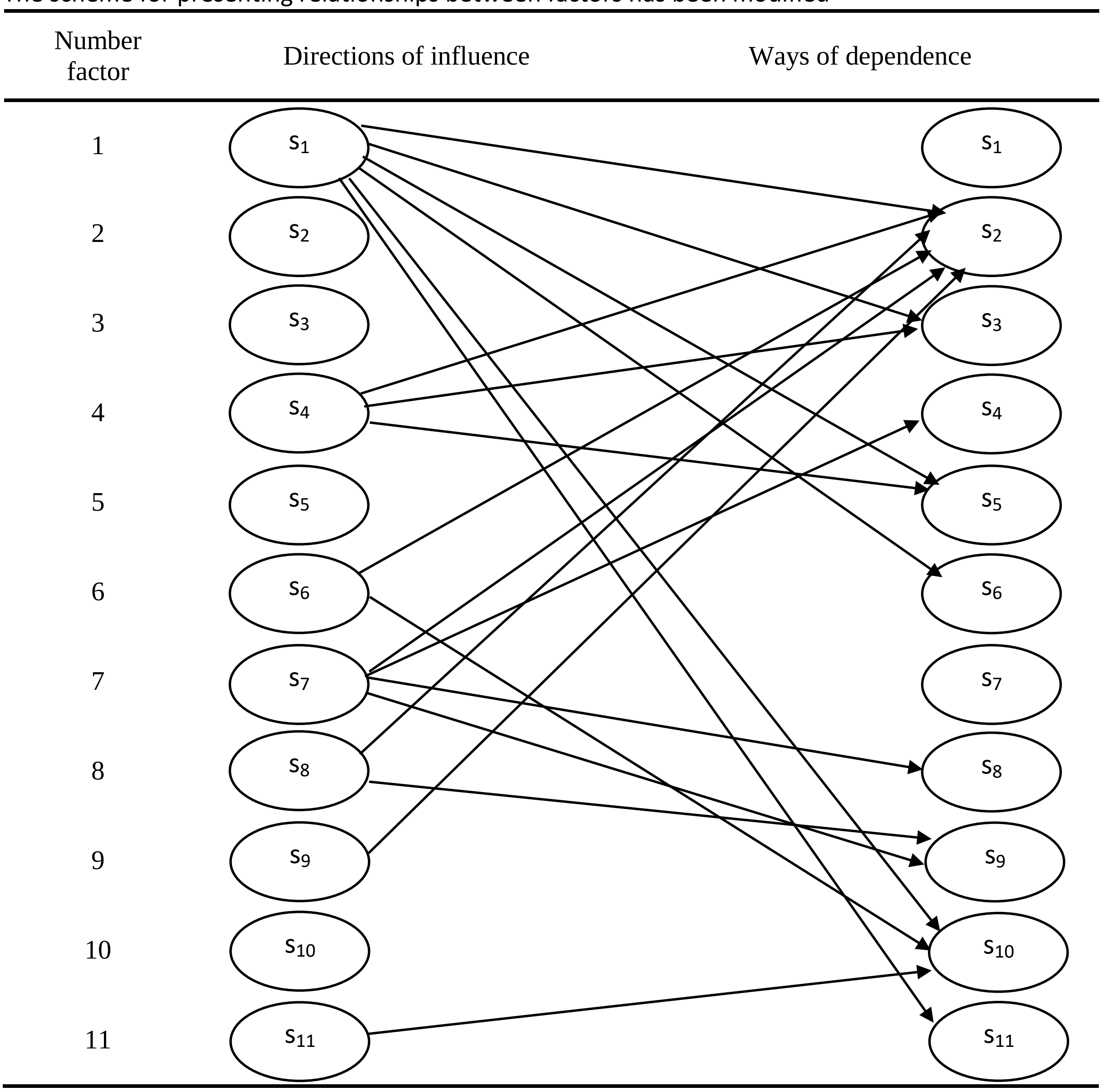


Table 2
Estimated data and ranking of factors creating a digital photo image

Number factor j	k_{1j}	k_{2j}	k_{3j}	k_{4j}	S_{1j}	S_{2j}	S_{3j}	S_{4j}	S_{Fj}	Rank factor r_j	**Level prioritie**
1	6	0	0	0	60	0	0	0	75	7	**5**
2	0	0	6	4	0	0	-60	-20	15	1	**11**
3	0	0	2	1	0	0	-20	-5	40	3	**9**
4	3	0	1	0	30	0	-10	0	90	10	**2**
5	0	0	2	1	0	0	-20	-5	45	4	**8**
