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# Optimiziranje tiskanja tkanin z uporabo statističnega programa za načrtovanje poskusov

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## *Optimization of printing using a statistical design of experiment*

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## Abstract

*This research on optimizing the printing of cotton fabrics with vat dyes was based on using a statistical design of experiment. The aim was to achieve prints with high colour values (K/S) by determining optimal conditions for printing. 100% cotton fabric was printed with Bezathren bordo RR vat dye purchased from Bezema, Switzerland. A screen printing technology with a two phase procedure was used. Following conditions were changed during printing: viscosity of the printing paste, the screen mesh, the diameter of the magnetic-rod squeegee and the number of passes of the squeegee. Thirty trial experiments, suggested by the statistical design of experiment used for printing process optimization, were performed. The CIELAB and K/S values of printed samples were measured spectrophotometrically. The obtained values were statistically processed by using Design-Expert (v. 6.0.8) statistical software. Experimental data analysis confirmed the existence of a quadratic model that describes a relationship between variables and experimental results. Parameters showing the greatest influence on K/S were determined after analysing the variance*

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## Izvleček

Raziskava vključuje optimizacijo tiskanja bombažnih tkanin z redukcijskimi barvili z uporabo statističnega programa za načrtovanje eksperimentov. Namen raziskave je bil poiskati pogoje, pri katerih dobimo odtise z najvišjimi možnimi barvnimi vrednostmi (*K/S*). V raziskavi je uporabljena 100 % bombažna tkanina. Tiskali smo z redukcijskim barvilom Bezathren bordo RR firme Bezema iz Švice. Tiskanje je potekalo s tehniko ploskega tiska po dvofaznem postopku. Pri tem smo spreminjali naslednje pogoje tiskanja: viskoznost tiskarske paste, finost šablone, debelino tiskarskega noža in število prehodov tiskarskega noža. Izvedli smo 30 eksperimentov, ki nam jih je predpisal statistični program za optimizacijo procesa tiskanja. Potiskanim vzorcem smo izmerili vrednosti CIELAB in *K/S* ter jih vnesli v računalniški program za statistično obdelavo Design-Expert (v. 6.0.8). Na osnovi eksperimentalnih podatkov je program izdelal regresijski model, ki opisuje zvezo med spremenljivkami in odgovorom eksperimenta. Po opravljeni analizi sipanja (ANOVA) za predlagani regresijski model smo določili pogoje, ki imajo največji vpliv na končno vrednost *K/S*. Ti pogoji so: viskoznost tiskarske paste, ki ji sledita število prehodov tiskarskega noža in finost šablone, medtem ko ima premer tiskarskega noža najmanjši vpliv. Vrednosti za globino barvnega tona, ki jih program napove, se dobro ujemajo z realiziranimi izmerjenimi vrednostmi.

Ključne besede: redukcijska barvila, tiskanje, optimizacija, viskoznost, barvne vrednosti, globina barve.

*(ANOVA) of the quadratic model. The parameters with the greatest effect on K/S were the viscosity of the printing paste, which is followed by the number of passes of the squeegee and the screen mesh, while the diameter of the squeegee has the lowest influence. Predicted and actual colour depth values correlated well.*

*Key words: vat dyes, printing, optimization, viscosity, colour values, colour depth.*

## 1 Introduction

*Screen printing is the most widely used textile printing technique today. This technique uses a screen as a printing form, which consists of a frame and synthetic gauze (stencil) stretched over it. The areas with the design are permeable to the printing paste, whereas the areas without the design are impermeable to the printing paste and are covered with a crosslinked polymer film, which is insoluble in water. The printing paste is forced through the design areas by using a printing blade or squeegee in such a way that paste spreads over the fabric lying under the screen during printing. In order to produce qualitative prints on textiles, it is necessary to harmonize many factors, which depend on the type and structure of the material, the device used, the type of dyes, the fineness of the stencil and other properties of the printing materials and equipment. Such factors include printing paste viscosity, printing paste particle size, fineness of the stencil, diameter of the squeegee, squeegee pressure, number of passes of the squeegee, etc.*

*A great amount of experience is necessary in order to be able to select the proper conditions and to achieve a suitable quality of printing. Since there is no comprehensive analysis of screen printing available, it is necessary to carry out a great number of experiments prior to achieving the desired result. The purpose of our research was to define the influence of printing conditions on a selected fabric in the laboratory using a computer-aided statistical design for the experiment. In this way the amount of required work is reduced, and the influence of particular factors on the quality of printing can be verified. [1].*

# 1 Uvod

Filmski tisk je danes najpogosteje uporabljena tehnika tiskanja tekstilij. Pri filmskem tisku je tiskovna forma šablona, ki sestoji iz okvirja, na katerem je napeta sintetična gaza. Vzorčna mesta so prepustna za tiskarsko pasto, medtem ko so nevzorčna mesta zanjo neprepustna in so prekrita z nevodotopnim zamreženim polimernim filmom. Skozi vzorčna mesta tiskarsko pasto potiskamo s tiskarskim nožem ali raklom, tako da se prelije na blago, ki leži med tiskanjem pod šablono. Za doseganje kvalitetnih odtisov na tekstilijah je pri filmskem tisku treba uskladiti številne dejavnike, ki so odvisni od vrste in strukture materiala, strojne naprave, vrste barvil, finosti vzorca ter drugih lastnosti tiskovnih materialov in opreme. Pomembnejši dejavniki so: viskoznost tiskarske paste, velikost delcev v pasti, finost šablone, premer tiskarskega noža, sila pritiska tiskarskega noža, število prehodov tiskarskega noža, hitrost prehodov tiskarskega noža in drugi.

Veliko izkušenj je potrebnih, da izberemo prave pogoje in dosežemo ustrezno kvaliteto tiska. Ker kompletna analiza filmskega tiska ne obstaja, je pogosto treba narediti veliko število poizkusov, da pridemo do želenega rezultata. Zato je bil namen naše raziskave definirati pogoje tiskanja na izbrano blago v laboratoriju s pomočjo računalniškega statističnega načrtovanja, s katerim bi si skrajšali delo in natančneje preverili vpliv nekaterih dejavnikov na kvaliteto tiska [1].

Za optimizacijo pogojev tiskanja smo uporabili statistični program za načrtovanje eksperimentov Design-Expert (v. 6.0.8). Optimizacija procesa tiskanja temelji na centralnem eksperimentalnem načrtu – central composite design (CCD). Program omogoča preučevanje vpliva neodvisnih spremenljivk (v našem primeru finosti šablone, premera tiskarskega noža, viskoznosti tiskarske paste in števila prehodov tiskarskega noža) na odvisno spremenljivko (v našem primeru vrednost K/S oz. globino barvnega tona).

Eksperimentalni načrt za štiristopenjski faktorski načrt predpisuje 30 eksperimentov. Naš eksperiment je vključeval tri variacije za vsak posamezen faktor (neodvisno spremenljivko), in sicer premer tiskarskega noža: 6 mm, 8 mm in 10 mm; finost šablone: 43 niti/cm, 55 niti/cm in 68 niti/cm; viskoznost tiskarske paste: 0,44 Pas, 1,09 Pas in 1,75 Pas; število prehodov tiskarskega noža: enkrat, dvakrat in trikrat. Za analizo dobljenih vrednosti K/S smo uporabili test analize sipanja (ANOVA).

Centralni eksperimentalni načrt poleg analize in grafičnega prikaza rezultatov omogoča tudi numerično, grafično in točkovno optimizacijo pogojev tiskanja.

