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STUDY OF USABILITY OF MACADAMS ELLIPSOIDS IN DEFINING QUALITY OF PRINTING DARK COLOURS

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Original scientific paper

Various technologies of printing processes induce various deviations in the quality of the printed graphic product. Labels as graphic products are sensitive to such changes, since they represent the first contact between the consumer and the product the label is applied on. This research is oriented towards imprints dominated by dark colours, printed using the offset printing technique. Goal of this research is to, based on the spectrophotometric measuring and visual evaluation of the printing quality, construct the MacAdams ellipsoids and establish whether it is possible to establish the printing quality in the area of dark colours using MacAdams ellipsoids. After conducted research it was established that the ellipsoids cover various areas within CIE $L^*a^*b^*$ system. By correlating the stated results, it was concluded that while establishing the printing quality of the dark colour it is possible to use MacAdams ellipsoids.

Keywords: *MacAdams ellipsoids; printing quality; dark colours; CIE LAB system; Delta E*

Studija upotrebljivosti MacAdamsovih elipsoida u određivanju kvalitete tiska tamnih boja

Izvorni znanstveni članak

Raznovrsne tehnologije tiskarskih procesa uzrokuju različita odstupanja u kvaliteti otisnutog grafičkog proizvoda. Etikete kao grafički proizvodi osjetljive su na takve promjene, budući najčešće predstavljaju prvi kontakt između kupca i proizvoda na koji je etiketa aplicirana. Ovo istraživanje usmjereno je na otiske kojima dominiraju tamnije boje, otisnute tehnikom ofsetnog tiska. Cilj ovih istraživanja je na osnovu spektrofotometrijskih mjerenja i vizualne ocjene kvalitete tiska, konstruirati MacAdamsove elipsoide i ustanoviti je li moguće MacAdamsovim elipsodima ustanoviti kvalitetu tiska u području tamnih boja. Nakon provedenih istraživanja, ustanovljeno je da elipsoidi pokrivaju različita područja unutar CIE $L^*a^*b^*$ sustava. Osim navedenog ustanovljeno je da je vizualnom procjenom moguće percipirati male promjene u tamnim bojama, ali ne u svim vrijednostima linearno. Korelacijom navedenih rezultata, zaključeno je da je prilikom ustanovljavanja kvalitete tiska tamnih boja moguće koristiti MacAdamsove elipsoide.

Ključne riječi: *MacAdamsovi elipsoidi; kvaliteta tiska; tamne boje; CIE LAB sustav; Delta E*

1 Introduction

Often observed as an advantage, large variety of printing processes has its faults as well. Except for advantages that in the first place enable printing a large number of different printing surfaces, it still very often becomes impossible to coordinate the quality of imprint with the various marketing demands. A special parameter, i.e. mistake factor is the oscillation in colouring through printing, especially when printing in larger circulations [1]. An average observer can, but does not need to notice such differences and deviations, which represents a problem that should not occur with the modern technology and scientific cognitions. Since today the quality of printing is extremely important on packaging, products are extremely sensitive to such changes, since the packaging most commonly represents the first contact between consumer and the product. Also, the quality of printing can be one of the main factors for the product purchasing decision making the above named quality one of the main success parameters of a particular product. Since, except in flexo printing, the labels on packaging are mostly printed in offset printing technique using various printing surfaces of small grammages, deviations are possible for various causes: different printing machines, different measuring equipment and methods of quality control of imprint, differences in printing surfaces, colours but also in the different observer [2, 3]. All the stated depends on the feeling for colour, but also on the calorimetric characteristics of colour considering that today colour science is widely used in a variety of industries such as textile, paint, plastic, packaging, paper, lighting, television, colorant, food, ceramic, cosmetics, etc. [4].

Quality perception is directly connected with colour perception that is caused by differences in the human eye, i.e. which is based on three kinds of cones (L-cone, M-cone and S-cone) in the retina [5÷8]. Several relevant models have been built to describe the cone-based visual characteristics [9, 10]. There has long been a great demand by industrialists for the ability to accurately quantify changes in colour appearance to minimize observer dependencies. The solution is to devise a standard colour appearance model capable of predicting the appearance of colours across a wide range of viewing conditions [11].

