UDK 667.5.032:621.926

Optimizacija procesa mletja barvnega pigmenta

Optimisation of Colour Pigment Grinding with Pearl Mills

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Mletje barvnega pigmenta s krogličnimi mlini je proces, pri katerem želimo zmleti izbrani pigment na določeno velikost delcev (zrnatost). Cilj optimizacije je bil v čim krajšem času in s čim manjšo porabo energije zmleti delce pigmenta na zahtevano zrnatost. Optimizacijo procesa smo izvedli z uporabo metod statističnega načrtovanja preizkusov, načrtovanja avtomatskega merilnega sistema za merjenje in zajemanje izmerkov, modeliranja z nevronskimi in polinomskimi modeli, statistično analizo in določitvijo najboljših razmer za mletje. Na podlagi analize rezultatov modeliranja smo določili najpomembnejše parametre procesa in določili najboljše razmere za mletje. Modela sta temelj za izdelavo nadzornega sistema ali sintezo krmilnega sistema.

The goal of colour pigment grinding with pearl mills is achieving granulation of pigment particles with defined size. By optimisation the time and energy consumption of the grinding process should be minimized. Optimisation was performed by using the following methods: statistical designing of experiments, planning and building an automatic measurement system for experimental data acquisition and analysis, modelling with neural networks and polynomials, statistical analysis and determination of optimum circumstances for the grinding process. By the analysis of models the most important parameters and optimum conditions for grinding were obtained. Models are also the base for the design of a control instrumentation and control system.

0 UVOD

Pri razvoju novih izdelkov, uvajanju novih in izboljševanju znanih tehnologij, odkrivanju napak v proizvodnji, pri optimiranju ter načrtovanju kompleksnih krmilnih sistemov ne gre brez preizkusov. Preizkušanje terja določene stroške za material, izdelavo objektov, merilno opremo, energijo in čas. Naloga raziskovalca je pridobiti čim več zanesljivih informacij v čim krajšem času in s čim manjšimi stroški. Vse to omogočajo metode načrtovanja preizkusov. Metode načrtovanja preizkusov niso nove, pač pa v zadnjih letih njihova uporaba z računalniško podporo dobiva nove razsežnosti. Podpora pri izbiri in izdelavi načrtov, avtomatski merilni sistemi, avtomatska obdelava podatkov in nove metode vrednotenja so bistveno skrajšale čas, potreben za izvedbo raziskav, in po drugi strani omogočile večji izkoristek informacij iz zbranih podatkov.

0 INTRODUCTION

Experiments are necessary for the development of new products, and the introduction of new and improvement of known technologies. All experiments involve costs for material, the development of the measurement system, and the consumption of energy and time. The goal of a successful investigation is to obtain as much reliable information as possible about the process. Good investigation is usually a balance between obtaining a lot of reliable data and limited time and costs. The methods of experimental design are the appropriate tool for achieving that goal. Methods of statistical experimental design are not new, but with the fast development of computers, their use has greatly increased. Computer support in design selection, automatic systems for data acquisition, automatic data analysis and methods of validation have decreased the time needed for research and enable better exploitation of information from the data obtained.

Pri modernem načrtovanju preizkusov prehajamo na statistično načrtovanje preizkusov [1], ki ima naslednja izhodišča:

— predpostavljamo, da ni odstranjen vpliv drugih dejavnikov, niti da smo ga zmanjšali na zanemarljivo vrednost,

— ne zahtevamo, da so razmere pri izvajanju preizkusa pri vseh ponovitvah enake, nasprotno, želimo, da se izbira vplivnih dejavnikov in njihovih vrednosti spreminja, seveda po izbranem načrtu,

— rezultati metod statističnega načrtovanja preizkusov dajejo podatke o medsebojnem vplivu dejavnikov,

— rezultati metod statističnega načrtovanja preizkusov omogočajo določitev merilne točnosti dobljenih rezultatov in tudi vpliva naključnih merilnih pogreškov.

V tem prispevku predstavljamo optimizacijo procesa mletja barvnega pigmenta, ki poteka v kregličnih mlinih. Keglični mlini so namenjeni mletju različnih vrst maž in emulzij, ki vsebujejo trdne delce. Z njimi je mogoče te delce zmleti do zrnatosti 1μm.

Delovanje krogličnega mlina je razmeroma preprosto. Mešalo se vrti v mlevni posodi. Posoda se prilega obliki mešala, tako da je med njima le ozka reža, tj. mlevni prostor. V reži so mlevne kroglice. Mlevna masa priteka v mlevni prostor navpično od spodaj, nato se giblje skozi režo ob mešalu in steni posode navzgor. Kroglice, ki so v reži, meljejo delce na njihovi poti. Mlevna masa zapušča posodo na vrhu navpično skozi ločilno špranjo, ki preprečuje izhod mlevnih kroglic, in nato vodoravno po cevovodu na plano. Pri mletju se sprošča toplota, ki jo moramo odvajati. Mlevna posoda je zato hlajena z vodo (sl. 1).

Modern research and development uses statistical methods of experimental design [1] widely with following:

— the influence of other factors is not assumed to be eliminated or reduced to a negligible level,

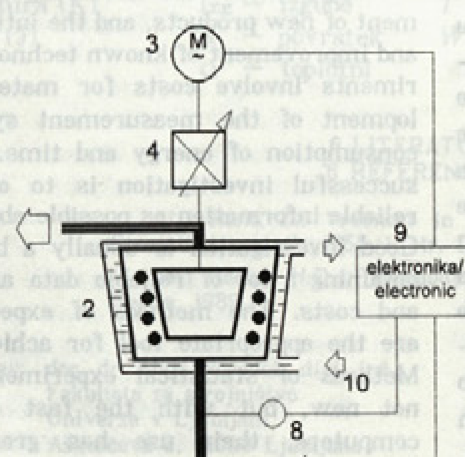
— the experimental conditions are not necessarily constant during all experiments and values of main factors can be changed from one experiment to another according to the experimental plan,

— the information on the correlation between factors is included in the results of statistical methods of experimental design,

— statistical methods of experimental design enable the evaluation of experimental accuracy and estimation of random measurement error.

The optimisation of the grinding process in a pearl mill is introduced in this paper. Such pearl mills are used to grind greases and emulsions containing solid particles. Pearl mills can grind the particles to granulation of 1 μm.

The function of a pearl mill is relatively simple. The agitator disc rotates in a mill vessel. The mill vessel fits the shape of the agitator disc with only a small gap between them. The gap contains mill pearls and the grinding process takes place there. The grinding mass flows into the vessel perpendicularly at the bottom, and moves through the gap along the agitator and the vessel wall upwards. The mill pearls in the gap mill the parts on their way. The grinding mass flows out at the top of the vessel perpendicularly through a separation slot which prevents the pearls from leaving, and then horizontally through the tube to the open place. Redundant heat produced in the grinding process must be led away. The mill vessel is cooled with water (Fig. 1).



1 mlevna baza / grinding mass,
2 mlevna posoda / mill vessel,
3 motor mešala / motor of mill,
4 jermenski variator / continual transmission gear,
5 motor črpalke / motor of pump,
6 brezstopenjski menjalnik / continual transmission gear,
7 črpalka / pump,
8 manometer in tlačno stikalo / pressure transducer,
9 elektronika / electronic,
10 hladilna voda / cooling water.

Sl. 1. *Shema krogličnega mlina*
Fig. 1. *Scheme of pearl mill*

1 OPIS POSAMEZNIH FAZ POSTOPKA OPTIMIZACIJE

Optimizacijo procesa mletja barvnega pigmenta smo izvedli po naslednjem postopku:

— oblikovanje problema in določitev ciljev,
— izbira spremenljivk (dejavnikov, odgovorov),
— izbira tipa načrta,
— načrtovanje merilnega sistema,
— izvedba meritev,
— modeliranje (regresije, nevronske mreže),
— vrednotenje modelov in analiza rezultatov,
— določitev optimalne strategije mletja.