6	2	0	1	0	20	0	-10	0	85	9	**3**
7	4	0	0	0	40	0	0	0	115	11	**1**
8	2	1	1	0	20	5	-10	0	80	8	**4**
9	1	0	2	1	10	0	-20	-5	50	5	**7**
10	0	0	3	2	0	0	-30	-10	25	2	**10**
11	**1**	**0**	**1**	**0**	**10**	**0**	**-10**	**0**	**70**	**6**	**6**

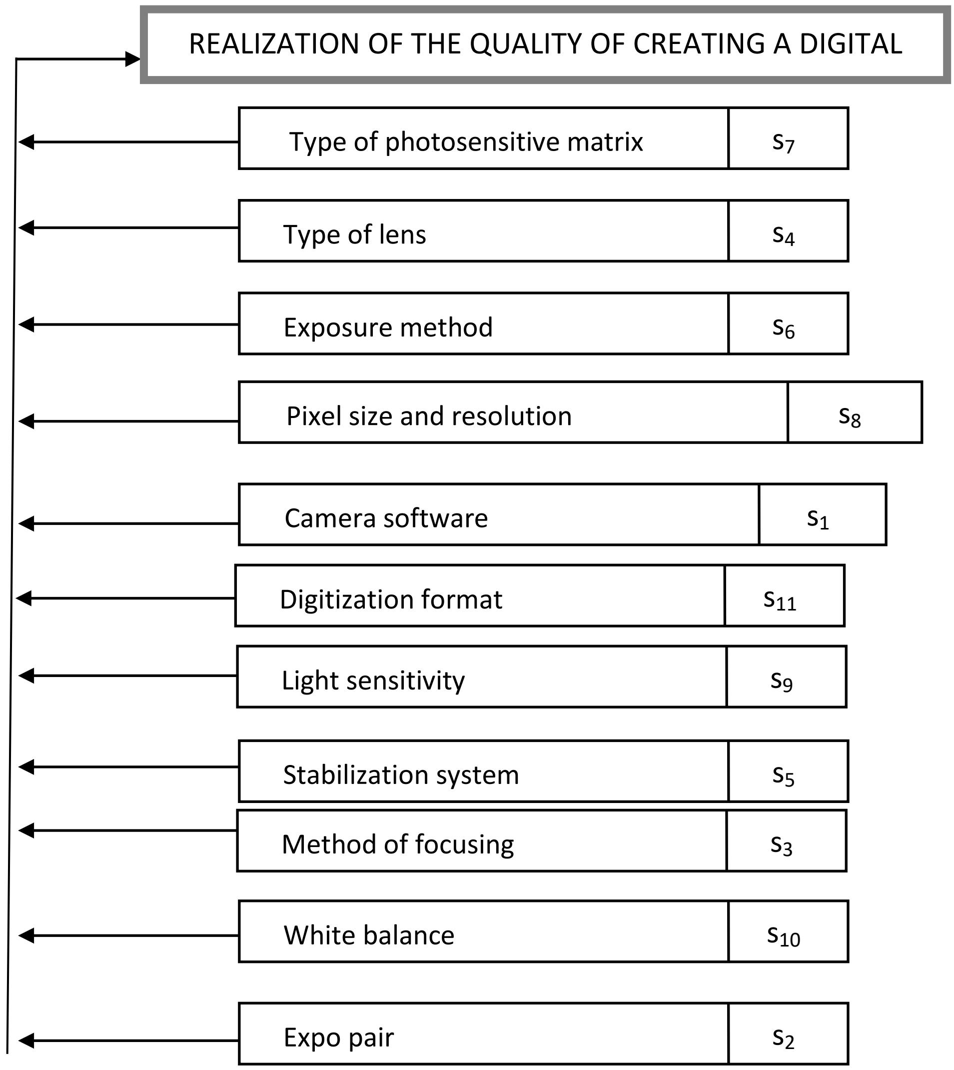


Figure 4. Model of the priority influence of factors on the quality of realization of a digital photoimage