Scientific research related to the perception of colour has not defined in how and in what way the human eye perceives more tonal image, when the image is composed of different dominant tonalities.

This problem is explicitly emphasized with dark tonalities that were researched in this paper, due to the fact that when printing various commercial products, different changes occur within the production itself primarily for commercial reasons, where an optimal relation between the price and quality of the product is trying to be achieved. That is why such products are often printed in different conditions in relation to the change of machines and appliances as well as materials for the making of the product, and due to this it is more and more difficult to conduct excellence in the quality control of the printed graphic product. Except for the necessity in clear defining primarily of colours, for the printing house the visual control of the printed product is often also essential [12]. However, the question is posed whether the average observer, user of the product, is even aware of the deviations that can occur in dark colours? In order to determine the stated problem it is necessary to conduct a research of the colorimetric characteristics of dark colour and deviations in dark colours, but also to research the subjective feeling of product quality and the feeling people can perceive with small changes in the named colours. The goal of this paper is to establish whether it is possible to establish and valorise the stated problem using the scientific method of designing MacAdams ellipsoids that cover a certain area of CIE $L^*a^*b^*$ system. By constructing the named ellipsoids you can achieve area of CIE $L^*a^*b^*$ system within which colorimetric values of colours for which an average observer perceives colour should be placed.

2 Experimental part

Research in this paper was conducted using measuring methods of spectrophotometric measuring that resulted in the calculation of colour coordinates in CIE $L^*a^*b^*$ system, calculation of brightness, tone and chromaticity of colour [13] and differences in the named parameters in relation to the reference sample that had results of the spectrophotometric measuring with the values: L^* = 19,1; a^* = −0,91; b^* = 1,2. After calculation of the named parameters the MacAdams ellipsoids have been constructed. Printing of samples has been done in real standardized conditions of temperature and humidity, and with exactly defined parameters of offset printing in the meaning of standardized making of printing form, quality of rubber blankets, value of fountain solution, and quality parameters of printing surface [14]. All the named parameters were within the allowed tolerance of printing.
Except for the named method of calculating MacAdams ellipsoids, in the paper a research was also conducted on the subjective experience of dark colours on printed samples, on a group of 140 observers of different age groups, which were slightly different by their colorimetric values, in order to be able to establish whether it is possible to valorise, using the MacAdams ellipsoids, the quality of printing in the area of small brightness, i.e. dark colours, and what is the correlation of colorimetric values and visual estimate of deviations in dark colours.

2.1 Methodology

Since the goal of this research is to establish the quality of print in the area of dark colours that very often appear on packaging materials as labels or direct imprint on the packaging, the research was conducted in real graphic production in the offset printing technique that is today one of the most used printing techniques in the production of labels. Samples for research were made so that imprints have been printed after the production parameters that affect the quality of imprint have been balanced in production (colour temperature, humidity, colour emulsifying etc.), whilst the imprints differ in entry raster-tone values of 2 %, 4 %, 6 % and 8 % of raster-tone value in order to achieve various nuances of dark colours. Shifts in dark colours have been made in the direction of blue (samples 1 ÷ 4), red (samples 5 ÷ 8), green (samples 9 ÷ 12) and yellow colour (samples 13 ÷ 16) in order to more easily find the correlation with CIE $L^*a^*b^*$ system that has exactly the four stated colours in four tone coordinates, 4 samples with small shifts in each of the named tone shifts were achieved, a total of 16 researched samples. All samples were printed in standardized conditions according to the international standard ISO 12647-2:2013 that defines parameters of separation of process colours, parameters of test imprint, and parameters of printing process [15].

Quality control of printing has been conducted using in-line densitometric measuring method with a control strip on which the fields of full tone as well as fields with defined 70 % raster-tone values were placed based on which a calibration of machine was done before printing in order to achieve controlled and standardized conditions [16]. The control strip used to establish the quality of print is shown in Fig. 1.

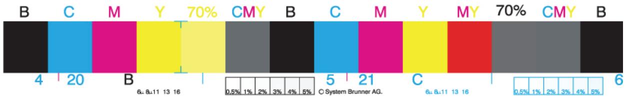

Figure 1 Control strip for measuring densitometric values

During printing standard process colours for offset print technique have been used. Samples have been printed on 80 g/m^2 printing surface with parameters corresponding to the technology of applying labels on packaging, as well as satisfying attributes during offset process of printing. Characteristics of printing surface are given in Tab. 1.