1.1 Oblikovanje problema in določitev ciljev

Pri mletju barvnih pigmentov s krogličnimi mlini se hkrati pojavljajo tri zahteve, in sicer zagotoviti:

— čim boljšo kakovost mletja,
— čim manjšo porabo energije in
— čim krajši čas mletja.

To so protislovne zahteve in vse tri hkrati ne morejo biti izpolnjene, zato je treba poiskati najboljši kompromis ali skupni optimum, to pa lahko storimo, če poznamo model procesa. Naš cilj je bil z uporabo metod načrtovanja preizkusov določiti najvplivnejše dejavnike in izdelati model procesa.

1.2 Izbira spremenljivk

Izbira spremenljivk je najpomembnejši korak v celotnem postopku načrtovanja preizkusov. Od tega so bistveno odvisni stroški in rezultati preizkusa. Določiti je treba dejavnike, odgovore (lastnosti) in spremljajoče dejavnike ter razpone njihovega delovanja. Proces mletja s krogličnimi mlini ni nova tehnologija, a tehnologi so si pridobili že precej izkušenj. Zato smo lahko že v prvem koraku dokaj zanesljivo izbrali spremenljivke:

Dejavniki: viskoznost mlevne baze, pretok hladilne vode, vrtilna frekvenca črpalke, vrtilna frekvenca mešala in količina kroglic.

Odgovori: čas, poraba energije, zrnatost, temperatura, tlak, masni tok mlevne mase.

1.3 Izbira tipa načrta meritev

Če smo prva dva koraka uspešno končali, potem imamo podatke, ki jih potrebujemo za izbor načrta. Obstaja veliko število različnih tipov načrtov, vsak ima svoje prednosti in pomanjkljivosti. Glede na cilj modeliranja obstajata dve skupini načrtov. Prva skupina je bolj namenjena začetnim raziskavam procesa in druga skupina optimizaciji procesa. V prvi skupini načrtov so delni dvonivojski načrti, ki omogočajo ovrednotenje velikosti vpliva posameznega dejavnika na vsak posamezni odgovor. Tronivojski in rotacijski načrti omogočajo natančnejšo optimizacijo procesa.

1 DESCRIPTION OF PHASES IN THE OPTIMISATION PROCEDURE

The procedure of optimisation of the grinding colour pigment was as follows:

— problem formulation and goals,
— selection of variables (factors, responses),
— selection of experimental design,
— planning and building the system for measurement,
— execution of measurements,
— modelling (regressions, neural network),
— evaluation of models and analysis of results,
— determination of optimum strategy of grinding process.

1.1 Problem formulation and goals

Three main goals are followed in grinding colour pigments with a pearl mill:

— to obtain the quality of grinding as good as possible,
— to keep the consumption of energy as low as possible
— to keep time spent for grinding as low as possible.

These are opposing goals and all three can not be fulfilled, so a compromise or common optimum must be found. The goal can easily be achieved from an appropriate model of process. The purpose of our work was to determine the most important factors and to obtain the appropriate model of process by using the methods of experimental design.

1.2 Selection of variables

The choice of variables is the most crucial step in the procedure of designing experiments. The costs and results the of whole procedure depend on this choice. The main factors and responses must be determined. We must also determine the upper and lower limits of the researched area for each factor and be aware of some limitation in responses. If possible, secondary factors should be determined at this step. The process of grinding with pearl mills is an old technology and engineers have much experience with it. So it was easy to determine the main factors and responses:

Factors: viscosity of grinding mass, the flow of cooling water, the rotation frequency of the pump, the rotation frequency of the mill, the number of pearls in the mill.

Responses: time, consumption of energy, the granulation temperature, pressure, flow of grinding mass.

1.3 Selection of experimental design

After the first two steps of the procedure are finished, the information needed for the selection of the experimental design are available. Many different types of experimental design are available and they all have advantages and disadvantages. If the use of different designs is observed further, then they can be divided two main groups. The first group of designs is intended for preliminary research of a process and the second group for optimisation of the process. In the first group are partial two level factorial designs, appropriate for the evaluation of the importance of the influence of every factor on a particular response. Three level and rotational designs enable a more precise optimisation of the process.

Naš primer je bil izveden kot uvodna raziskava, zato smo izbrali delni dvonivojski faktorski načrt za pet dejavnikov s 16 različnimi kombinacijami njihovih vrednosti. Da bi dobili tudi okvirno optimalno točko, smo dodali pet ponovitev središčne točke.

1.4 Načrtovanje merilnega sistema

Pri tem koraku je treba za vse dejavnike in odgovore izbrati primerne merilne metode in opremo. Zavedati se moramo, da je od zanesljivosti izmerkov v dobršni meri odvisen uspeh optimizacije. Glavne aktivnosti pri načrtovanju merilnega sistema so:

— izbira merilne opreme,
— umerjanje,
— poskusne meritve,
— analiza merilne negotovosti merilnega sistema ter dobljenih izmerkov.

Spremenljivke, pri katerih smo želeli ugotoviti tudi časovni potek, smo spremljali z avtomatskim sistemom za merjenje in zajemanje izmerkov, ki je bil načrtovan in izveden ter umerjen v raziskavi [2]. Te spremenljivke so: temperature na različnih mestih, tlak, pretok hladilne vode, masni tok mlevne mase in čas. Druge spremenljivke, za katere smo napovedali, da bodo ostale med potekom preizkusa konstantne, smo merili ročno.

Glavni elementi avtomatskega sistema za merjenje in zajemanje izmerkov:

— računalnik PC,
— večfunkcijska merilna kartica (pretvornik A/D),
— pretvorniško/napajalno elektronsko vezje,
— merilna zaznavala in
— računalniški program.

Sistem za avtomatsko merjenje in zajemanje izmerkov postane celota šele skupaj z osebnim računalnikom in posebej za ta primer izdelanim programom (COLOR.BAS). Aktivnosti računalniškega programa so bile:

— periodično zajemanje izmerkov,
— preračun izmerkov glede na znane odzivne značilnice zaznaval,
— izračun veličin na podlagi posrednih merilnih metod,
— prikaz rezultatov na zaslonu,
— shranjevanje izmerkov in rezultatov v datoteko,
— opozarjanje na prekoračitve dovoljenih mej merjenih lastnosti.

1.5 Izvedba meritev

Za popolni dvonivojski faktorski načrt za pet dejavnikov moramo narediti 32 različnih preizkusov. Uporabili smo delni dvonivojski faktorski načrt za pet dejavnikov, ki terja 16 preizkusov.

Our work was mainly preliminary research so we chose partial two level factorial design for five factors with 16 different combinations of their values (experimental points). To enable approximate optimisation we added 5 replications of the central point.

1.4 Planning the measurement system

This step requires the choice of the appropriate measurement equipment and the technique for obtaining every factor and response. Successful optimisation depends on accurate measurements. The main tasks in building a measurement system are:

— choice of measurement equipment,
— calibration,
— measurements for testing,
— analysis of uncertainty in the measurement system and in obtained measurements.

The variables, for which we wanted to observe time dependence were recorded with an automatic system for measurement monitoring and acquisition. This system was planned and produced during research [2]. The time dependent variables were: temperature at different parts of the mill, pressure in the vessel, flow of the cooling water, mass flow of the grinding mass and time spent for the process. Other variables, which were assumed to be constant during the experiment, were measured manually.

The main elements of the automatic system for measurement monitoring and acquisition:

— computer (PC type),
— multi-function acquisition board (converter A/D),
— multiplexer amplifier electronic circuit,
— sensors, and
— computer program.

The system for automatic measurement monitoring and acquisition is completed with a personal computer and the proper software. Own software was used (COLOR.BAS). The activities of the computer program were:

— periodical acquisition of measurements,
— calculation of measurement values from known response characteristics of sensors,
— calculation of measurement values from indirect measurement methods,
— on-line representation of results on display,
— saving measurements and results in a computer file,
— alarming or warning if the limits of measured variables are exceeded.

1.5 Performation of measurements

Two-level full factorial design for five factors requires 32 different experiments. We used partial two level factorial design for five factors requiring 16 different experiments.