## *1.1 Redukcijska barvila*

Redukcijska barvila za tiskanje tekstilij spadajo po pomembnosti šele na četrto mesto. Največ se uporabljajo pigmenti, potem reaktivna barvila, tretja pa so disperzna barvila. Redukcijska barvila uporabljamo predvsem za tiskanje celuloznih vlaken in mešanice PES/bombaž. Odlikujejo se po dobrih mokrih in svetlobnih ob-

*For the optimization of the printing conditions the statistical Design-Expert software (v. 6.0.8) was used. The optimization of the printing process is based on central experimental design – central composite design (CCD) software. This software enables the investigation of the influence of independent variables (in our case, the fineness of the stencil, the diameter of the squeegee, the printing paste viscosity and the number of passes of the squeegee) on a dependent variable (in our case the K/S value or the color hue depth).*

*The experimental design prescribes 30 experiments for a four-level factorial design. Our experiment involved three levels for each individual factor (independent variable), i.e., the diameter of squeegee: 6 mm, 8 mm and 10 mm; the fineness of the stencil: 43 threads/cm, 55 threads/cm and 68 threads/cm; the printing paste viscosity: 0.44 Pas, 1.09 Pas and 1.75 Pas; the number of passes of the squeegee: one, two and three. The analysis of variance (ANOVA) was used for analyzing the K/S values obtained. In addition to the analysis and graphic presentation of the results, the central experimental design also enables numerical, graphic and point optimization of the printing conditions.*

### 1.1 Vat Dyes

*Vat dyes are ranked fourth among textile printing dyes, after pigments, which are ranked first, reactive dyes, which are ranked second, and disperse dyes, which are ranked third. Vat dyes are mainly used for printing cellulose fibers and PES/cotton blends. They are distinguished for their good wet and light fastness. With regard to their chemical composition, vat dyes belong to the following three types: indigoid, thioindigoid and anthraquinone vat dyes. Each of them contains one or more carbonyl groups.*

*It is typical for vat dyes to be water-insoluble, and as such they do not have affinity to fibers. To impart to them an affinity to fibers, vat dyes must be previously reduced to the water-soluble leuco form (leuco salt). This reaction proceeds in the setting phase during steaming. As a result, dyes diffuse into fibers in the water-soluble form. By hydrolysis, which proceeds during scouring with water, and by oxidation, which proceeds in peroxide liquor, the water-solu-*

stojnostih. Glede na kemično sestavo ločimo tri vrste redukcijskih barvil: indigoidna, tioindigoidna in antrakinonska. Vse tri vrste vsebujejo eno ali več karbonilnih skupin.

Značilno za redukcijska barvila je, da v vodi niso topna in kot taka nimajo afinitete do vlaken. Da barvila dobijo afiniteto do vlaken, jih moramo predhodno reducirati v vodotopno levko obliko (levko sol). Ta reakcija poteče pri fazi fiksiranja, med parjenjem. Barvilo tako difundira v vlakno v vodotopni obliki. S hidrolizo, ki poteče pri spiranju z vodo, in z oksidacijo, ki poteče v peroksidni kopeli, pretvorimo barvilo zopet iz vodotopne v nevodotopno obliko.

Glede na to, ali sta reducent in alkalija prisotna v tiskarski pasti, ločimo dva postopka:

– enofazni ali rongalit/pepelika postopek,
– dvofazni postopek.

Pri dvofaznem postopku tiskanje poteka v dveh fazah. V prvi fazi blago potiskamo z barvilom in zgostilom ter ga nato sušimo. V drugi fazi pa ga impregniramo z raztopino alkalije in reducenta ter naknadno parimo. Tako potiskano blago je pred fiksiranjem manj občutljivo na zunanje dejavnike. Ker ne vsebuje reducenta, ga lahko manj ostro in počasneje sušimo, posušeno blago pa lahko daljši čas odleži pred fiskiranjem [2].

### 1.2 Viskoznost tiskarskih past

Od viskoznosti tiskarske paste sta odvisna nanos paste na blago ter širjenje paste po površini blaga in v njegovo notranjost. Viskoznost mora biti prilagojena površinski strukturi blaga, pogojem tiskanja in zahtevani ostrini odtisov. Vsi tekstilni substrati sestojijo iz skupkov vlaken, prostor med vlakni, posebno kadar so vlakna zložena vzporedno in se stikajo, pa ima dimenzije in lastnosti kapilar. Tekočine, ki omakajo vlakna, se kapilarno širijo vzdolž teh vmesnih prostorov. Ustrezna viskoznost paste omeji kapilarno širjenje, s čimer zagotovi ostrino odtisov.

Določeno širjenje paste je neizogibno in celo zaželeno, vendar mora biti kontrolirano. Viskozne lastnosti dajejo pastam različne snovi, ki jih imenujemo zgostila. Izbira zgostila pa ne vpliva le na viskoznost paste, temveč – zaradi njegovih fizikalno-kemijskih lastnosti – tudi na barvno izdatnost tiskov. Tiskarske paste vsebujejo povprečno 50 % zgostila, zato je njihovo obnašanje pri tiskanju v veliki meri odvisno od zgostil, zlasti od njihove viskoznosti oziroma spremembe viskoznosti pod vplivom strižne napetosti.

Viskoznost ali dinamična viskoznost η ($kgm^{-1}s^{-1}$ oz. Pas) je fizikalna količina, ki podaja odziv tekočine na strižno deformacijo. Določena je kot razmerje med strižno napetostjo in strižno hitrostjo ter podaja notranje trenje tekočin. V idealnih tekočinah je viskoznost konstantna ter je neodvisna od strižne napetosti in gradienta strižne hitrosti. Te tekočine imenujemo newtonske [3]. Viskoznost newtonskih tekočin je podana z razmerjem strižne napetosti in strižnega gradienta (enačba 1):

$$\eta = \delta / D;\ \text{pri tem je}\ \delta = F/S\ \text{in}\ D = dv/dx \quad (1)$$

*ble form is converted into the water-insoluble form.*

*The following two procedures are used depending on whether a reducing agent and alkali are present in the printing paste:*

*– single-stage or rongalite/potash procedure,*

*– two-stage procedure.*

*In the two-stage procedure, printing is performed in two stages. In the first stage a fabric is first printed with dye and a thickening agent and then dried. In the second stage a fabric is impregnated with a solution of alkali and a reducing agent and subsequently steamed. This procedure offers less complex drying and provides the possibility of delayed steaming [2].*

### 1.2 Printing Paste Viscosity

*Application of printing paste on a fabric, and its spreading over the fabric surface and into it, depend on the viscosity of the printing paste. An upper limit of viscosity is determined by the fabric surface structure and printing conditions. A lower limit of viscosity is determined by the printing conditions and by the required sharpness of the prints. All textile substrates consist of fiber assemblies; the spaces between the fibers have dimensions and properties of capillaries, particularly when fibers are arranged horizontally and touch each other. Fiber wetting liquids spread by capillary action along these interspaces, which results in unsharpness of prints if the viscosity of the printing paste is not high enough to confine spreading.*

*Although a certain degree of printing paste spreading is inevitable and even desired, it must be controlled. Various agents, the so-called thickening agents, impart viscous properties to printing pastes. However, in addition to the viscosity of the printing paste, a thickening agent with its physical and chemical properties also influences the color yield of prints. Since printing pastes contain 50% of a thickening agent on average, their behavior during printing highly depends on the thickening agents, especially on their viscosity or the change of their viscosity under the influence of shear stress.*

*Viscosity or dynamic viscosity η (kg $m^{-1}$ $s^{-1}$ or Pas) is a physical parameter, which denotes the reaction of a fluid to shear strain. It is defined as the ratio of shear stress to shear rate and de-*

kjer $\eta$ predstavlja viskoznost (Pas), $\delta$ strižno napetost (N/$m^2$, Pa), $D$ strižni gradient ($s^{-1}$), $F$ strižno silo (N), $S$ površino, na katero deluje strižna sila ($m^2$), in $dv/dx$ spremembo hitrosti po površini ($s^{-1}$).
Tiskarske paste spadajo v skupino nenewtonskih tekočin. Pri teh viskoznost ni konstantna, temveč je funkcija gradienta strižne hitrosti, $dv/dx$, v nekaterih primerih pa tudi strižnega časa. Za večino tiskarskih past je značilno psevdoplastično, plastično in tiksotropno obnašanje [2, 3].