Table1 Technical characteristics of printing surface (testing conditions: ISO 187, 23 °C, 50 % relative humidity)

Characteristics	Standard	Unit	Tolerance
Substance	ISO 536	g/m^2	80 ± 3 %
Caliper	ISO 534	µm	65 ± 5 %
Brightness	ISO 2470, R457 D65	%	93 ± 2 %
Opacity dry	ISO 2471	%	88 ± 2 %
Gloss Lehmann	Tappi 480, 75°	%	60 ± 5 %
Smoothness Bekk	ISO 5267	Bekk sec.	1200
Cobb 60"	ISO 535	g/m^2	22 ± 4 %
Relative Humidity	Hygromer Rotronic	%	50 %

3 Results and discussion

Standardized printing process is in accordance with prescribed standards and values of colouring densities of process colours are within tolerance and shown in Tab. 2 [17].

Table 2 Values of colouring densities of researched imprints

Colouring densities of basic process colours of printing	D_i
C	1,61
M	1,53
Y	1,48
K	1,88

Sixteen test samples were measured by remission spectrophotometer X-Rite SpectroEye and its intrinsic error is typical 0,3 ΔE^* CIE $L^*a^*b^*$.

Measuring the colour tolerance by using CIE $L^*a^*b^*$ system was conducted by measuring each sample and comparison with the reference sample. After conducted measuring of 16 samples, the results of CIE $L^*a^*b^*$ values have been received as shown in Tab. 3.

Table 3 CIE $L^*a^*b^*$ sample values

Sample	L^*	a^*	b^*
1	19,89	4,15	0,66
2	17,40	8,27	1,70
3	18,01	8,23	0,92
4	18,37	7,09	2,28
5	20,86	−2,92	−4,29
6	19,42	0,83	−5,54
7	16,23	3,85	−6,78
8	14,61	−0,26	−1,11
9	21,77	−9,03	1,58
10	20,23	−9,14	3,38
11	19,91	−8,71	3,51
12	20,25	−9,38	3,37
13	21,04	−1,44	4,11
14	22,26	−3,47	8,98
15	22,76	−2,37	6,52
16	23,69	−3,09	8,39

Table 4 Differences of tone and chromaticity, and total difference of colour of samples according to reference sample with measured reference values L^* = 19,1; a^* = −0,91; b^* = 1,2

Sample	h	Δh	C^*	ΔC	ΔH	ΔE
1	0,16	0,76	4,20	2,70	1,33	5,15
2	0,20	0,72	8,44	6,94	1,77	9,35
3	0,11	0,81	8,28	6,78	1,97	9,21
4	0,31	0,61	7,45	5,94	1,42	8,11
5	0,97	0,05	5,19	3,68	0,10	6,11
6	1,42	0,50	5,60	4,10	1,02	6,97
7	1,05	0,13	7,80	6,29	0,32	9,72
8	1,34	0,42	1,14	0,37	0,39	5,09
9	0,17	0,75	9,17	7,66	1,92	8,56
10	0,35	0,57	9,74	8,24	1,52	8,59
11	0,38	0,54	9,39	7,88	1,42	8,18
12	0,34	0,58	9,97	8,46	1,56	8,82
13	1,23	0,31	4,35	2,85	0,56	3,54
14	1,20	0,28	9,63	8,12	0,75	8,78
15	1,22	0,30	6,94	5,43	0,68	6,62
16	1,22	0,30	8,94	7,43	0,77	8,80