Pri preizkusu številka 5 je bil že na začetku preizkusa presežen mejni tlak 2,5 bar. Mlin je bil po nekaj sekundah ustavljen in preizkusa nismo zapisali v preglednico 1, ker je bil neizvedljiv. Poleg tega smo izvedli še dodatnih pet ponovitev središčne točke, ki omogočajo približno optimizacijo procesa in določitev ponovljivosti meritev. Za vsak preizkus smo naredili zapisnik in posneli datoteke izmerkov. Z obdelavo teh datotek smo pripravili podatke v obliki matrike (preglednica 1). V preglednici so z X označeni dejavniki in z Y odgovori. Dejavniki so napisani v naslednjem vrstnem redu: viskoznost mlevne mase (X1), pretok hladilne vode (X2), vrtilna frekvenca črpalke (X3), vrtilna frekvenca mešala (X4) in odstotek kroglic v mlinu (X5). Odgovori so v naslednjem vrstnem redu: čas mletja kilograma mlevne mase (Y1), zrnatost delcev po mletju (Y2), porabljena energija pri mletju kilograma mlevne mase (Y3), izstopna temperatura mlevne mase (Y6), masni tok mlevne mase (Y9), tlak v mlevni posodi (Y10), razlika med vstopno in izstopno temperaturo hladilne vode (Y7).

At experimental point no. 5, the critical pressure 2.5 bar was exceeded. The grinding process was stopped in a few seconds and the experiment was not recorded (Table 1). The central experiment (central point in design) had five repetitions. Central experiments and repetition enable rough optimisation of the process and a determination of the accuracy of measurements. Every experiment was written on paper and recorded on file. The important data was extracted, in matrix form (Table 1), from all recorded files. In the table, all factors are denoted with an X and all responses with a Y. Factors are written as follows: viscosity of grinding mass (X1), flow of cooling water (X2), rotation frequency of pump (X3), rotation frequency of mill (X4), the amount of pearls in the mill (X5). Responses are written as follows: time for grinding one kilogram of grinding mass (Y1), granulation of particles (Y2), consumption of energy per one kilogram of grinding mass (Y3), temperature of outflow grinding mass (Y6), flow of grinding mass (Y9), pressure in mill (Y10), difference between temperature of inflow and outflow cooling water (Y7).

Preglednica 1: *Dejavniki in odgovori pri prvem mletju*
Table 1: *Values of factors and responses at first grinding*

Št. vzor.	X1	X2	X3	X4	X5	Y1	Y2	Y3	Y6	Y9	Y10	Y7
No. exp.	s	l/h	min^{-1}	min^{-1}	%	s/kg	µm	Wh/kg	°C	kg/h	bar	K
1	20	232	234	1764	70	44.6	13	37.77	39.9	85.59	1.25	7.8
2	20	795	43	1746	70	220.8	9	208.21	33	17.1	0.08	3.9
3	20	741	236	1046	70	53.1	12	36.29	39.2	72.26	1.42	3
4	20	194	42	1030	70	258.4	8.5	120.03	30.8	13.82	0.08	6.4
5	60	800	230	1800	70	-	-	-	-	-	>3.5	-
6	60	799	40	1020	70	217.4	10	173.74	30.9	16.69	0.56	3.4
7	60	202	40	1750	70	190.2	6.5	200.95	47.7	18.93	0.28	12.8
8	60	212	232	1020	70	47.1	10	54.47	65.6	87.59	3.12	9.5
9	20	187	45	1813	30	258.6	14	127.74	32.1	13.75	0.11	6.1
10	20	794	45	1075	30	254.2	16	83.08	20.8	12.35	0.13	1.6
11	20	188	232	1082	30	59.9	21	13.05	25	70.19	1.42	3.8
12	20	735	232	1750	30	45.7	21	5.92	28.7	80.53	1.4	2.3
13	58	181	40	1060	30	218.2	17	93.05	27.8	16.26	0.52	5.3
14	62	199	232	1791	30	40.2	33	35.88	44.4	95.56	3.14	12
15	62	776	42	1764	30	201.7	11.5	180.84	30.5	17.77	0.25	3.8
16	58	804	235	1060	30	51.8	27	23.17	29.3	81.68	3.14	1.9
s1	43	474	125	1425	50	94.5	15	76.28	38.6	39.88	2.32	5.4
s2	43	464	125	1425	50	88.7	16	66.56	37.2	42.61	2.91	4.2
s3	42	520	133	1405	50	77.8	13	63.42	40	52.49	1.56	4.5
s4	42	525	136	1382	50	68.9	12	58.9	40.6	54.07	1.6	5.2
s5	42	552	139	1377	50	74	11.5	66.24	40.8	53.01	1.59	4.7

1.6 Modeliranje

Ko opravimo preizkuse, poznamo obnašanje procesa samo v točkah preizkusa. Če želimo spoznati odvisnosti odgovorov od dejavnikov in medsebojne soodvisnosti med dejavniki, moramo poiskati najustreznejši model procesa.

1.6 Modelling

After the experimental work is done, the performance of process is known only in experimental points. To achieve deeper knowledge of dependence of the responses on factors and the mutual correlation between factors, the most

Model je simuliranje preiskovanega procesa. Z modelom lahko napovemo obnašanje procesa v neznanih razmerah (vrednostih dejavnikov) znotraj razpona preizkusov (interpolacija) in zunaj razpona preizkusov (ekstrapolacija). Model je lahko analitična funkcija, nevronska mreža [3] ali podobno. Parametre analitične funkcije najpogosteje določamo z linearnimi (polinomske funkcije) in nelinearnimi (eksponentne, logaritemske, druge) regresijami. Simulirane vrednosti odgovorov, ki jih dobimo z modelom, dajo lahko pomembne informacije o optimumu procesa in nas opozarjajo o mogoči kritični prekoračitvi odgovora pri danih vrednostih dejavnikov.

Polinomski model odvisnosti posameznega odgovora od vseh dejavnikov dobimo z (multivariantno) linearno regresijo za več dejavnikov. Za določitev polinomskih modelov smo uporabili sistem SAS in lastni programski paket (EKS). Nevronski model je bila nevronska mreža z vzvratnim popravljanjem napak. Za nevronski model smo uporabili učenje po standardnem pravilu delta [4]. Aktivacijska funkcija je bila sigmoidna. Učenje smo izvajali na lastnem programu (NEVROGEN) [5].

1.6.1 Modeliranje temperaturne odvisnosti tlačnega pretvornika KPY55A

Pri postavitvi merilne verige za merjenje tlaka smo uporabili modeliranje za izvedbo temperaturne kompenzacije tlačnega pretvornika. Karakteristika uporabljenega piezouporovnega tlačnega pretvornika KPY55A (Siemens) je temperaturno odvisna.

Dobavitelj je na izbranem pretvorniku opravil serijo meritev, ki podajajo odvisnost izhodne napetosti merilne verige od temperature in tlaka (preglednica 2).

Temperatura in tlak v preglednici 2 sta dejavnika, ki vplivata na en odgovor (napetost). Izvedli smo linearno regresijo in izračunali linearni, kvadratični in kubični model. Po pravilu delta smo učili tudi dvonivojsko nevronsko mrežo s šestimi nevroni na skritem nivoju. Šest nevronov na skritem nivoju smo izbrali, ker je pri dvonivojskih nevronskih mrežah najpogosteje optimalno število od pet do sedem nevronov na skritem nivoju. Učenje poteka v več iteracijah. Ena iteracija učenja pomeni popravljanje uteži glede na eno točko v skupini za učenje. Ena doba pomeni eno obravnavo celotne skupine podatkov (preglednica 2). Pri problemu kompenzacije smo pustili, da je potekalo učenje v 770 000 iteracijah (10 000 dobah).

suitable model of the process must be obtained. A model is a simulation of the researched process. A model enables the prediction of behaviour of the process inside (interpolation) or outside (extrapolation) the researched area of factors. Models can be in the form of an analytical function, neural network [3] etc. Parameters of analytical functions are usually determined with linear (polynomials) and non-linear (exponential, logarithmic, other) regression. The simulated responses obtained from the model, can provide important information for optimisation of the process and warn about possible exceeding. The critical limit of a particular response if selected values of factors were implemented to the process.