### 1.3 Statistični program za načrtovanje eksperimentov – central composite design (CCD)

Za uspešno izvedbo eksperimenta moramo opraviti naslednje tri korake:

– načrtovanje,

– izvršitev in

– interpretacija podatkov oziroma analiza le-teh [4].

#### 1.3.1 Metoda ustreznih površin

Metoda ustreznih površin (*angl*. response surface method, RSM) je primerna, kadar imamo kvantitativne neodvisne spremenljivke in želimo na podlagi teh spremenljivk oceniti (napovedati) vrednosti odvisnih spremenljivk. Ugotavljamo statistično značilnost in stopnjo povezanosti med posameznimi spremenljivkami ter napovedujemo vrednosti odvisne spremenljivke. Vpliv vsake od neodvisnih spremenljivk je ocenjen tako, da je neodvisen od medsebojnih vplivov neodvisnih spremenljivk. Program bo tako v model vključeval po eno neodvisno spremenljivko po vrstnem redu glede na velikost vpliva na odvisno spremenljivko.

RSM je zelo uporaben za optimizacijo procesov, kot je npr. tiskanje, pri katerem želimo doseči optimalno barvno globino odtisov ($K/S$) ob prilagajanju različnih pogojev dela.

Omogoča raziskovanje linearnih vzročnih povezanosti med eno odvisno spremenljivko (v našem primeru je to $K/S$) in eno ali več neodvisnimi spremenljivkami (finost šablone, premer tiskarskega noža, viskoznost tiskarske paste, število prehodov tiskarskega noža itd.).

Optimizacija procesa temelji na centralno sestavljenem načrtu eksperimentov (*angl*. central composite design, CCD) in računalniško podprti linearni regresiji. Analiza obsega vrednotenje načrta eksperimentov in regresijskih modelov. Načrt podpirajo različne cenilke regresijske matrike, medtem ko analiza regresijskih modelov vključuje analizo sipanja, aproksimativne polinome in površine odgovora.

CCD je eden od najbolj priljubljenih RSM-načrtov. Paket CCD predstavlja sistem postopkov, namenjenih analizi podatkov, ki jih povezuje uporabniški vmesnik. Omogoča menijsko ali ukazno vodenje obdelav.

Osnovni koraki v analizi podatkov s CCD:

– zagon CCD,

– priprava podatkov,

*scribes internal friction between fluids. The viscosity of ideal fluids is constant and independent of shear stress and the shear rate coefficient. Such fluids are called Newtonian fluids [3]. The viscosity of Newtonian fluids is denoted by the ratio of shear stress to shear gradient (Equation 1):*

*$\eta$ is the viscosity (Pas), $\delta$ is the shear stress (N/m$^2$, Pa), D is the shear gradient (s$^{-1}$), F is the shear force (N), S is the surface on which shear force is acting (m$^2$), and dv/dx is the change of rate over the cross section (s$^{-1}$).*

*Printing pastes typically belong to the group of non-Newtonian fluids. The viscosity of these fluids is not constant and is the function of a shear rate gradient, dv/dx, and in some cases even of the time of shear. Pseudoplastic, plastic and thyxotropic behavior is characteristic of most printing pastes [2, 3].*

### 1.3 Statistical Design of Experiments Software – Central Composite Design (CCD)

*In order to successfully accomplish the experiments, the following three steps must be taken:*
- *designing,*
- *implementation, and*
- *data interpretation and/or analysis [4].*

#### *1.3.1 Response Surface Method*

*The response surface method (RMS) is appropriate when quantitative independent variables are available and we want to evaluate (predict) the values of dependent variables on that basis. We identify a statistical feature and the strength of the relation between the individual variables, and we predict the values of a dependent variable. The influence of each independent variable is evaluated independently of the interactions between the independent variables. Thus, the software will enter independent variables into the model one by one by considering the influence of each of them on a dependent variable.*

*RSM is a highly useful method for the optimization of processes, such as printing, where we want to achieve the highest color depth of prints (K/S) along with adjusting various conditions of the work.*

*It enables investigation of linear design relations between one dependent variable (in our case*

- izbor in zagon postopka ter
- pregled rezultatov (ANOVA, urejevalnik grafikonov, prenos rezultatov obdelav v druge aplikacije, napovedovanje itd.).

Pri izdelavi načrta CCD upošteva tri skupine točk:

a) točke za dvostopenjski faktorski ali delni faktorski načrt (*angl.* two-level factorial or fractional factorial design points),
b) osne točke (zvezdne točke; *angl.* axial points, „star“ points),
c) središčna točka (*angl.* center point).

Število eksperimentov (N) se izračuna po enačbi 2. V primeru štiristopenjskega faktorskega načrta je predvideno število eksperimentov 30. V to število je zajetih 6 ponovitev središčne točke, 16 poskusov na faktorskih točkah in 8 poskusov na zvezdnih točkah.

$$N = 2^n + 2n + 6 = 30 \text{ eksperimentov; } n = 4 \tag{2}$$

Pri tem je:
N … število eksperimentov, ki jih je treba opraviti,
n … število faktorjev načrta.

Po opravljeni analizi sipanja (ANOVA) za predlagani regresijski model bodo izločene tiste spremenljivke modela, ki niso statistično značilne, tj. so manjše od statističnega zaupanja S = 95 % (oz. večje od $p > 0{,}05$, kot se izražajo v anglosaškem svetu).

CCD poleg statistične analize in grafičnega prikaza rezultatov omogoča še numerično, grafično in točkovno optimizacijo procesnih pogojev.

Z numerično optimizacijo dobimo niz možnih rešitev na podlagi izbrane ciljne vrednosti posameznega faktorja ali odgovora. Z grafično optimizacijo napovemo optimalno območje delovanja za posamezen faktor, v katerem so najverjetnejši odgovori. Točkovna optimizacija se uporablja za napovedovanje odgovora glede na spreminjanje pogojev posameznega faktorja [5].

## 2 Eksperimentalni del

### 2.1 Materiali

Uporabili smo 100 % bombažno tkanino, v vezavi keper, s površinsko maso 294 g/m$^2$, gostoto votka 29 niti/cm in gostoto osnove 54 niti/cm. Tkanina je bila izdelana v tovarni Tekstina d. d. v Ajdovščini.

Tiskali smo z redukcijskim barvilom Bezathren bordo RR firme Bezema iz Švice [1].