Taking (10) into account, we get the partial sums of the factor weights, calculate the correction for negative values of the sums and, based on (9), form table (2), which ensures the establishment of factor ranks and their corresponding priority levels of influence on the process of creating a digital photo image. As can be seen from the table. 2, $\max\left|S_{3j}\right| = 60; \max\left|S_{4j}\right| = 5$. The specified values are added in each of the rows to the partial total values of the weights in the columns S_{1j}, S_{2j} S_{3j}, та S_{4j}

The resulting weight S_{Fj} serves as the basis for establishing the rank of the factor r_j and its level, which is equivalent to the priority of the influence of the factor on the process of creating a digital photo image. Using the data from the "Rank of the factor" column, we build a multi-level model of the priority influence of factors on the quality of implementation of a digital photo image (Fig. 4).

As a result of the application of the ranking method, the ranks of the factors were calculated, on the basis of which a multi-level model of their priority influence on the quality of the realization of a digital photo image was synthesized, which can be used for further optimization of the weighting values of the factors and the calculation of alternative options for the implementation of the process of creating a digital photo image.

4. Evaluation of quality indicators of digital photographs

The obtained results of mathematical modelling make it possible to more accurately formulate the conditions of an experimental study of the quality characteristics of digital photographic images obtained by photosystems of different technical classes.

As a test object for evaluating the listed quality indicators, a color image on a material medium was used, which consists of an achromatic scale and a set of fields colored in the colors of the additive space (red, green, and blue) and the subtractive space (blue, magenta and yellow). Also, the test image includes objects of memorable colors, in particular, human skin, orange, etc. The indicated test object was photographed with an EOS 80D SLR camera (Canon) and an iPhone 11 smartphone (Apple) in the mode of manual selection of the exposure pair with a light source balanced in terms of spectral composition (mercury gas discharge lamps TL'D/950 de Luxe by Phillips, color temperature - 5300K). The resulting digital photo images were digitized in parallel in JPEG, RAW and DNG formats.

First of all, we evaluate the accuracy of color reproduction by the location of the color points of additive and subtractive colors on the color chart a*b*. For comparison, the chromaticity points of the colors of the test object are marked on this diagram (Fig. 5).

Photos taken by a smartphone camera and digitized in DNG format and in JPEG format generated from DNG - lgtr_dng.dng shapes - came closest to the color coverage of the original. and lgtr_jpeg.dng respectively. The DNG format, known as a digital negative, is a universal RAW format from Adobe Corporation that contains information directly from photosensitive matrix receivers, unprocessed by the camera software.

Instead, the images are digitized immediately into the format JPEG software "Camera" in smartphone and format HEIC (figures iphone_jpg and iphone_heic respectively) are characterized by a significant narrowing of the color gamut and the exit of most colors (red, magenta, cyan and blue) beyond the color gamut of the original. Therefore, it can be concluded that this happened as a result of additional image processing by smartphone camera software, which is configured to increase the saturation of colors in the photo image.

Regarding photos taken with an SLR camera in formats RAW and JPEG (figures cam_raw.tiff and cam_jpeg.jpeg відповідно), then their color gamut is the narrowest, but not due to the distortion of color shades, but only due to reduced saturation, because the shape of the color gamut figure of the specified photographs quite accurately corresponds to the color gamut figure of the original.

It can be concluded that in the formats JPEG and HEIC the smartphone software creates a specific reproduction of colors that do not correspond to the real ones. And the best color reproduction without additional processing was achieved when shooting with a smartphone and digitizing in the format

DNG. Photos from an SLR camera also have realistic color reproduction and require minimal saturation correction during post-photographic processing.