For a better understanding of usability of MacAdams ellipsoids in the matter of defining the quality it has been necessary to calculate the changes in tone, chromaticity and brightness of the named samples, and for that purpose the values of tone h, chromaticity C^*, differences in relation to reference sample Δh and ΔC, Euclidean differences of tone ΔH and total differences of colour ΔE have been calculated. Calculation of the named values has been done according to the mathematical relations [18]:

$$h_1 = \arctan(b_1^*/a_1^*) \quad (1)$$

$$h_2 = \arctan(b_2^*/a_2^*) \quad (2)$$

$$C_1^* = [(a_1^*)2 + (b_1^*)2]1/2 \quad (3)$$

$$C_2^* = [(a_2^*)2 + (b_2^*)2]1/2 \quad (4)$$

$$\Delta h = h_1 - h_2 \quad (5)$$

$$\Delta C^* = C_1^* - C_2^* \quad (6)$$

$$\Delta H^* = 2(C_1^* C_2^*)1/2 \sin(\Delta h/2) \quad (7)$$

where a_1^*, b_1^*, h_1^*, C_1^* are values of reference sample, and a_2^*, b_2^*, h_2^*, C_2^* values of individual samples. Value ΔE^*_{00} is calculated according to mathematical model:

$$\Delta E^*_{00} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right) + \left(\frac{\Delta C'}{k_C S_C}\right) + \left(\frac{\Delta H'}{k_H S_H}\right) + R_T \cdot \frac{\Delta C' \Delta H'}{k_C S_C k_H S_H}}. \quad (8)$$

The k_L, k_C, and k_H are usually unity and in graphic industry the value is 1. By calculation of stated parameters, values shown in Tab. 4 have been obtained.

3.1 Constructing MacAdams ellipsoids

The obtained CIE $L^*a^*b^*$ values were used for the calculation of MacAdam ellipsoids, in which the program Mathcad was used according to the mathematical model [18]:

$$g_{11} = \frac{1}{a^2}\cos^2\Theta + \frac{1}{b^2}\sin^2\Theta, \quad (9)$$

$$g_{12} = \left(\frac{1}{a^2} - \frac{1}{b^2}\right)\sin\Theta \cdot \cos\Theta, \quad (10)$$

$$g_{22} = \frac{1}{a^2}\sin^2\Theta + \frac{1}{b^2}\cos^2\Theta, \quad (11)$$

where

$$\Theta < 90° \text{ when } g_{12} < 0 \quad (12)$$

$$\Theta > 90° \text{ when } g_{12} > 0 \quad (13)$$

$$\frac{1}{a^2} = g_{22} + g_{12}\cot\Theta, \quad (14)$$

$$\frac{1}{b^2} = g_{11} + g_{12}\cot\Theta, \quad (15)$$

for a - major semi-axis, b - minor semi-axis, Θ - angle in degrees.

The values of g_{11}, g_{12}, g_{22} are constant for each MacAdam ellipse, it is computed from the lengths a, and b of the major and minor semi-axis of each ellipse and the angle of inclination Θ of the major axis, to the axis of the x-coordinates as showed in Fig. 2.

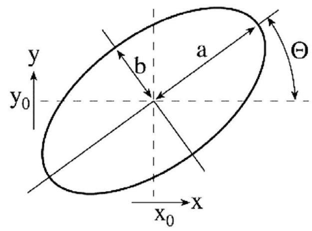

Figure 2 Major and minor semi-axis of ellipse

Since tested samples have been made in groups of four imprints with each having a small shift in colour toward one direction of CIE $L^*a^*b^*$ system, results and calculation of MacAdams ellipsoids have been made separately for each of the groups of imprints that are being shifted in some direction of CIE $L^*a^*b^*$ system.

The stated has been separated because it was necessary to establish whether overlapping of MacAdams ellipsoids occurs. Overlapping of ellipsoids signifies that there are areas that overlap in colorimetric values and the question is posed whether it is possible in such case to use MacAdams ellipsoids to establish a small difference in dark colours, where human eye is extremely limited in its subjective experience.