Za pripravo tiskarskih past in vezanje (fiksiranje) barvil na vlakna smo uporabili naslednje kemikalije:
- Boraks dekahidrat (Belinka, Slovenija): dinatrijev tetraborat dekahidrat,
- Cotoblanc RS (CHT, Nemčija): koloidni sistem na osnovi anorganskih soli,
- Prisulon CMS 10 (Bezema, Švica): zgostilo, karboksimetiliran škrob,

*the K/S value) and one or more independent variables (fineness of stencil, diameter of squeegee, printing paste viscosity, number of passes of squeegee, etc.).*

*The optimization of the process is based on central composite design (CCD) and computer-aided linear regression. The analysis involves the evaluation of the design of experiments and regression models. Various regression matrix estimators support the design, whereas the analysis of regression models includes analysis of variance, polynomial approximation and response surfaces.*

*CCD is one of the most popular RSM-designs. A CCD package includes a system of procedures for data analysis, which are linked by a user interface. It enables menu- or command-driven data processing.*

*Basic steps of the data analysis by using the CCD software package:*

*– CCD start-up,*
*– data preparation,*
*– procedure selection and start-up, and*
*– review of results (ANOVA, graph editor, transfer of processing results to other applications, predicting, etc.).*

*When creating a design, CCD takes into account three groups of points:*

*a) two-level factorial or fractional factorial design points,*
*b) axial points (»star« points), and*
*c) a center point.*

*The number of experiments (N) is calculated by using Equation 2. Thirty experiments are anticipated for a four-level factorial design. This number encompasses 6 repeats of a center point, 16 experiments on factorial points and 8 experiments on "star" points. (Equation 2)*

*where N is the number of experiments to be conducted, and n is the number of design factors.*

*After the analysis of variance (ANOVA) has been completed for the proposed regression model, statistically uncharacteristic variables of the model, i.e., variables which are bellow the statistical confidence interval S = 95% (or higher than p > 0.05, as expressed in the Anglo-Saxon territory), are eliminated.*

*In addition to the statistical analysis and graphic presentation of the results, CCD provides nu-*

– Prisulon 530 R (CHT, Nemčija): zgostilo, mešanica polisaharidov,
– Rapidoprint SC 10 (Bezema, Švica): alifatska hidroksi spojina,
– Rapidoprint H4 (CHT, Nemčija): specialno mineralno olje v kombinaciji z emulgatorji,
– Redulit C (CHT, Nemčija): derivat sulfinske kisline, redukcijsko sredstvo,
– Subitol LS-N (CHT, Nemčija): omakalno-pralno sredstvo, mešanica površinsko aktivnih snovi,
– Vodikov peroksid (Belinka, Slovenija) $H_2O_2$ 35 %, oksidacijsko sredstvo.

## 2.2 Analize

Viskoznost tiskarskih past smo izmerili na laboratorijskem viskozimetru RheolabQC proizvajalca Anton Paar iz Avstrije, in sicer pri temperaturi 24,3 °C v območju strižne hitrosti do 300 obratov/s.

Barvne vrednosti smo merili na dvožarkovnem spektrofotometru Datacolor International Spectraflash SF 600 PLUS CT pri naslednjih pogojih:

– velikost merilne odprtine: LAV 9 mm,
– standardizirana svetloba: D65,
– standardni opazovalec: 10°,
– geometrija osvetlitve in opazovanja: d/0,
– število plasti tkanine: 4 plasti,
– število meritev: 5 meritev na enem vzorcu.

Barvno globino ali vrednost *K*/*S* smo izračunali po enačbi Kubelka-Munk [6] (enačba 3):

$$K/S = \frac{(1-R)^2}{2R} \quad (3)$$

V njej je:
*K* … absorpcija svetlobe,
*S* … sipanje svetlobe,
*R* … refleksija svetlobe (vrednosti 0–1).

Stopnjo pretiska, *P*, ki pove, kolikšen delež barvila je prešel na hrbtno stran tkanine, smo izračunali po naslednji enačbi (enačba 4):

$$P = \frac{K/S_{back}}{(0.5 \times [K/S_{front} \times K/S_{back}])} \times 100\ [\%] \quad (4)$$

Ostrino odtisov na potiskanih vzorcih smo ocenili na osnovi merjenja širine odtisnjenih črt s povečevalnim steklom z vgrajenim merilnim trakom dolžine 10 mm. Širino odtisnjene črte je bilo možno odčitati do 0,1 mm natančno.

*merical, graphic and point optimization of processing conditions.*

*Numerical optimization provides a series of optional solutions on the basis of the selected target value of an individual factor or response. By graphic optimization it is possible to predict the optimal range of activity for each individual factor, which contains the most probable responses. Point optimization is used for response predicting with regard to the changing conditions of each individual factor [5].*

## 2 Experimental

### 2.1 Materials

*The experiments were performed on 100% cotton fabric, supplied by Tekstina d.d., Slovenia. The fabric was industrially desized, scoured, bleached and mercerized. Fabric specifications were: weight 294 g $m^{-2}$, warp 54 threads $cm^{-1}$, weft 29 threads $cm^{-1}$.*

*Vat dye Bezathren bordo RR from Bezema (Swiss) [1] was used for printing.*

*The chemicals used for printing paste preparation were:*

- *Borax decahydrate (Belinka, Slovenia): disodium tetraborate decahydrate,*
- *Cotoblanc RS (CHT, Germany): washing-dispersing agent*
- *Prisulon CMS 10 (Bezema, Swiss): thickener, carboxymethyl starch,*
- *Prisulon 530 R (CHT, Germany): thickener, polysaccharide mixture,*
- *Rapidoprint SC 10 (Bezema, Swiss): aliphatic hydroxy compound,*
- *Rapidoprint H4 (CHT, Germany): special mineral oil,*
- *Redulit C (CHT, Germany): reduction agent,*
- *Subitol LS-N (CHT, Germany): washing-dispersing agent,*
- *Hydrogen peroxide (Belinka, Slovenija) $H_2O_2$ 35 %, oxidizing agent.*

### 2.2 Analysis

*The rheological properties of the printing pastes were measured on a rheometer RheolabQC from Anton Paar (Austria) at 24.3 °C and at shear rates up to 300 $s^{-1}$.*

*The color properties were determined by a Datacolor Spectraflash® SF 600 PLUS-CT spectro-*

### 2.3 Tiskanje

Po recepturah, prikazanih v preglednici 1, smo pripravili osnovna zgostila z različno vsebnostjo suhe snovi (Prisulon 530 R) in posledično z različno viskoznostjo.

Tiskarske paste smo pripravili tako, da smo ustrezno količino prahastega barvila in pomožnih sredstev dodali v pripravljeno osnovno zgostilo po recepturi, prikazani v preglednici 2. Osnovno zgostilo je bilo pripravljeno najmanj dve uri pred izdelavo tiskarske paste, tako da je zgostilo nabreknilo v polni meri. Pripravili smo tri tiskarske paste, z vsakim osnovnim zgostilom po eno, z viskoznostmi 0,44 Pas, 1,09 Pas in 1,75 Pas, pri strižni hitrosti 53,4 $s^{-1}$.

*Table 1: Stock pastes with different quantities of a dry thickener*

| Ingredient | Stock paste 1(g) | Stock paste 2 (g) | Stock paste 3 (g) |
|---|---|---|---|
| Prisulon 530 R | 40 | 50 | 60 |
| $H_2O$ demin. | 960 | 950 | 940 |
| Σ | 1000 | 1000 | 1000 |

*Table 2: Recipes of printing pastes*

| Ingredient | Quantity (g) |
|---|---|
| Stock paste | 550 |
| Rapidoprint SC 10 | 3 |
| Rapidoprint H4 | 20 |
| Bezathren bordo RR | 30 |
| $H_2O$ demin. | Y |
| Σ | 1000 |

Tiskali smo na laboratorijski magnetni tiskarski mizi Mini MDF R390, J. Zimmer, Avstrija, pri stopnji magnetne sile 2 in hitrosti tiskarskega noža 80 %. Tiskali smo z magnetnimi valjčnimi tiskarskimi noži premera 6 mm, 8 mm in 10 mm, in to z enkratnim, dvakratnim in trikratnim prehodom tiskarskega noža. Uporabili smo šablone finosti 43 niti/cm, 55 niti/cm in 68 niti/cm.

Potiskane vzorce smo sušili eno minuto pri 110 °C na laboratorijskem razpenjalno-sušilnem stroju firme Benz iz Švice. Posušene, potiskane vzorce smo impregnirali na laboratorijskem dvovaljčnem fularju s 100 % ožemalnim učinkom. Sestava impregnirne kopeli je prikazana v preglednici 3. Za pripravo impregnirne kopeli smo uporabili demineralizirano vodo.