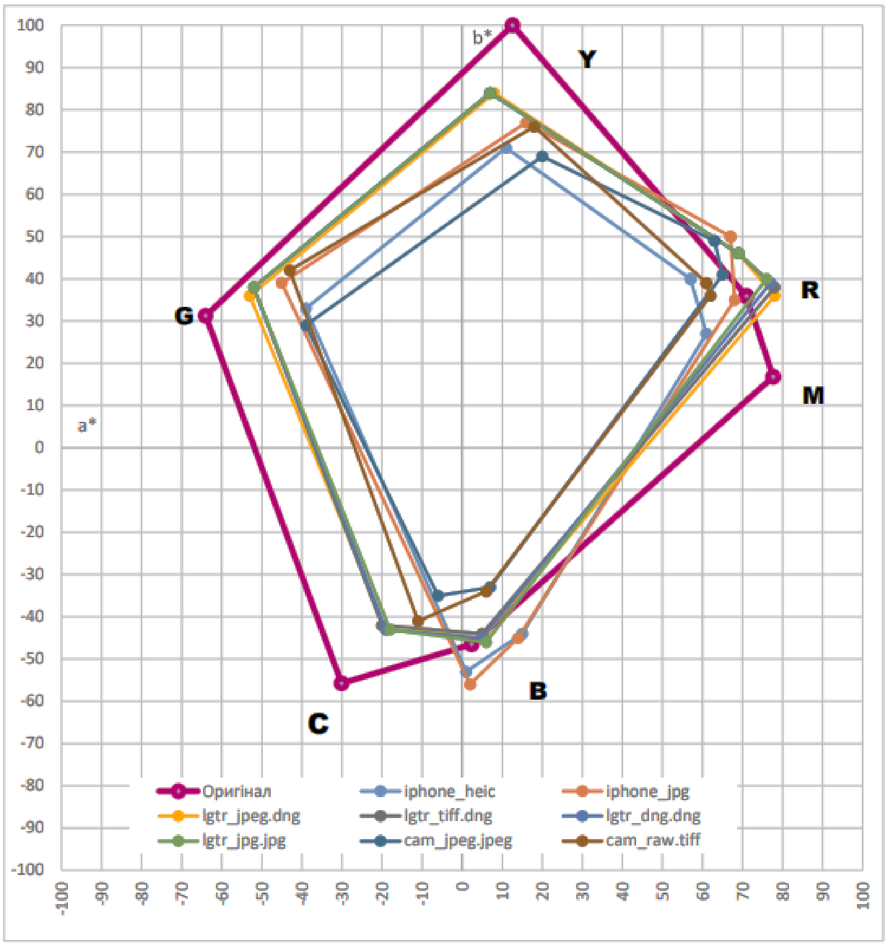


Figure 5. Color diagram of digital photo images obtained by an SLR camera EOS 80D (Canon) and a smartphone iPhone 11 (Apple)

In addition, for the purpose of a more complete analysis of color reproduction in images, was evaluated the reproduction of one of the most critical memorable colors — skin color. For this, the value of color contrast was calculated ΔE between the test picture and the resulting photo images. The following values were determined on the photo images obtained by the smartphone camera: in format HEIC ΔE – 9; in the format JPEG ΔE – 8,8; in the format DNG ΔE – 8,1. This is a significant value of color contrast, which indicates a visually noticeable difference between colors, since ΔE exceeds the maximum permissible value of 5 units. In photographs obtained by a SLR camera, the value of color contrast is also significant: on a digitized RAW format — ΔE is 8.5, on digitized to format JPEG ΔE – 9. That is, visually, the consumer of visual information will see the difference in shades.

Thus, on the basis of the above, we can conclude that the smartphone camera, even in combination with advanced software, does not provide satisfactory color reproduction of the photo image.

To evaluate color balance, we analyze the content of the main colors of additive synthesis by achromatic shades. According to the achromatic degree scale available on the test image, we determine the coordinates Lab, which are converted into RGB coordinates. Based on the data obtained in this way, the following graphical dependencies were constructed (Fig. 6-7).