The polynomial model of dependence of a particular response on all factors can be obtained with multivariate linear regression. The polynomial models were obtained with an SAS system and our own software (EKS). The neural model was a »back propagation« neural network. The training procedure was standard delta rule [4]. The activation function was sigmoid function. The training was done with our own software (NEVROGEN) [5].

1.6.1 Modelling pressure transducer KPY55A dependency on temperature

In the phase of building a surveyor's chain for measuring pressure, we used modelling for obtaining a temperature compensation of response from the pressure transducer. The characteristic of a piezo resistor in pressure transducer KPY55A (Siemens) is temperature dependent.

The supplier made a series of measurements with a selected pressure transducer. With the measurements, the dependence of the output voltage of a surveyor's chain on temperature and pressure was sought (Table 2).

Temperature and pressure in table 2 are factors affecting one response (voltage). With the use of linear regression linear, quadratic and cubic polynomial models were obtained. Providing delta rule training, a two-level neural network with six nodes (neurones) on the hidden layer was trained. Six nodes on the hidden layer were used because with two-level neural networks, the most frequent optimum number of nodes on the hidden layer is between five and seven. The training process runs in many iterations. In one iteration of the training process, the weights in the neural network are corrected to fit one point (experiment) in the training set. In one epoch, all experiments in the training set are treated once (Table 2). To solve the temperature compensation problem the training process was performed in 770 000 iterations (10 000 epochs).

Preglednica 2: *Izhodna napetost (V) merilne verige s tlačnim pretvornikom KPY55A v odvisnosti od nadtlaka (bar) in temperature pretvornika (°C)*

Table 2: *Output voltage (V) of surveyor's chain with pressure transducer KPY55A at different pressure (bar) and temperature (°C)*

Nadtlak / Pressure	Izhodna napetost U v V / Output voltage *U* in V units						
	Temperatura pretvornika °C / Temperature of transducer in °C						
bar	1	5	10	15	20	25	30
0	1.78	1.79	1.82	1.84	1.87	1.9	1.93
1	2.09	2.09	2.12	2.15	2.17	2.2	2.22
2	2.43	2.44	2.46	2.48	2.5	2.53	2.56
3	2.75	2.76	2.78	2.79	2.81	2.83	2.86
4	3.08	3.09	3.10	3.11	3.12	3.14	3.16
5	3.39	3.39	3.41	3.42	3.42	3.44	3.46
6	3.72	3.72	3.73	3.73	3.74	3.75	3.77
7	4.04	4.04	4.05	4.05	4.05	4.06	4.06
8	4.36	4.35	4.35	4.35	4.35	4.35	4.36
9	4.68	4.66	4.66	4.66	4.66	4.66	4.67
10	5.00	4.88	4.98	4.97	4.97	4.96	4.96

Preglednica 3: *Povprečja kvadratov razlik med izmerjenimi in izračunanimi odgovori za linearne, kvadratične, kubične in nevronske modele*

Table 3: *The mean square of difference between measured and simulated responses for linear, quadratic, cubic polynomial and neural models*

Model	*MS* V^2
linearni / linear	0.0238
kvadratni / quadratic	0.0126
kubični / cubic	0.0122
nevronski / neural	0.0413

Spremljali smo povprečja kvadratov razlik med izmerjenimi in izračunanimi odgovori (*MS* = povprečni kvadrat).

Izkazalo se je, da že kvadratični model dobro opiše odvisnost napetosti od temperature in tlaka. Med vrednostjo *MS* za linearni in kvadratični model je precejšnja razlika. Kubični členi so zanemarljivo majhni in z njimi se *MS* skoraj nič ne zmanjša. Členi kvadratičnega modela so bili naslednji:

During the training process, the mean square of difference between measured and simulated responses was calculated (*MS* — mean square).

It can be seen that the quadratic model describes the dependence of voltage on temperature and pressure well enough. The difference between the *MS* for linear and quadratic polynomials is relatively significant. With cubic terms, which are small, the decrease in *MS* value is relatively small. The terms of the quadratic model are as follows:

$$U_0 = 1{,}7657 + 0{,}3305\ p + 0{,}00393\ T - 0{,}0009\ p^2 + 0{,}00004\ T^2 - 0{,}00059\ p\ T \qquad (1).$$

Temperaturna odvisnost, ki je podana v preglednici 2, je bila izmerjena z merilno verigo dobavitelja, pri ojačanju signala K_0. Izračunani model velja za to ojačanje. Če želimo model uporabiti za korekcijo v našem merilnem sistemu, moramo določiti še linearno problikovanje, ki bo izhodno napetost našega merilnega sistema z ojačanjem K_1, preoblikovala v napetost z ojačanjem K_0.

Linearno preoblikovanje določimo na podlagi regresijskih premic izračunanih na podlagi izmerkov dobljenih pri umerjanju našega merilnega sistema (preglednica 4) in izmerkov temperaturne karakteristike pri 22 °C (preglednica 5).

Temperature dependency, shown in table 2, was measured with the supplie's chain with amplified signal K_0. The obtained model is valid for this amplification only. If the linear transformation from our to the supplier's chain voltages determined, the obtained model can be used for temperature correction of the measurement system. Linear transformation must convert the output voltage of our system with amplification K_1, to output voltage with amplification K_0.

Linear transformation's determined from the regression line obtained from calibration measurements with our surveyor's chain and from a quadratic model (simulating the supplier's measurements). Voltage from our surveyor's chain was calibrated at 22 °C (Table 4) and compared to the response of the quadratic model at the same temperature (Table 5).

Preglednica 4: *Izmerjeni padci napetosti pri različnih referenčnih tlakih in konstantni temperaturi okolice 22 °C*

Table 4: *The measured drop in voltage at different reference pressures and constant temperature (22 °C)*

p_{ref} bar	0	0.5	1	1.5	2	2.5	3	2.5	2	1.5	1	0.5	0
U_2 V	3.53	4.17	4.94	5.79	6.63	7.52	8.43	7.53	6.65	5.79	4.96	4.17	3.53

Po podatkih, v preglednici 4, smo izračunali enačbo premice:

From information in table 4 the following linear equation was obtained:

$$U_2 = 1{,}65392\ p + 3{,}37339 \qquad MS = 0{,}0065 \qquad (2).$$

Umerjanje našega merilnega sistema je potekalo pri temperaturi zraka okolice 22 °C, zato iz modela izračunamo tudi vrednosti izhodne napetosti pri tej temperaturi. Teoretične vrednosti izhodnih napetosti smo izračunali za isti razpon tlakov iz enačbe (2).

Calibration of our surveyor's chain was made at air temperature 22 °C, so output voltages at this temperature were calculated from a quadratic model. From equation (2) theoretical values of voltage were calculated for the same range of pressure.

Preglednica 5: *Izračunane vrednosti izhodnih napetosti pri konstantni temperaturi 22 °C, ki so dobljene na podlagi podatkov dobavitelja*

Table 5: *Calculated drop in voltage at constant temperature (22 °C) obtained from information delivered by the supplier*

p bar	0	0.5	1	1.5	2	2.5	3
U_1 izračunan V U_1 calculated V	1.871	2.030	2.188	2.346	2.503	2.660	2.816

Po podatkih v preglednici 5 smo izračunali enačbo premice:

From numbers in Table 5, the linear equation was calculated:

$$U_1 = 0{,}31482\ p + 1{,}87265 \qquad MS = 0{,}00001 \qquad (3).$$

Linearno transformacijo izračunamo iz regresijskih premic:

Linear transformation is calculated from regression lines:

$$k = \frac{\left(U_1(1) - U_1(0)\right)}{\left(U_2(1) - U_2(0)\right)} = \frac{0{,}31482}{1{,}65392} = 0{,}190348$$

$$n = U_1(1) - kU_2(1) = 2{,}18747 - 0{,}190348 \cdot 5{,}0273 = 1{,}23122$$

$$U_0 = kU_1 + n = 0{,}190348\ U_1 + 1{,}23122 \qquad (4).$$

Pri izvajanju preizkusov in zajemanju izmerkov smo opisani postopek temperaturne kompenzacije uporabili, ko smo že zajeli v računalnik prek merilne kartice z zaznavalom odbrano temperaturo mlevne mase T in s tlačnim pretvornikom odbrano napetost U_2. Z računalniškim programom smo po enačbi (4) izračunali napetost U_1 in iz izračunane napetosti in temperature smo po enačbi (1) izračunali tlak.