Takoj po impregniranju smo vzorce parili na laboratorijskem parilniku DHE 20675 švicarskega proizvajalca Werner Mathis AG, in sicer 8 minut pri temperaturi 102 °C v nasičeni pari.

*photometer, under illuminant D65 using the 10° standard observer, d/8° measurement geometry and a measurement area of 20 mm in diameter. Five measurements were done on each sample.*
*The color strengths (expressed as K/S value) were calculated by the Kubelka-Munk equation (Equation 3):*
*where K represents the absorption, S the scattering and R the reflection of light.*
*Penetration was calculated by Equation 4. It represents the rate of the dye on the back side of the fabric. (Equation 4)*
*The sharpness of the prints were estimated by measuring of the width of printed lines at 0.1 mm accuracy.*

### 2.3 Printing

*Table 1 represents the recipes for stock pastes with different quantities of dry thickener (Prisulon 530 R) and consequently with different viscosities.*
*Printing pastes were prepared by addition of a dry vat dye and auxiliaries into the stock pastes as represented in Table 2. Three printing pastes were prepared from three different stock pastes with final viscosities of 0.44 Pas, 1.09 Pas and 1.75 Pas, at a shear rate of 53.4 $s^{-1}$.*
*Printing was performed on the laboratory flat screen printer Mini MDF R-390, Johannes Zimmer AG (Austria) at magnet pressure level 2 and printing speed 80%. Magnetic roller squeegees with diameters of 6 mm, 8 mm and 10 mm were used for printing. One, two or three passes of the squeegee were done. The stencils of the screens had 43, 55 and 68 threads/cm.*

*Table 3: Impregnation bath*

| Ingredient | Quantity (g) |
|---|---|
| Subitol LS-N | 3 |
| Rapidoprint SC | 2 |
| Redulit C | 150 |
| Prisulon CMS 10 (10 %) | 100 |
| Boraks 1 : 9 | 100 |
| NaOH 36 ° Be | 120 |
| $H_2O$ demin | Y |
| | 1000 |

Po parenju smo vzorce spirali najprej z mrzlo in nato s toplo tekočo vodo. Sledili so oksidacijska kopel s 4 ml/l $H_2O_2$ 35 % in 2 g/l $CH_3COOH$ 80 %, segreta na 60 °C, spiranje s toplo tekočo vodo, vrelo miljenje z 2 g/l Cotoblanca RS (CHT) in nazadnje še vroče ter toplo spiranje. Za kopeli pri naknadnih obdelavah smo uporabili demineralizirano vodo.

### 2.4 Optimizacija tiskanja

Za optimizacijo tiskanja smo uporabili statistično programsko opremo Design-Expert (v. 6.0.8.), proizvod podjetja Stat-Ease, Inc. (Minneapolis, MN), ki na osnovi CCD in ustreznega odgovora izdela matematični model z najboljšim ujemanjem za napovedovanje pravilnih odgovorov.
Določili smo štiri faktorje, ki lahko vplivajo na izvedbo tiskanja oz. na rezultat: finost šablone, premer tiskarskega noža, viskoznost tiskarske paste in število prehodov tiskarskega noža. Naš eksperiment je vključeval tri stopnje za vsak posamezen faktor (–1, 0, 1). Osrednje vrednosti so prikazane v preglednici 4.

*Table 4: Factor values*

| Factors | Unit | –1 | 0 | 1 |
|---|---|---|---|---|
| A | Stencil fineness (threads/cm) | 43 | 55 | 68 |
| B | Squeegee diameter (mm) | 6 | 8 | 10 |
| C | Print paste viscosity (Pas) | 0.44 | 1.09 | 1.75 |
| D | No. of squeegee passes | 1 | 2 | 3 |

Program je za štiristopenjski faktorski načrt predpisal 30 eksperimentov, ki so prikazani v preglednici 5.

*The printed samples were dried for one minute at 110°C on a laboratory stenter frame from Benz (Swiss). The dry, printed samples were impregnated on the two-roll padder W. Mathis AG (CH) at a wet pick-up of 100%. The recipe of the padding solution is shown in Table 3. Immediately after impregnation the samples were steamed for 8 minutes at 102°C in saturated steam on a laboratory steamer DHE 20675 from Werner Mathis AG (Swiss).*

*Steamed samples were rinsed with cold and warm tap water followed by oxidizing in a solution of 4 ml/l $H_2O_2$ 35% and 2 g/l $CH_3COOH$ 80%, at 60°C, rinsing with warm water and hot soaping with a solution of 2 g/l Cotoblanc RS. The treatment was finished with warm rinsing and air drying.*

### 2.4 Optimization of printing

*A software for statistical evaluation, Design-Expert (v. 6.0.8.), from Stat-Ease, Inc. (Minneapolis, MN) was used for printing optimization. The program gives the mathematical model for the prediction of exact answers on the basis of CCD.*

*Four factors that affect the printing quality were chosen: stencil fineness, squeegee diameter, viscosity and number of passes. Our experiment included three steps for each factor (–1, 0, 1). The central values are represented in Table 4.*

*The program prescribed 30 experiments for a four step factorial design, which are represented in Table 5.*

## 3 Results and discussion

*The Design of Experiments Statistical Software was used for the optimization of cotton fabric printing with vat dyes. By using this software, it is possible to design the number of experiments and to optimize a printing process.*

*Table 6 presents the measured K/S values after printing for each individual proposed recipe, the K/S values predicted by the software and the difference between the measured and the predicted K/S values. On the basis of the experimental data the software confirmed the regression model, which was calculated by the smallest square method and which describes the relation between variables and the experimen-*

*Table 5: Experimental design*

| Experiment No. | A | B | C | D |
|---|---|---|---|---|
| 1 | 43 | 6 | 0.44 | 1 |
| 2 | 68 | 6 | 0.44 | 1 |
| 3 | 43 | 10 | 0.44 | 1 |
| 4 | 68 | 10 | 0.44 | 1 |
| 5 | 43 | 6 | 1.75 | 1 |
| 6 | 68 | 6 | 1.75 | 1 |
| 7 | 43 | 10 | 1.75 | 1 |
| 8 | 68 | 10 | 1.75 | 1 |
| 9 | 43 | 6 | 0.44 | 3 |
| 10 | 68 | 6 | 0.44 | 3 |
| 11 | 43 | 10 | 0.44 | 3 |
| 12 | 68 | 10 | 0.44 | 3 |
| 13 | 43 | 6 | 1.75 | 3 |
| 14 | 68 | 6 | 1.75 | 3 |
| 15 | 43 | 10 | 1.75 | 3 |
| 16 | 68 | 10 | 1.75 | 3 |
| 17 | 43 | 8 | 1.09 | 2 |
| 18 | 68 | 8 | 1.09 | 2 |
| 19 | 55 | 6 | 1.09 | 2 |
| 20 | 55 | 10 | 1.09 | 2 |
| 21 | 55 | 8 | 0.44 | 2 |
| 22 | 55 | 8 | 1.75 | 2 |
| 23 | 55 | 8 | 1.09 | 1 |
| 24 | 55 | 8 | 1.09 | 3 |
| 25 | 55 | 8 | 1.09 | 2 |
| 26 | 55 | 8 | 1.09 | 2 |
| 27 | 55 | 8 | 1.09 | 2 |
| 28 | 55 | 8 | 1.09 | 2 |
| 29 | 55 | 8 | 1.09 | 2 |
| 30 | 55 | 8 | 1.09 | 2 |

## 3 Rezultati in razprava

Za optimizacijo tiskanja bombažnih tkanin z redukcijskimi barvili smo uporabili statistični program za načrtovanje eksperimentov.