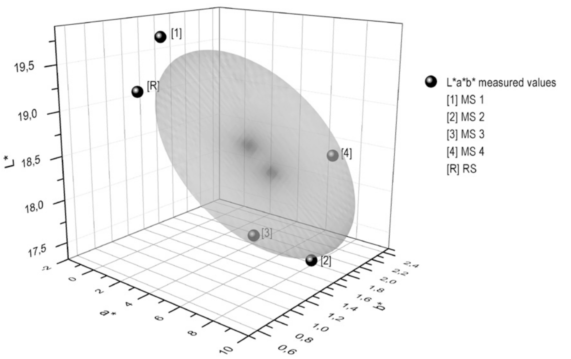

Figure 3 CIE $L^*a^*b^*$ values of samples 1÷4

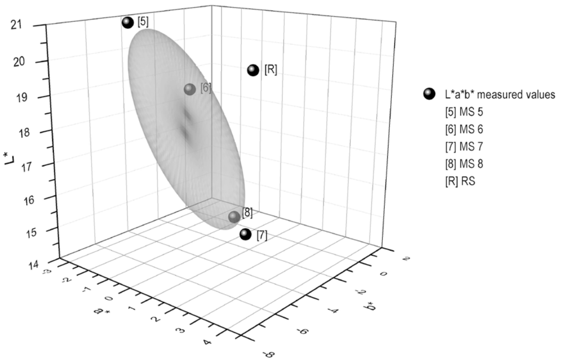

Figure 4 CIE $L^*a^*b^*$ values of samples 5÷8

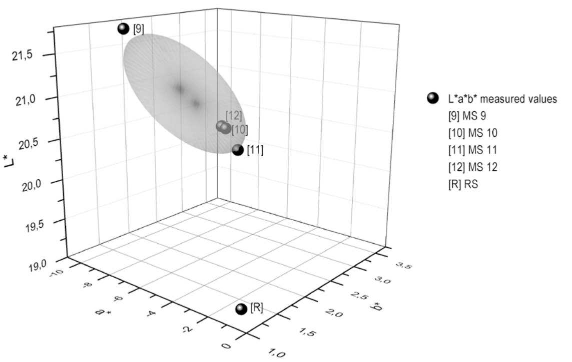

Figure 5 CIE $L^*a^*b^*$ values of samples 9÷12

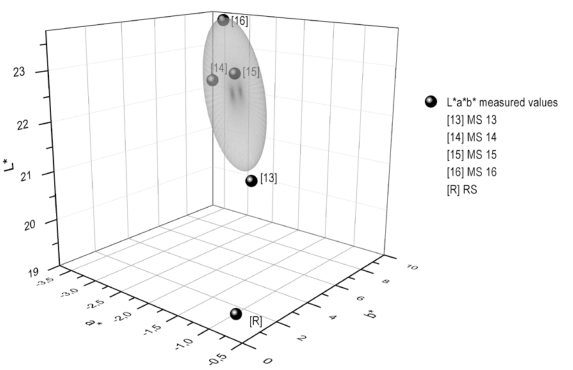

Figure 6 CIE $L^*a^*b^*$ values of samples 13÷16

After calculation, MacAdams ellipsoids were obtained as shown in figures 3-7. In each figure the value of reference sample (R) has been shown. Since the areas encompassed by MacAdams ellipsoids are in different areas of CIE $L^*a^*b^*$ system, presentation of CIE $L^*a^*b^*$ system is not identical for all samples, except in figure 7 where all ellipsoids are shown within one coordinate CIE $L^*a^*b^*$ system.

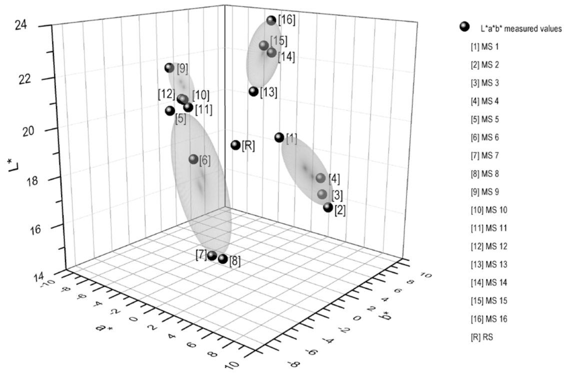

Figure 7 CIE $L^*a^*b^*$ values of all samples

By calculating and constructing MacAdams ellipsoids and placing ellipsoids within CIE $L^*a^*b^*$ system, it is visible that it is possible to use cover with ellipsoids the area that represents the colorimetric values of imprints situated in shifts toward some of the colours of CIE $L^*a^*b^*$ system. In order to establish whether overlapping of colorimetric values occurs, when observing Fig. 7 in which all MacAdams ellipses are constructed, it is visible that no overlapping of ellipsoids occurs. This data is scientifically interesting due to the reason that by no overlapping of ellipsoids the areas are defined that are directly connected to shifting toward one of the four named colours. From a scientific standpoint this data leads to sense that there could be differences between size of ellipsoids and in other areas of CIE L*a*b* system, i.e. when other colours with small shifts are observed.