S temperaturno kompenzacijo smo prikazali, da je modeliranje uporabno že v fazi zajemanja podatkov.

In the phase of experimentation and acquisition of measurements, the result of temperature compensation was used. The temperature of grinding mass T and voltage U_2 from the pressure transducer were simultaneously acquired in the computer. A computer program was used for automatic calculation of voltage U_1, by using equation (4) and final pressure, by using equation (1).

Temperature compensation is an example of implementig a model in a system for measurement acquisition and control.

1.6.2 Linearni modeli delovanja krogličnega mlina

Ko so bili preizkusi končani, smo vse pomembne podatke zbrali v obliki ASCII datoteke (preglednici 1). Ti podatki so bili temelj za modeliranje in za določitev strategije mletja. Najprej smo izračunali preproste linearne modele za naslednje odgovore:

- čas na enoto mase Y1
- zrnatost delcev Y2,
- porabo energije na enoto mase Y3,
- temperaturo mlevne mase na izhodu iz mlevne posode Y6,
- masni tok mlevne mase Y9,
- tlak mlevne mase Y10,
- izhod med vstopno in izstopno temperaturo hladilne vode Y7.

Dejavniki so bili:

- viskoznost mlevne mase X1,
- pretok hladilne vode X2,
- vrtilna frekvenca črpalke X3,
- vrtilna frekvenca mešala X4,
- količina kroglic X5.

Za vsak odgovor smo izračunali linearni model v obliki:

1.6.2 Linear models of grinding with a pearl mill

When all measurements had been executed, the selected data were gathered in the form of an ASCII (Table 1) file. The models and strategy of the grinding process were determined from the data. First, linear models were calculated. The responses are as follows:

- time for grinding one kilogram of grinding mass Y1,
- the granulation of particles Y2,
- consumption of energy per weight unit of grinding mass Y3,
- temperature of outflow grinding mass Y6,
- flow of grinding mass Y9,
- pressure in mill Y10, and
- difference between temperature of inflow and outflow cooling water Y7.

Factors are as follows:

- viscosity of grinding mass X1,
- flow of cooling water X2,
- rotation frequency of pump X3,
- rotation frequency of mill X4,
- amount of pearls in the mill X5.

One linear model was calculated for every particular response:

$$Y_i = A + BX_1 + CX_2 + DX_3 + EX_4 + FX_5 \qquad (5),$$

i= 1, 2, 3, 6, 7, 9, 10 so zaporedne številke merjenih odgovorov Y.

A, B, C, D, E in F so parametri linearnega modela.

Ustreznost vsakega modela smo ugotavljali z računanjem naslednjih statističnih parametrov, npr:

- Fisherjevo razmerje (neujemanje) (F_{lof}),
- faktor regresije (F_{reg}),
- deterministični koeficient (DK),
- korelacijski koeficient (KK).

Za dober model veljajo različna merila:

- $F_{reg} >> F_{lof}$,
- DK čim bližji vrednosti 1,
- KK čim bližji vrednosti 1,
- F_{lof} manjši od tabelirane vrednosti v preglednicah kritičnih vrednosti F.

V preglednicah kritičnih vrednosti F v [1] vidimo, da so odvisne od dveh prostostnih stopenj. V preglednicah kritičnih vrednosti F za 4 in 10 prostostnih stopenj je, pri intervalu zanesljivosti α = 0,05, zapisana vrednost 5,964.

i= 1, 2, 3, 6, 7, 9, 10 are sequential numbers of measured responses Y.

A, B, C, D, E, and F are parameters of the linear model.

The accuracy of all models was validated with statistical parameters as follows:

- Fisher ratio (»Lack of fit«) (F_{lof}),
- factor of regression (F_{reg}),
- deterministic coefficient (DK),
- correlation coefficient (KK).

Criteria for a good model are as follows:

- $F_{reg} >> F_{lof}$,
- DK as close as possible to value 1,
- KK as close as possible to value 1,
- F_{lof} smaller than critical F value obtained from statistical tables.

In tables containing the critical F value [1], it can be seen that they depend on two degrees of freedom. The value of critical F value for 4 and 10 degrees of freedom at interval of confidence α = 0.05 obtained is 5.964.

Preglednica 6: *Ovrednotenje linearnih modelov z izračunom različnih statističnih parametrov*
Table 6: *Values of statistical parameters used for validation of linear models*

Odgovor Response	F_{lof}	F_{reg}	*DK*	*KK*
Y1	15.38	19.91	0.90	0.86
Y2	4.82	8.65	0.76	0.67
Y3	21.44	21.32	0.92	0.89
Y6	19.39	8.21	0.74	0.65
Y9	0.39	133.31	0.98	0.97
Y10	1.27	8.06	0.76	0.67
Y7	8.76	19.68	0.88	0.84

V preglednici 6 vidimo, da so izračunane vrednosti F_{reg} pri vseh odgovorih razmeroma visoke. To pomeni, da odgovori niso neodvisni od dejavnikov. Primerjava F_{lof} s tabelirano kritično vrednostjo F pokaže, da je samo za Y2, Y9, in Y10 primeren linearni model. Visoke vrednosti drugih F_{lof} nam povedo, da so primernejši modeli polinomi višjega reda ali celo neka druga enačba (eksponentna, logaritmična itn.). Glede na vrednosti determinističnih in korelacijskih koeficientov so najprimernejši modeli za Y1, Y3 in Y9.

Sklenemo lahko, da je bila izbira dejavnikov pravilna za večino odgovorov. Linearni model je zadosten le za Y2, Y9, in Y10. Za vse druge odgovore bi morali modelirati s polinomi višjega reda. Ker že kvadratični model s petimi spremenljivkami vsebuje 21 členov, 16 različnih preizkusov za postavitev takega modela ne zadostuje. Za postavitev in ovrednotenje kvadratičnega modela bi morali narediti vsaj še 5 dodatnih preizkusov.

Ker pri modeliranju prve serije preizkusov ni bil upoštevan peti preizkus (preglednica 1), smo naredili še dva dodatna preizkusa. Z dodatnima preizkusoma smo dobili enakomernejšo razporeditev preizkusov v prostoru dejavnikov. Poleg tega je bil tretji preizkus ponovljen (preglednica 7).

It can be seen in table 6, that all F_{reg} values are relatively high. If the values of F_{reg} are significant, it can be assumed that responses actually depend on factors. Comparison of F_{lof} with critical F value in the tables shows thata linear model is apropriate only for Y2, Y9, and Y10 responses. High values of other F_{lof} indicate, that other models (higher polynomials, exponential, logarithmic etc.) are more adequate to describe other responses. From the value of deterministic and correlation coefficients, it can be said that responses Y1, Y3, and Y9 are appropriately described with linear models.

From the linear models it can be concluded that factors are correctly chosen for the simulation of selected responses. Linear models describe responses Y2, Y9, and Y10 well enough. For simulating all other responses, another analytical function should be chosen. A quadratic model for five factors contains 21 terms (free parameters) and is too large to be retrieved from only 16 different experiments. For obtaining a quadratic model, at least 5 experiments must additionally be performed.

Because the planned fifth experimental point (Table 1) was not completed in the first series of experiments, two additional experiments were made. The purpose of the additional experiments was to keep an equal distribution of experiments in the factorial area. A repetition of the third experiment was also made (Table 7).