*tal response (in our case the measured K/S value). The analysis of variance test was used for evaluation of the model and for comparison of the mean values between three or more different groups of investigated variables. After the analysis of variance for the proposed regression model was completed, we eliminated variables that had a statistically uncharacteristic influence on the model (B, $A^2$, $B^2$, D2, AB, AC, AD, BC, BD and CD), or those that had a value below the statistical 95% confidence interval (or had a p value higher than 0.05). Variables with statistically characteristic influences are presented in Table 7; they are A, C, D and $C^2$. A statistically characteristic feature of the model is confirmed by statistical confidence or by the p value, which is lower than 0.0001 in our results. The printing paste viscosity (C) has the highest influence on final K/S value; it is followed by the number of passes of the squeegee (D) and the fineness of the stencil (A), whereas the influence of the diameter of squeegee (B) is the lowest. The higher the value for assessment of coefficients and for F-value is, the higher the influence of an individual variable on the K/S value.*

*By using the smallest square method, the software calculated a polynomial equation for the regression for predicting the K/S values (Equation 5). The polynomial equation contains linear, quadratic and mixed members; the values of the above-mentioned four variables represent independent variables. (Equation 5)*

*The regression straight line ($R^2 = 0.9584$) in Figure 1 shows good correlation between the measured K/S values and the values predicted by the software on the basis of the smallest square method.*

*Each spatial diagram in Figure 2 presents the influence of interactions between two of four variables on the color hue depth. In each diagram both of the variables that are not presented are constant. The observed variables are: fineness of stencil 55 threads/cm, diameter of squeegee 8 mm, printing paste viscosity 1.09 Pas, and two passes of squeegee. The color plane inclination indicates how high the influence of individual variables is on the K/S value. The comparison of Figures 2a to 2f reveals that among all the variables investigated the diameter of the squeegee has the lowest influence*

Program omogoča načrtovanje števila eksperimentov in optimizacijo procesa tiskanja.

V preglednici 6 so prikazane izmerjene vrednosti *K/S* po tiskanju za posamezno predlagano recepturo, vrednosti *K/S*, ki jih je napovedal program, ter razlika med izmerjeno in napovedano vrednostjo *K/S*. Na osnovi eksperimentalnih podatkov je program potrdil regresijski model, ki je izračunan po metodi najmanjših kvadratov ter opisuje zvezo med spremenljivkami in odgovorom eksperimenta (v našem primeru je to izmerjena vrednost *K/S*). Test analize sipanja smo uporabili za ovrednotenje modela in primerjavo povprečnih vrednosti med tremi ali več različnimi skupinami preiskovank. Po opravljeni analizi sipanja za predlagani regresijski model smo izločili tiste spremenljivke, katerih vpliv na model ni bil statistično značilen (B, $A^2$, $B^2$, D2, AB, AC, AD, BC, BD in CD), oz. tiste, katerih vrednost je bila manjša od statističnega zaupanja 95 % (oz. p večji od 0,05). Spremenljivke s statistično značilnimi vplivi so prikazane v preglednici 7; to so A, C, D, $C^2$. Statistično značilnost modela potrjuje statistično zaupanje oz. vrednost p, ki je pri naših rezultatih manjša od 0,0001. Na končno vrednost *K/S* ima največji vpliv viskoznost tiskarske paste (C), ki ji sledita število prehodov tiskarskega noža (D) in finost šablone (A), medtem ko ima premer tiskarskega noža (B) najmanjši vpliv. Višja ko je vrednost za oceno koeficientov in za F-vrednost, večji je vpliv posamezne spremenljivke na vrednost *K/S*.

*Table 6: K/S values of prints produced by using the experimental design for the optimization of direct printing with vat dyes*

| Experiment | *K/Si* | *K/Sn* | *K/Si – K/Sn* |
|---|---|---|---|
| 1 | 6.78 | 6.76 | 0.018 |
| 2 | 5.44 | 5.81 | –0.360 |
| 3 | 6.79 | 6.60 | 0.190 |
| 4 | 6.46 | 6.36 | 0.100 |
| 5 | 12.47 | 12.78 | –0.310 |
| 6 | 11.78 | 11.14 | 0.640 |
| 7 | 11.96 | 12.01 | –0.051 |
| 8 | 10.48 | 11.08 | –0.600 |
| 9 | 11.71 | 11.24 | 0.460 |
| 10 | 9.90 | 9.89 | 0.010 |
| 11 | 12.04 | 12.72 | –0.680 |
| 12 | 12.26 | 12.08 | 0.180 |
| 13 | 16.01 | 16.15 | –0.150 |

*on the K/S value (Figures a, d and e), which is in accordance with the statistical analysis. By comparing the influence of individual variables on the K/S value, provided that the diameter of squeegee remains constant, we see that the color hue depth depends mostly on the printing paste viscosity, the number of passes of the squeegee is second, and the fineness of the stencil is third (Figures b, c and f).*

*In addition to statistical analysis and graphic presentation of the results the Design of Experiments Statistical Software provides numerical, graphic and point optimization of the processing conditions. We chose numerical optimization, because it provided the possibility of selecting target values for an individual factor or response. It offers a series of optional solutions among which we can select the most appropriate combination of printing conditions. Our presumption was that we wanted to achieve a maximal value of K/S at a constant viscosity of printing paste. Among the combinations offered, we selected the five most appropriate ones, which are presented in Table 8. Table 9 shows the designed and obtained K/S values at the selected optimized work conditions. We can see that the differences are small, which means that the prognoses were correct.*

*The experiments were completed with the prognosis of a response at an optimal setting of the printing conditions. By using point optimiza-*

| Experiment | K/Si | K/Sn | K/Si – K/Sn |
|---|---|---|---|
| 14 | 13.78 | 14.11 | –0.320 |
| 15 | 17.24 | 17.01 | 0.230 |
| 16 | 15.62 | 15.68 | –0.061 |
| 17 | 13.63 | 13.34 | 0.290 |
| 18 | 12.62 | 12.20 | 0.420 |
| 19 | 12.46 | 12.44 | 0.018 |
| 20 | 13.84 | 13.15 | 0.690 |
| 21 | 8.11 | 8.04 | 0.079 |
| 22 | 13.47 | 12.85 | 0.630 |
| 23 | 10.06 | 9.68 | 0.380 |
| 24 | 14.55 | 14.22 | 0.330 |
| 25 | 12.09 | 12.21 | –0.120 |
| 26 | 11.27 | 12.21 | –0.940 |
| 27 | 12.01 | 12.21 | –0.200 |
| 28 | 10.52 | 12.21 | –1.690 |
| 29 | 11.57 | 12.21 | –0.640 |
| 30 | 13.67 | 12.21 | 1.470 |

*K/Si … measured K/S, K/Sn … planned K/S,*
*K/Si – K/Sn … difference between measured and planned K/S.*

*Table 7: Influence and characteristics of individual variables in accordance with the analysis of variance ANOVA (R2 = 0.9584)*

| Variable | Assessment of Coefficients | Stat. Error | Lower Limit | Upper Limit | Value F | Value P |
|---|---|---|---|---|---|---|
| Model | 12.21 | 0.25 | 11.68 | 12.74 | 24.70 | < 0.0001 |
| A – Fineness of Stencil | –0.57 | 0.19 | –0.97 | –0.17 | 9.15 | 0.0085 |
| C – Viscosity | 2.41 | 0.19 | 2.00 | 2.81 | 162.11 | < 0.0001 |
| D – No. of Passages | 2.27 | 0.19 | 1.87 | 2.67 | 144.43 | < 0.0001 |
| $C^2$ | –1.77 | 0.50 | –2.83 | –0.71 | 12.61 | 0.0029 |