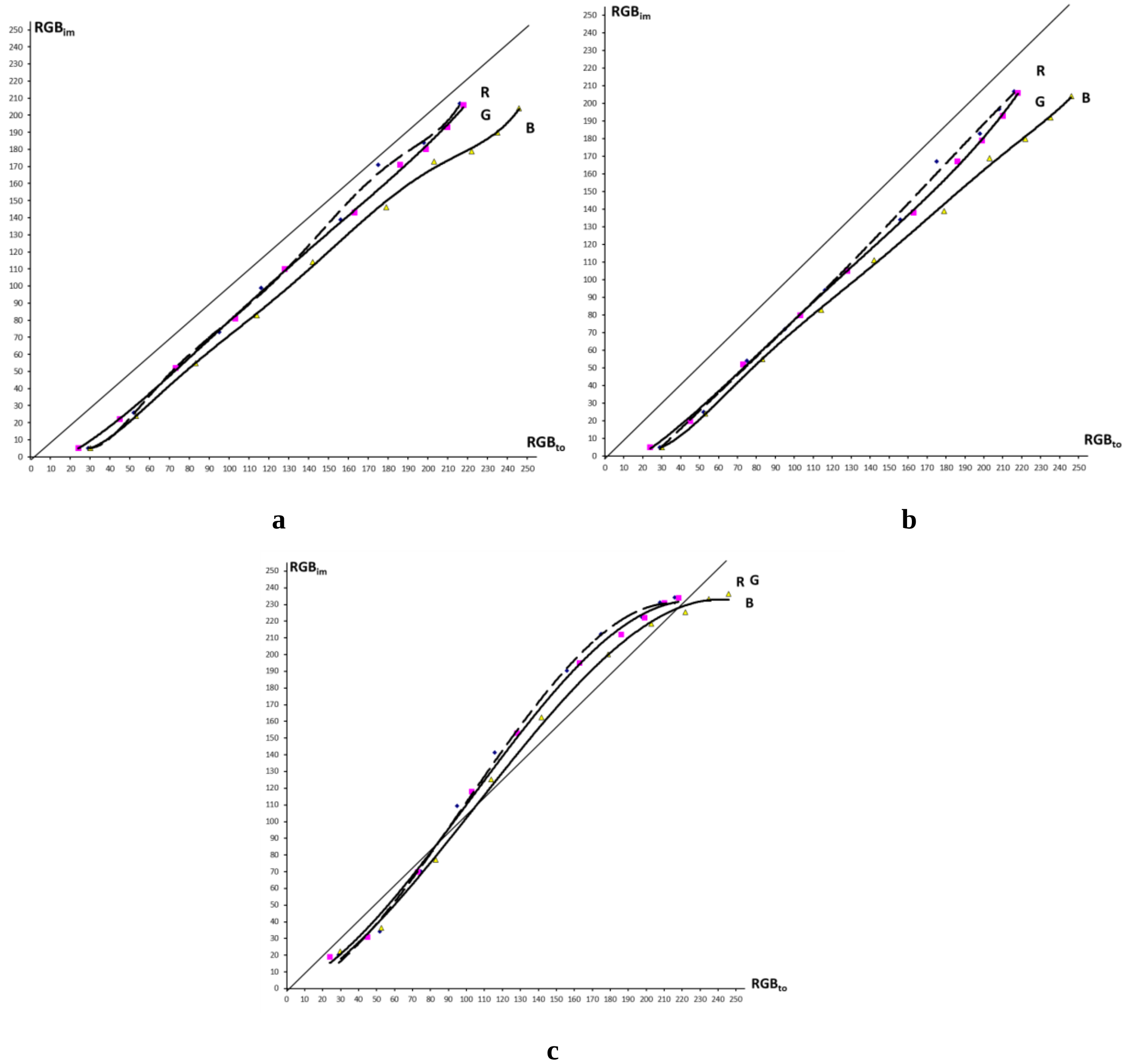
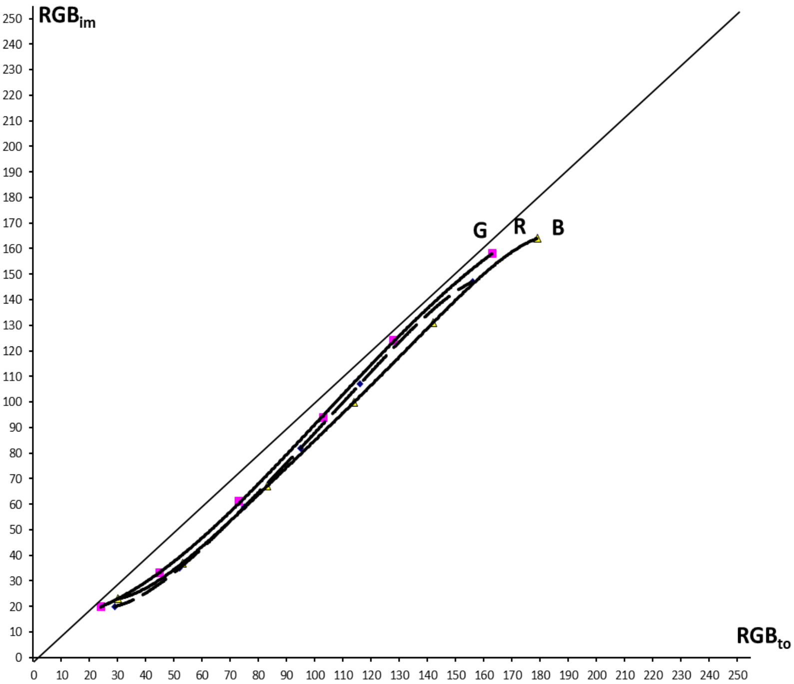