Preglednica 7: *Dejavniki in odgovori pri dodatnih preizkusih*
Table 7: *Values of factors and responses at additional experiments*

Št. vzor. No. exp.	X1	X2	X3	X4	X5	Y1	Y2	Y3	Y6	Y9	Y10	Y7
	s	l/h	min^{-1}	min^{-1}	%	s/kg	μm	Wh/kg	°C	kg/h	bar	K
1	58	277	40	1774	30	214.8	12	143.62	35.7	19.23	0.33	7.1
2	58	807	236	1774	30	40.3	20	30.05	35.9	99.49	2.84	2.1
3*	20	727	236	1030	70	48.6	13	38.75	42.8	75.37	1.87	2.9

Dodatne preizkuse smo vključili v našo datoteko in izdelali še eno skupino linearnih modelov. Rezultati statistične analize so bili tudi pri drugi skupini modelov podobni kakor pri prvi.

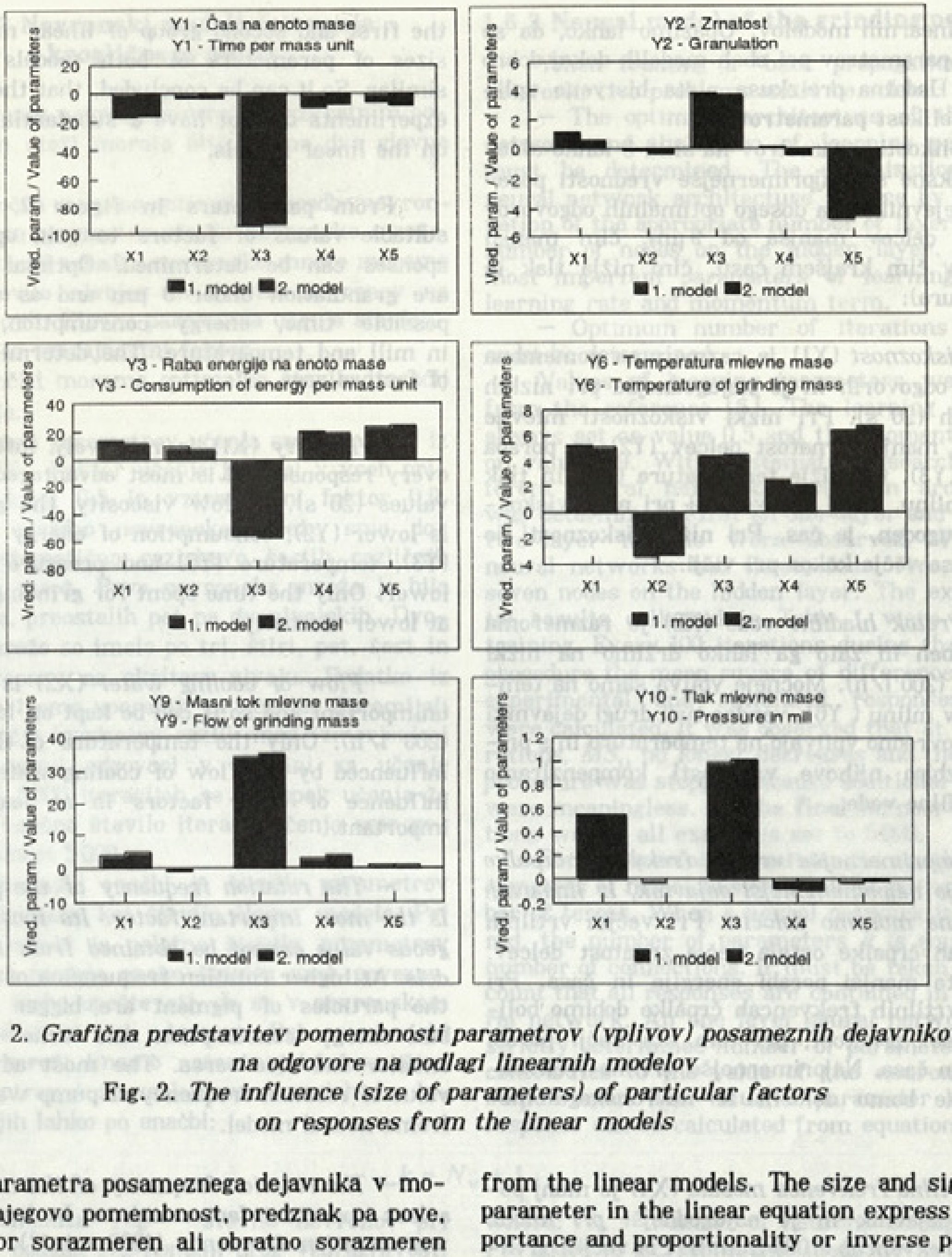
Kljub neustreznosti nekaterih linearnih modelov lahko iz njih določimo glavne odvisnosti odgovorov od posameznih dejavnikov.

Prve ugotovitve, ki jih lahko razberemo iz linearnih modelov, se nanašajo na pomembnost vpliva posameznih dejavnikov na izbrani odgovor.

Results of additional experiments were included in the file and a second group of linear models was calculated. The result of statistical analysis of the second group of models was similar to the results of analysis of the first group.

Although some linear models are not appropriate to describe a process, some basic dependencies of every response on a particular factor can be determined from them.

First, the size of influence of particular factors on a selected response can be obtained



Sl. 2. *Grafična predstavitev pomembnosti parametrov (vplivov) posameznih dejavnikov na odgovore na podlagi linearnih modelov*

Fig. 2. *The influence (size of parameters) of particular factors on responses from the linear models*

Velikost parametra posameznega dejavnika v modelu kaže njegovo pomembnost, predznak pa pove, ali je faktor sorazmeren ali obratno sorazmeren odgovoru. Ker so velikostni redi posameznih dejavnikov zelo različni, so bile vrednosti vseh dejavnikov pred modeliranjem linearno transformirane v območje med 0 in 1 po enačbi:

from the linear models. The size and sign of the parameter in the linear equation express the importance and proportionality or inverse proportionality of the factor. To eliminate the effect of different sizes of factor, they were all linearly transformed in the range from 0 to 1 prior to modelling:

$$X^t = \left(X - X_{min}\right) / \left(X_{maks} - X_{min}\right) \quad (6).$$

Za prvi dejavnik (viskoznost) na primer velja:

For example, the first factor (viscosity) was:

$$X1^t = (X1 - 20)/(62 - 20)$$

Pri analizi pomembnosti vplivov posameznih dejavnikov na izbrani odgovor si lahko pomagamo z diagrami na sliki 2. Stolpični diagrami ponazarjajo vrednosti parametrov za prvi in drugi

To visualise the influence of particular factors on a selected response, diagrams (as in figure 2) can be helpful. The two different greyness of columns represent the value of parameters for skupini linearnih modelov. Opazimo lahko, da se velikosti parametrov pri obeh modelih dokaj dobro ujemajo. Dodatna preizkusa nista bistveno vplivala na velikost parametrov.

Iz velikosti parametrov na sliki 2 lahko sklepamo, kakšne so najprimernejše vrednosti posameznih dejavnikov za dosego optimalnih odgovorov (zrnatost delcev manjša od 9 µm, čim manjši stroški, v čim krajšem času, čim nižja tlak in temperatura):

— *Viskoznost* (X1) je razmeroma pomembna pri vseh odgovorih in je najugodnejša pri nizkih vrednostih (20 *s*). Pri nizki viskoznosti mlevne mase sta manjši zrnatost delcev (Y2) in poraba energije (Y3), ter nižja temperatura (Y6) in tlak (Y10) v mlinu. Edini odgovor, ki pri nižji viskoznosti ni ugoden, je čas. Pri nižji viskoznosti je poraba časa večja kakor pri višji.

— *Pretok hladilne vode* (X2) je razmeroma nepomemben in zato ga lahko držimo na nizki vrednosti (200 l/h). Močneje vpliva samo na temperaturo v mlinu (Y6), vendar tudi drugi dejavniki vsaj enakovredno vplivajo na temperaturo in s primerno izbiro njihove vrednosti kompenziramo vpliv hladilne vode.