*At a 95% confidence interval*

Z metodo najmanjših kvadratov je program izračunal regresijsko enačbo polinomskega tipa za napoved K/S (enačba 5). Polinom vsebuje linearne, kvadratne in mešane člene, kot neodvisne spre-

*tion, new conditions can be optionally entered into the model. The software then gives the response along with the related confidence intervals on the basis of the equation for the K/S value prognosis (Equation 5).*

*Table 10 presents the calculated values of penetration and the evaluated prints sharpness.*

## 4 Conclusions

*Central composite design (CCD) confirmed our expectations that the highest color values would be obtained with a medium viscosity printing paste, with coarse stencils, with a higher diameter of squeegee and with multiple passes of the squeegee, as shown in Tables 6 and 8 and Figure 2. Since we printed on a fabric with a high density of threads and a high thickness and mass per unit area, a large amount of printing paste had to be applied in order to cover the entire material with dye. The application of printing paste on a fabric is higher with coarse stencils and multiple passes of the squeegee. Low viscosity enables higher application of printing paste but at the same induces higher penetration to the fabric back side, the result of which is a reduced color hue depth on the fabric face side. If the printing paste is too viscous, the application on the fabric is too low. However, it is not only the color hue depth that is important at printing, but also the sharpness of prints, which is frequently inversely proportional to the amount of the applied printing paste. The sharpness of prints on the selected fabric was not high in any of our cases. We printed on 0.2 to 0.4 mm wide strips. We calculated that in our case there was no correlation between the color hue depth and the print sharpness; therefore, optimal conditions were those at which we obtained the highest color hue depth.*

*It can be concluded that the computer-aided design of experiments is the appropriate method for the optimization of the printing process.*

menljivke pa nastopajo vrednosti za štiri že omenjene spremenljivke.

$$K/S = 12.21 - 0.57 \times A + 0.35 \times B + 2.41 \times C + 2.27 \times D + 0.56 \times A2 + 0.59 \times B2 - 1.77 \times C2 - 0.26 \times D2 + 0.18 \times A \times B - 0.17 \times A \times C - 0.10 \times A \times D - 0.15 \times B \times C + 0.41 \times B \times D - 0.28 \times C \times D \quad (5)$$

Regresijska premica ($R^2$ = 0,9584) na sliki 1 prikazuje dobro ujemanje med izmerjenimi vrednostmi *K/S* in tistimi, ki jih je napovedal program na podlagi metode najmanjših kvadratov.

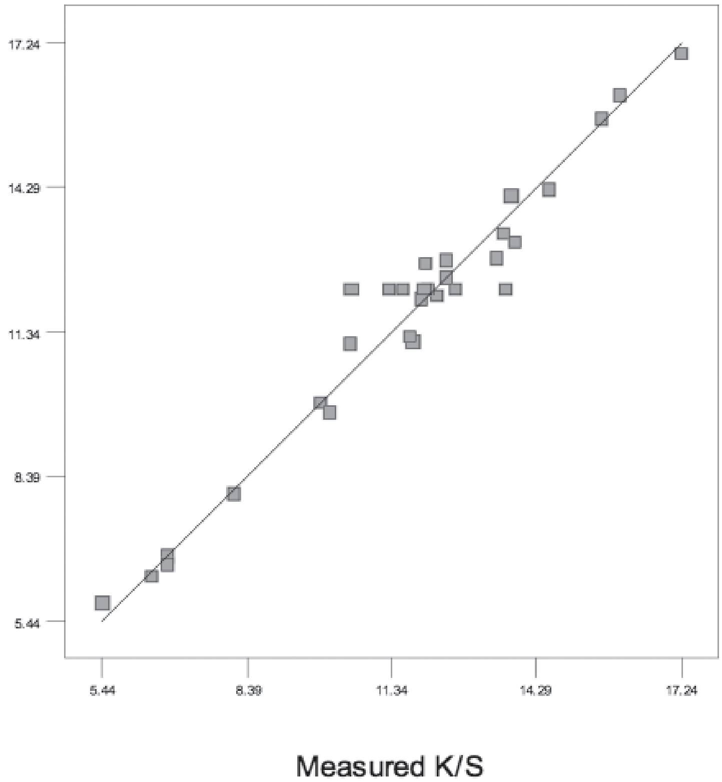


*Figure 1: Regression straight line for predicted K/S values depending on the measured K/S values*

Na posameznem prostorskem diagramu na sliki 2 je prikazan medsebojni vpliv dveh izmed štirih spremenljivk na globino barvnega tona. Pri vsakem diagramu sta obe neprikazani spremenljivki konstantni. Opazovane spremenljivke so: finost šablone 55 niti/cm, premer tiskarskega noža 8 mm, viskoznost tiskarske paste 1,09 Pas in dvakratno tiskanje. Naklon barvne ploskve nazorno nakazuje velikost vpliva posameznih spremenljivk na vrednost *K/S*. Pri primerjanju slik 2a do 2f vidimo, da ima na vrednost *K/S* med vsemi preučevanimi spremenljivkami najmanjši vpliv premer tiskarskega noža (slike a, d in e), kar je v skladu s statistično analizo. Če pri konstantnem premeru tiskarskega noža primerjamo vpliv