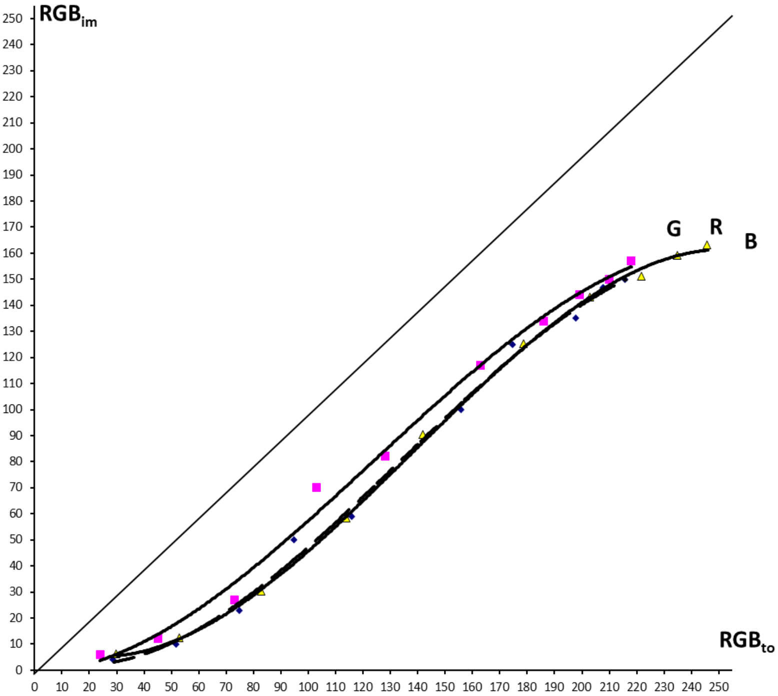
Figure 6. Graphical dependencies of the content of colors of additive synthesis on the achromatic scale in the photos taken by the smartphone camera (a – JPEG; b – HEIC, c – DNG format respectively)

The graphical dependencies presented demonstrate that photos digitized by smartphone software into formats HEIC and JPEG are characterized by a significant imbalance of color components in achromatic colors. Image in raw format DNG has a higher degree of color balance, but some imbalance is still observed (Fig. 6).

A better balance of color components (Fig. 7), especially in a photo in RAW format – the curves of the content of single-color components almost completely coincide.



a



b

Figure 7. Graphical dependences of the color content of additive synthesis on the achromatic scale in photographs obtained by an SLR camera (a – RAW, b – JPEG format respectively)

The same graphical dependencies (Figs. 6 and 7) allow us to evaluate the gradation transfer in the evaluated photo images since the dependence on the actual brightness (power) of the single-color components is reflected here. Thus, we can draw an unequivocal conclusion that the most accurate tonal reproduction (closest to the tonal reproduction of the original) is characteristic of a photo obtained by an SLR camera and digitized into RAW (Fig.7), since the curves on the coordinate plane are as close as possible to directly proportional tone reproduction.

Another evaluated quality indicators — sharpness and digital noise level — are the so-called structural characteristics. For a consumer of visual information, these indicators are among the most critical, especially sharpness, which determines the separate reproduction of small details. It is advisable to evaluate this indicator quantitatively by the width of the blurred zone at the border of the transition of a dark part on a light background or vice versa (Fig.8).