— *Najprimernejše vrtilne frekvence črpalke* (X3), *ki je najpomembnejši dejavnik, iz linearnih modelov ne moremo določiti.* Pri večjih vrtilnih frekvencah črpalke ostaja večja zrnatost delcev, vendar sta manjši porabi energije in časa. Pri manjših vrtilnih frekvencah črpalke dobimo boljšo (manjšo) zrnatost, pri tem sta večji porabi energije in časa. Najprimernejšo vrtilno frekvenco črpalke bomo določili iz nevronskega modela.

— *Vrtilna frekvenca mešala* (X4) je manj pomemben dejavnik in je najugodnejši *pri nizkih vrtilnih frekvencah* (1000 min^{-1}). Pri večjih vrtilnih frekvencah mešala se porabi več energije in poveča se temperatura mlevne mase v mlinu. Na preostale odgovore vrtilna frekvenca mešala ne vpliva bistveno.

— *Najprimernejšega deleža kroglic v mlinu* (X5), *ki je zelo pomemben dejavnik, iz linearnih modelov ne moremo določiti.* Pri večjem deležu kroglic dobimo boljšo (manjšo) zrnatost, toda pri tem sta poraba energije in temperatura v mlinu večji. Pri manjšem deležu kroglic v mlinu ostaja večja zrnatost delcev, vendar sta manjši poraba energije in nižja temperatura. Najprimernejši delež kroglic v mlinu bomo določili iz nevronskega modela.

the first and second group of linear models. The sizes of parameters at both models are very similar. So it can be concluded, that the additional experiments did not have a substantial influence on the linear models.

From parameters in figure 2, the most suitable values of factors to gain optimal responses can be determined. Optimal responses are granulation under 9 µm and as reduced as possible time, energy consumption, pressure in mill and temperature. The determined values of factors are:

—*Viscosity* (X1) is relatively influential on every response and is most advantageous at low values (20 *s*). At low viscosity, the granulation is lower (Y2), consumption of energy is smaller (Y3), temperature (Y6) and pressure (Y10) are lower. Only the time spent for grinding is longer at lower viscosity.

— *Flow of cooling water* (X2) is relatively unimportant and so it can be kept on lower value (200 l/h). Only the temperature of the mill is influenced by the flow of cooling water, but the influence of other factors is at least equally important.

— *The rotation frequency of the pump* (X3) *is the most important factor. Its most advantageous value cannot be obtained from linear models.* At higher rotation frequencies of the pump, the particles of pigment are bigger on outlet, but energy consumption and time spent are smaller and vice versa. The most advantageous value of rotation frequency of pump was obtained froma neural model.

— *The rotation frequency of the mill* (X4) is a less important factor and can be kept on a *lower rotation frequency* (1000 min^{-1}). At higher rotation frequencies of the mill, the consumption of energy is bigger and the temperature in the mill is higher. The influence of the rotation frequency of the million other responses is negligible.

— *Percentage of pearls in the mill* (X5) *is a important factor. Its most advantageous value cannot be obtained from linear models.* At a higher percent of pearls in the mill, the granulation of pigment particles is better, but energy consumption is larger and the temperature in the mill is higher and vice versa. The most advantageous value of this factor was obtained from a neural model.

1.6.3 Nevronski modeli delovanja krogličnega mlina

Pri učenju nevronske mreže z vzvratnim popravljanjem uteži morata biti rešena dva glavna problema:

— Določiti moramo optimalno zgradbo nevronske mreže in parametre učenja nevronske mreže. Pri optimizaciji zgradbe nevronske mreže moramo določiti število nivojev in število nevronov na skritih nivojih. Glavna parametra učenja sta faktor učenja in vztrajnostni faktor.

— Določiti moramo optimalno število iteracij (dob) učenja.

Vrednosti parametrov učenja smo prevzeli iz literature [6]. Faktor učenja je imel v vseh primerih vrednost 0,5 in vztrajnostni faktor 0,9. Optimalno zgradbo nevronske mreže smo določili s sistematično raziskavo šestih različnih nevronskih mrež. Prva nevronska mreža je bila enonivojska, preostalih pet pa dvonivojskih. Dvonivojske mreže so imele po tri, štiri, pet, šest in sedem nevronov na skritem nivoju. Podatke iz preglednice 1 smo uporabili za učenje. Spremljali smo povprečje kvadratov razlik med izmerjenimi in izračunanimi odgovori v skupini za učenje (MS_u). Pri 5000 iteracijah se postopek učenja že ustavi. Za končno število iteracij učenja smo postavili vrednost 5000.

V polinomski enačbi je število parametrov modela k določeno kot število členov modela. Pri nevronski mreži je celotno število parametrov nevronskega modela enako številu vseh povezav. Pri tem je treba upoštevati, da so v nevronskem modelu vsebovani vsi odgovori. Pri enonivojski nevronski mreži imamo natančno določeno število parametrov k za vsak nevron na izhodu. Izračunamo jih lahko po enačbi:

$$k = N_v + 1 \tag{7}$$

pri tem pomenita: N_v — število nevronov pri vhodu, 1 — dodana N_v pomeni prag vzdražljivosti (bias).

Iz enačbe (7) lahko vidimo, da je vrednost parametra k enonivojske nevronske mreže enako vrednosti parametra k linearnega modela.

1.6.3 Neural model of the grinding pearl mill

When training a 'back propagation' neural network, two problems must be solved:

— The optimum architecture of the neural network and the value of learning parameters must be determined. The optimisation of the neural network architecture is done by determination of the appropriate number of layers and the number of nodes on the hidden layer. The two most important parameters of learning are the learning rate and momentum term.

— Optimum number of iterations (epochs) must be determined.

Values of learning parameters were taken from the reference [6]. The learning rate was always set on value 0.5 and the momentum term on value 0.9. With systematic research of different neural networks, optimum architecture was determined. First an one-layer and then five two-layer neurals were observed. Two-layer neural networks had three, four, five, six, and seven nodes on the hidden layer. The experimental results collected in Table 1 were used for training. Every 100 iterations during the training procedure the mean square of difference between experimental and simulated responses (MS_u) were calculated. It was observed that at 5000 iterations, MS_u no longer decreases and the training procedure was stopped because additional iterations were meaningless. So the final number of iterations was in all examples set to 5000.

For a polynomial equation, the number of parameters of model k is determined with the number of terms. When a neural network is considered, the number of parameters k is equal to the number of connections. It must be taken in to account that all responses are contained in one neural network. An one level neural network has a strictly determined number of parameters k that contributes to the value of the neurone on the output layer. The value of parameter k for one response can be calculated from equation:

$$k = N_v + 1 \tag{7}$$

where: N_v — number of neurons on input layer, 1 — added to N_v represents bias.

From equation (7) it can be seen that the value of parameter k for one-layer neural networks is equal to the value of parameter k for linear model.

Preglednica 8: *Potek MS_u pri učenju vseh šestih nevronskih mrež*
Table 8: *Course of MS_u at training all six neural networks*

Število iteracij Number of iterations	MS_u pri različnem številu nevronov na skritem nivoju / MS_u at different number of nodes on hidden layer					
	0 nevronov 0 neurone	3 nevroni 3 neurones	4 nevroni 4 neurones	5 nevronov 5 neurones	6 nevronov 6 neurones	7 nevronov 7 neurones
1000	0.113658	0.107063	0.095479	0.087256	0.112953	0.077028
2000	0.110477	0.103607	0.088760	0.077982	0.086196	0.062389
3000	0.107663	0.102069	0.086550	0.069851	0.071457	0.056944
4000	0.107653	0.101719	0.085873	0.068827	0.069872	0.056095
5000	0.106165	0.101624	0.085585	0.068440	0.069254	0.055787

Za statistično analizo dvonivojskega nevronskega modela nimamo natančno določene vrednosti parametra *k*. Za povezave na izhodnem nivoju lahko natančno določimo, kateremu odgovoru pripadajo. Povezave na skritem nivoju so skupne vsem odgovorom. Pri nevronski mreži lahko določimo vrednosti parametra *k* s predpostavko, da so vse lastnosti v nevronskem modelu enakomerno udeležene v povezavah na skritem nivoju. Vrednost parametra *k* določimo po enačbi:

When statistical analysis of a two-layer neural network model is applied, the value of parameter *k* is not strictly determined. For all connections on the output layer, the corresponding response can be determined, but connections on the hidden layer are common to all responses. For a two-layer neural network, the value of parameter *k* can be determined with the presumption that all responses are influenced equally by the connections on the hidden layer. The value of parameter *k* for one response can be determined as follows:

$$k = \frac{(N_v + 1)\, N_s}{N_1} + (N_s + 1) \quad (8),$$

kjer so: N_v — število nevronov pri vhodu, N_s — število nevronov pri skritem nivoju, N_1 — število nevronov pri izhodu, enici, dodani N_v in N_s pomenita prag vzdražljivosti.