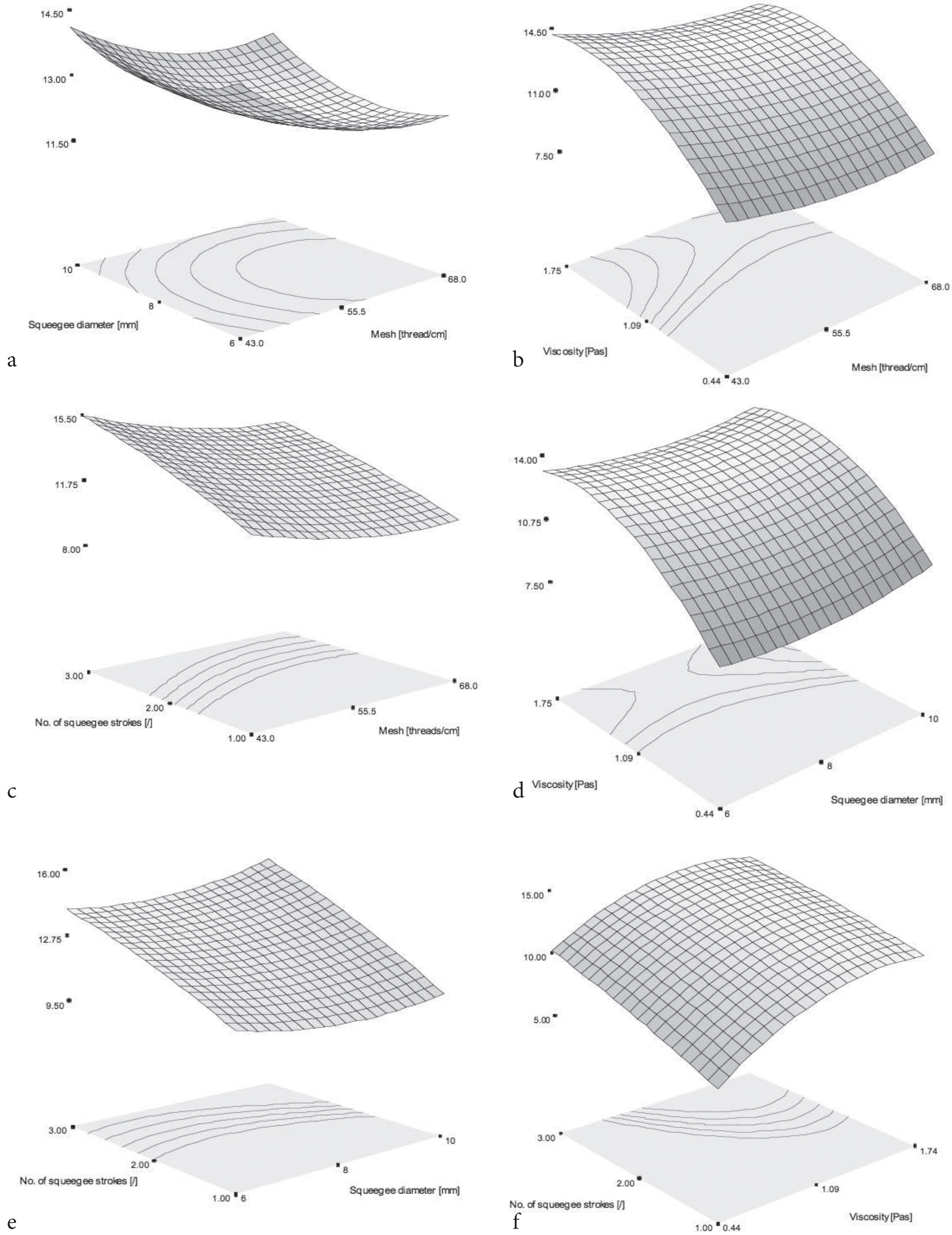


*Figure 2: Spatial presentation of the influence of individual variables (fineness of stencil, diameter of squeegee, printing paste viscosity, number of passes of squeegee) on the K/S values: a) printing paste viscosity 1.09 Pas, number of passages of squeegee 2; b) diameter of squeegee 8 mm, number of passages of squeegee 2; c) diameter of squeegee 8 mm, printing paste viscosity 1.09 Pas; d) fineness of stencil 55 threads/cm, number of passages of squeegee 2; e) fineness of stencil 55 threads/cm, printing paste viscosity 1.09 Pas; f) fineness of stencil 55 threads/cm, diameter of squeegee 8 mm.*

posamezne spremenljivke na vrednost *K*/*S*, opazimo, da je globina barvnega tona odvisna od viskoznosti tiskarske paste in števila prehodov tiskarskega noža ter finosti šablone (slike b, c in f), in to v padajočem vrstnem redu.
Statistični program za načrtovanje eksperimentov omogoča poleg statistične analize in grafičnega prikaza rezultatov tudi numerično, grafično in točkovno optimizacijo procesnih pogojev. Izbrali smo numerično optimizacijo, saj smo želeli imeti možnost izbiranja ciljnih vrednosti za posamezen faktor ali odgovor. Ta ponuja niz možnih rešitev, med katerimi lahko izberemo najprimernejšo kombinacijo pogojev tiskanja. Predpostavili smo, da želimo doseči maksimalno vrednost *K*/*S* pri konstantni viskoznosti tiskarske paste. Izmed ponujenih smo izbrali pet najprimernejših kombinacij, ki so prikazane v preglednici 8. Preglednica 9 pa prikazuje načrtovane in dobljene vrednosti *K*/*S* pri izbranih optimiziranih pogojih dela. Vidimo, da so razlike majhne, kar pomeni, da so bile napovedi pravilne.
Eksperimente končamo z napovedjo odgovora pri optimalni nastavitvi pogojev tiskanja. S točkovno optimizacijo lahko v model poljubno vnašamo nove pogoje. Program nato poda odgovor skupaj s pripadajočimi intervali zaupanja na podlagi enačbe za napoved vrednosti *K*/*S* (enačba 5).

*Table 8: Proposed work conditions by numerical optimization*

| Experiment | Fineness of Stencil | Diameter of Squeegee | Printing paste Viscosity | No. of Passes of Squeegee |
|---|---|---|---|---|
| 1 | 55 | 10 | 0.586 | 3 |
| 2 | 55 | 6 | 0.586 | 3 |
| 3 | 55 | 6 | 0.586 | 2 |
| 4 | 43 | 10 | 0.586 | 3 |
| 5 | 43 | 6 | 0.586 | 3 |

*Table 9: K/S values obtained after work conditions optimization*

| Experiment No. | K/Si | K/Sn | K/Si – K/Sn |
|---|---|---|---|
| 1 | 12.83 | 13.01 | –0.18 |
| 2 | 11.59 | 11.22 | 0.37 |
| 3 | 10.41 | 9.39 | 1.02 |
| 4 | 13.52 | 13.80 | –0.28 |
| 5 | 11.43 | 12.47 | –1.04 |

*K/Si … measured K/S, K/Sn … designed K/S, K/Si – K/Sn … difference between the measured and designed K/S.*

V preglednici 10 so prikazane izračunane vrednosti pretiska in ocenjene ostrine odtisov.

*Table 10: Penetration, P, and print sharpness*

| Experiment No. | P (%) | Sharpness (mm) |
|---|---|---|
| 1 | 9.02 | 0.3 |
| 2 | 5.61 | 0.4 |
| 3 | 12.89 | 0.3 |
| 4 | 7.22 | 0.4 |
| 5 | 2.15 | 0.3 |
| 6 | 1.39 | 0.4 |
| 7 | 2.26 | 0.5 |
| 8 | 1.87 | 0.4 |
| 9 | 40.81 | 0.3 |
| 10 | 23.85 | 0.4 |
| 11 | 52.70 | 0.3 |
| 12 | 36.80 | 0.4 |
| 13 | 1.87 | 0.3 |
| 14 | 2.32 | 0.4 |
| 15 | 2.60 | 0.3 |
| 16 | 2.29 | 0.3 |
| 17 | 5.68 | 0.2 |
| 18 | 4.42 | 0.2 |
| 19 | 3.86 | 0.2 |
| 20 | 4.55 | 0.2 |
| 21 | 27.88 | 0.2 |
| 22 | 2.32 | 0.3 |
| 23 | 3.55 | 0.3 |
| 24 | 9.34 | 0.2 |
| 25 | 3.74 | 0.3 |
| 26 | 4.46 | 0.2 |
| 27 | 5.39 | 0.2 |

| Experiment No. | P (%) | Sharpness (mm) |
|---|---|---|
| 28 | 5.79 | 0.2 |
| 29 | 4.32 | 0.3 |
| 30 | 4.32 | 0.3 |

## 4 Zaključek

Centralni eksperimentalni načrt je potrdil predvidevanja, da bodo najvišje barvne vrednosti dosežene s tiskarsko pasto srednje viskoznosti, z grobimi šablonami, pri večjem premeru tiskarskega noža in pri večkratnem potegu tiskarskega noža, kot lahko vidimo iz preglednic 6 in 8 ter s slike 2. Glede na to, da smo tiskali na tkanino z veliko gostoto niti, veliko debelino in površinsko maso, je bilo treba za prebarvanje vsega materiala nanesti veliko količino tiskarske paste. Nanos tiskarske paste na blago pa je večji ob uporabi grobih šablon in večkratnem potegu tiskarskega noža. Nizka viskoznost omogoča večji nanos paste, vendar pa povzroči večji pretisk na hrbtno stran blaga, zaradi česar je globina tona na lični strani manjša. Pri previsoki viskoznosti tiskarske paste pa je nanos na blago premajhen. Vendar pa je pri tiskanju poleg globine barvnega tona pomembna tudi ostrina odtisov, ki je pogosto obratno sorazmerna s količino nanesene tiskarske paste. Izkazalo se je, da ostrina pri izbrani tkanini v nobenem primeru ni visoka. Natisnili smo črte širine 0,2 do 0,4 mm. Izračunali smo, da korelacije med globino barvnega tona in ostrino v našem primeru ni, zato so optimalni pogoji tisti, pri katerih dosežemo največjo globino tona.
Zaključimo lahko, da je računalniško načrtovanje poskusov primerna metoda za optimizacijo procesa tiskanja.

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