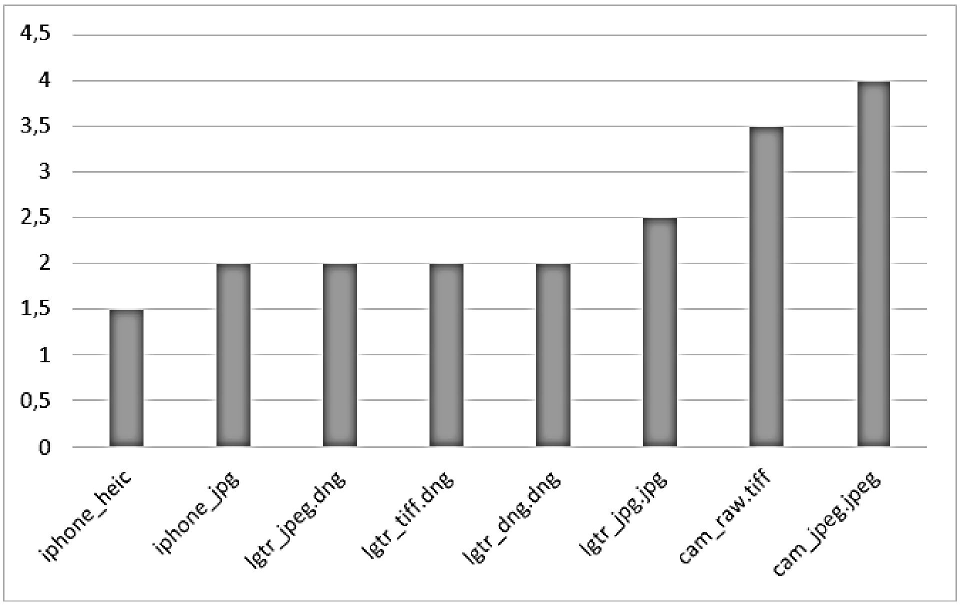
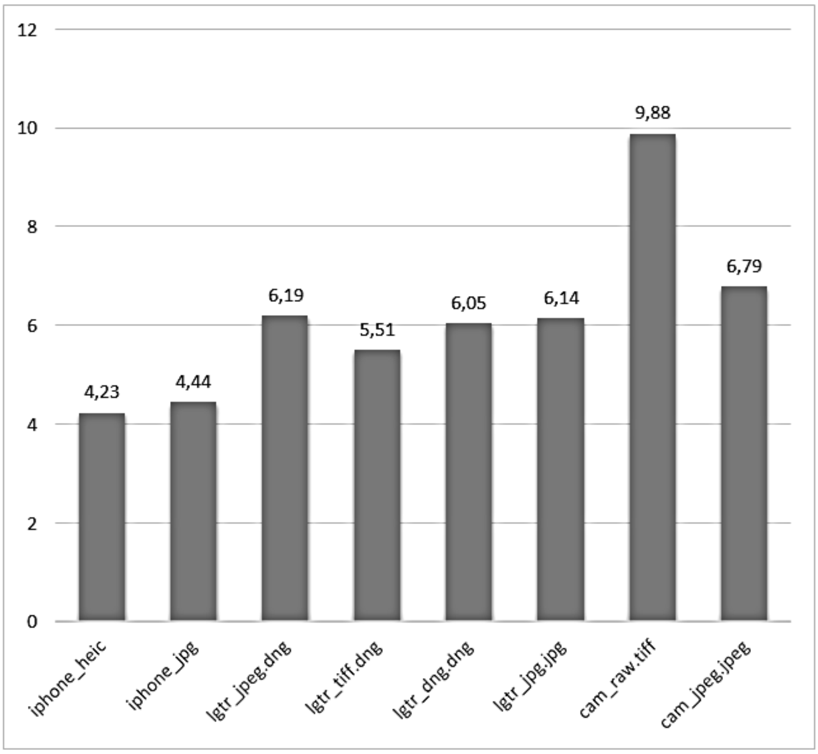


Figure 8. The width of the blurred zone (pixels) in the photo images obtained by photo-recording systems of different classes and digitized in different graphic formats