3.2 Visual estimate of quality

In order to establish correlation between colorimetric measuring and construction of MacAdams ellipsoids and visual estimate in order to establish whether an average observer sees the stated changes in colours [19], a research of subjective estimate has also been conducted in a way that samples were given to a group of 140 observers who, in standard conditions of observation in laboratory with lighting D_{50} and strength of lighting on surface of imprint of 2000 Lx, were supposed to estimate which of the named imprints has a shift toward certain colour and whether observers even see the small shifts in dark colours. Observers have according to priorities separated imprints that have been graded with points according to frequency of separation and the results are shown in Fig. 8 in which samples with more points have a larger similarity toward reference sample.

The goal of the conducted research was to establish whether observers see differences in colours, which this research has proven. However, the results of the research have proven that observers do not see small differences in dark colours equally toward all shifting in colours, which can pose a problem for establishing the quality of dark colours when printing considering the problems in inequality of inflow of colour in printing and oscillations in quality of print. What is important for this research is the fact that, among all the imprints, observers see the differences, except in three pairs of samples for which results are the same (samples 3 and 9, 10 and 11, and 12 and 16). However, when the results of researching visual estimate are compared with values of differences in colour from Tab. 4, it is visible that values of differences in colour surpass the allowed tolerance as shown in table 5, except in sample 13 where that value is within tolerance. However, through subjective estimate of differences in colours and in sample 13 the observers have seen a difference in colour, which poses a problem that can lead to different interpretations of quality between orderer and producer that makes the imprints according to international quality standard [13].

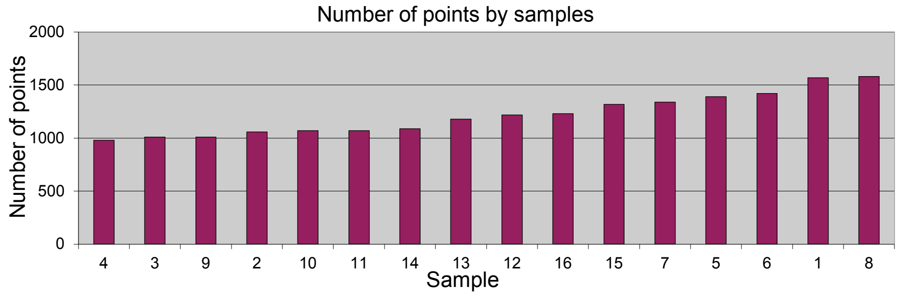

Figure 8 Presentation of subjective estimate of observers

Table 5 Values and tolerance of ΔE differences of colour

Value Δ*E*	Tolerance
<1	Average human eye does not see the difference
1÷2	Very small difference, difference optimal
2÷3,5	Moderate difference
3,5÷5	Difference
5>	Large difference

4 Conclusion

Printing of dark colours in graphic industry represents one extremely important segment considering the very common use of dark colours, especially in printing packaging. Through research conducted in this paper we tried to establish whether it is possible to define the quality of printing by MacAdams ellipsoids, except for the already existing methods by which it is very difficult to establish small differences in dark colours [20].

By constructing MacAdams ellipsoids it is possible to get an area of accepted values within CIE $L^*a^*b^*$ system according to specific criteria. What posed a problem for which it was not clear whether it will appear before the conducted research was that overlapping of MacAdams ellipsoids could have occurred, which means we would get an area that satisfies shifting in two colours that people experience in the same way. Such research results would in praxis mean that a shift in one colour could appear, and the end-purchaser sees this change as a change in another colour, which is an extremely sensitive area in experiencing dark colours considering the insensibility of cells by small entry spectral reflection (< 30 Lx), i.e. reduced sensitivity with very small reflections which happen in dark colours.

Through research in this paper it was proven that there is no overlapping in MacAdams ellipsoids, which allows us to conclude that when establishing quality of dark colours the MacAdams method can be used. This paper sets the foundations for establishing usability of MacAdams ellipsoids, and further research will establish whether MacAdams ellipsoids can be used for other colours as well, but also for printing techniques in which small changes in colour occur, which can violate the quality of the product.

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