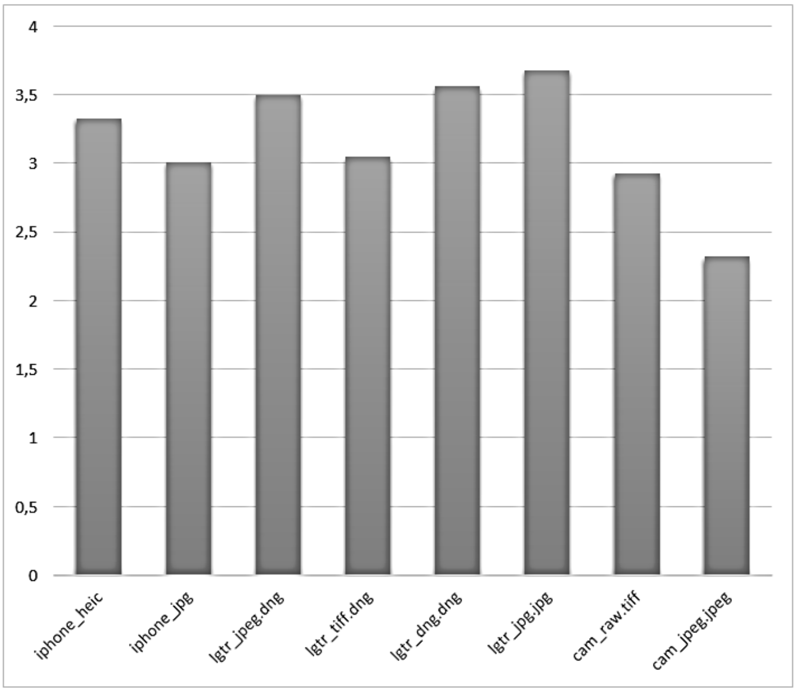
The diagram in fig. 8 shows that the highest sharpness is characteristic of a photo image obtained by a smartphone camera and digitized in the HEIC format.

It is advisable to quantitatively estimate the level of digital noise (color and brightness components) in a graphic editor PhotoShop (Adobe) by the Std Dev standard deviation parameter in the Histogram palette, expressed in brightness levels [10]. The obtained results are displayed in the diagrams in fig. 9. The lowest level of color noise is characterized by a photo image obtained by a smartphone camera, and the highest level of noise is recorded on a photo obtained by a SLR camera and digitized in the format RAW.

So, the smartphone software is better at implementing the noise reduction algorithm. A photo image digitized in RAW format is characterized by a high level of noise noise because the data from the light-sensitive matrix has not been processed by the camera software, and this is the specifics of this graphic format. This is explained by the fact that photos taken on a smartphone have already been pre-processed by artificial intelligence during recording, which is programmed to "further improve" the clarity and quality of the image. While an image file recorded in RAW format contains raw data.



a)



b)

Figure 9. The level of color (a) and luminance (b) noise (Std Dev) on photo images obtained by photo-recording systems of different classes and digitized in different graphic formats

5. Conclusion

The conducted studies proved that none of the studied photo-recording systems can be considered perfect. Photos taken by a smartphone camera are characterized by a low noise level and high sharpness. This is an unequivocal advantage and is achieved only by developing the camera software. Instead, the color reproduction, tonal reproduction and color balance of these halftone images are unsatisfactory. Digitizing the data in DNG format simultaneously with the smartphone matrix gives the opposite result: color reproduction, tonal reproduction and color balance are significantly improved, but the level of color noise is higher and sharpness is reduced. Thus, it can be argued that the material support of the smartphone camera still does not reach the desired level, which is due to certain technical limitations of the devices themselves (the special structure of the optics to ensure its compactness, the small dimensions of the light-sensitive matrix).

Photo images obtained by a SLR camera are characterized by almost perfect color balance and good reproduction of individual single colors and memory colors (skin color), for which the color contrast is within tolerance (the number of thresholds is less than 5). But the structural characteristics of the mentioned photo are somewhat outside the tolerance limits (Std Dev is more than 3.5 units), but their level is not critical and can be corrected during post-photographic processing.

So far, no advantages of any of the photo-registration systems have been identified within the scope of this study. The obtained experimental results are consistent with the results of mathematical modeling, which indicates the priority of the material support of the photo-recording system (in particular, the light-sensitive matrix and optics), and the weight of the influence of the software is lower. Therefore, it can be predicted that the competition of these systems will continue, and the improvement of the material base and software will open up new opportunities for consumers of this product.

The analysis of the quality indicators of digital photo images, taking into account the determined priority of influencing factors, will allow us to look for ways to improve the technical base of digital photo technology and its software.

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