Najboljši nevronski model smo določili na podlagi vrednosti F_{lof}. V preglednici 9 so podane vse vrednosti F_{lof} za vseh šest nevronskih modelov po 5000 iteracijah učenja. Parametre *k* smo izračunali iz enačb 7 in 8. Pri odbiranju iz preglednic kritičnih vrednosti F [1] smo uporabili zaokroženo vrednost parametra *k*.

where: N_v — number of neurones on input, N_s — number of neurones on hidden layer, N_1 — number of neurones on output layer, one added to N_v and N_s represent biases.

The most appropriate neural model was determined from the values of F_{lof}. In table 9, all values of F_{lof} for all six neural models (after 5000 training iterations) are presented. Parameters *k* were calculated from equations 7 and 8. Values were not integer number, rounded values of parameters *k* were used, when critical F values were read from the tables [1].

Preglednica 9: *Vrednosti* F_{lof} *za sedem lastnosti pri vseh šestih nevronskih mrežah*
Table 9: *Values of* F_{lof} *for seven responses obtained at all six different neural networks*

Št. nevronov na skritem nivoju / No. of nodes on hidden layer	Izračunani parameter k / Calculated parameter k	Izračunani F_{lof} / Calculated F_{lof}							Zaokroženi parameter k / Rounded value of param. k	Kritična F vrednost / Critical *F* value
		Y1	Y2	Y3	Y6	Y9	Y10	Y7		
0	6	9.33	3.97	14.16	17.69	0.35	1.14	5.30	6	5.964
3	6.67	4.19	1.08	20.05	18.03	1.98	1.12	8.50	7	5.999
4	8.43	5.33	2.96	17.34	10.87	2.00	0.50	8.39	8	6.041
5	10.29	4.53	0.82	6.32	16.83	1.01	0.34	4.99	10	6.163
6	12.14	7.49	4.58	17.04	19.72	1.04	0.40	4.90	12	6.388
7	14	6.31	2.84	19.21	17.95	0.94	0.57	2.78	14	6.944

Že enonivojski nevronski model (preglednica 9) ima vse vrednosti F_{lof} nižje od linearnega modela (preglednica 6). Iz preglednice 9 vidimo, da je za večino lastnosti nevronska mreža s petimi nevroni na skritem nivoju najugodnejši model. Model je neprimeren le za Y6 (temperatura mlevne mase na izhodu). Nekoliko čez tabelirano vrednost je še F_{lof} za Y3 (poraba energije na enoto mase). Iz drugih vrednosti F_{lof} lahko sklepamo, da je model primeren. Za nevronski model s petimi nevroni na skritem nivoju smo izračunali še nekaj statističnih parametrov (preglednica 10), ki dokazujejo ustreznost nevronskega modela.

Even the neural network with one layer (Table 9) has all values F_{lof} lower than linear (Table 6). In table 9 it can be seen that almost all responses are simulated best with a neural network with five nodes on the hidden layer. The selected model is not complex enough only for Y6 (temperature of outflow grinding mass). The value of F_{lof} for Y3 (consumption of energy per kilogram of grinding mass) is a bit higher than critical F value. From F_{lof} values calculated for other responses, it can be assumed that the model is appropriate. For a selected neural model with five nodes on the hidden layer some additional statistical parameters were calculated (Table 10) which demonstrate the adequacy of the selected model.

Preglednica 10: *Ovrednotenje nevronskega modela s petimi nevroni na skritem nivoju z izračunom različnih statističnih parametrov: Fisherjevo razmerje* (F_{lof}), *faktor regresije* (F_{reg}), *deterministični koeficient* (DK) *in korelacijski koeficient* (KK) *za vse obravnavane lastnosti*

Table 10: ***Validation of neural model with five neurons on hidden layer with calculation of sta- tistical parameters: Fisher ratio*** (F_{lof}), ***factor of regression*** (F_{reg}), ***deterministic coef ficient*** (DK) ***and correlation coefficient*** (KK)

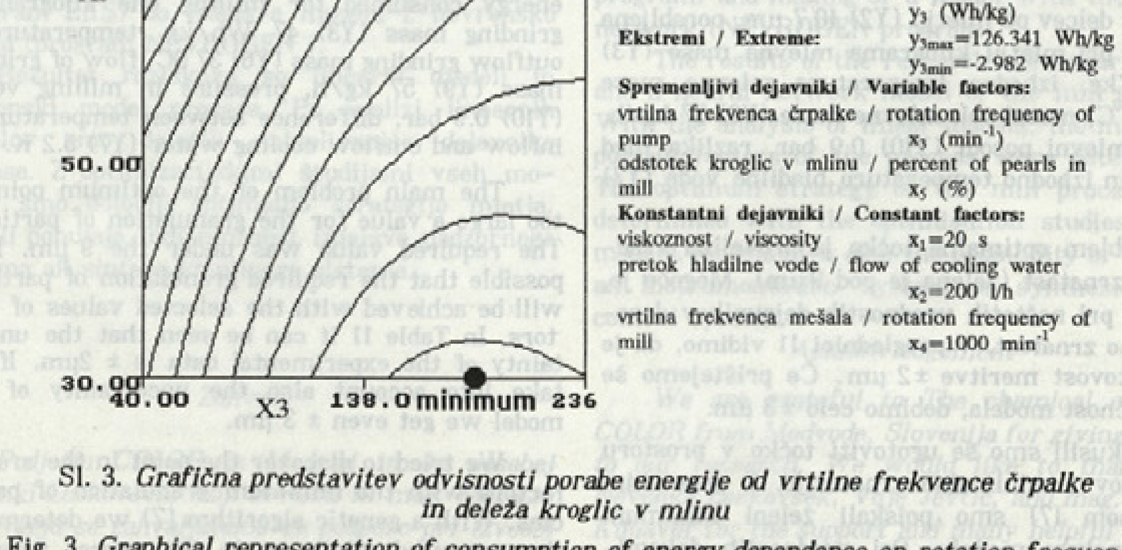
Odgovor Response	F_{lof}	F_{reg}	*DK*	*KK*
Y1	4.53	43.34	0.97	0.94
Y2	0.82	24.22	0.95	0.90
Y3	6.32	45.26	0.94	0.88
Y6	16.83	7.35	0.91	0.84
Y9	1.01	40.85	0.98	0.97
Y10	0.34	10.17	0.90	0.81
Y7	4.99	23.30	0.97	0.94

Za določitev strategije mletja smo preučili grafično predstavitev porabe časa (Y1), rabe energije (Y3) in zrnatosti delcev (Y2) v odvisnosti od vrtilne frekvence črpalke (X3) in deleža kroglic v mlinu (X5). Pri konstantni viskoznosti 20 s (X1), pretoku hladilne vode 200 l/h (X2) in vrtilni frekvenci mešala 1000 min^{-1} (X4) smo izrisali prereze izračunane na podlagi nevronskega modela.

Pri prvem mletju lahko dosežemo najmanjšo zrnatost delcev pri 70 odstotkih kroglic v mlinu. Od 40 do 150 min^{-1} vrtilne frekvence črpalke je območje minimuma zrnatosti. Poraba energije in časa je manjša pri vrtilni frekvenci črpalke 150 min^{-1}.

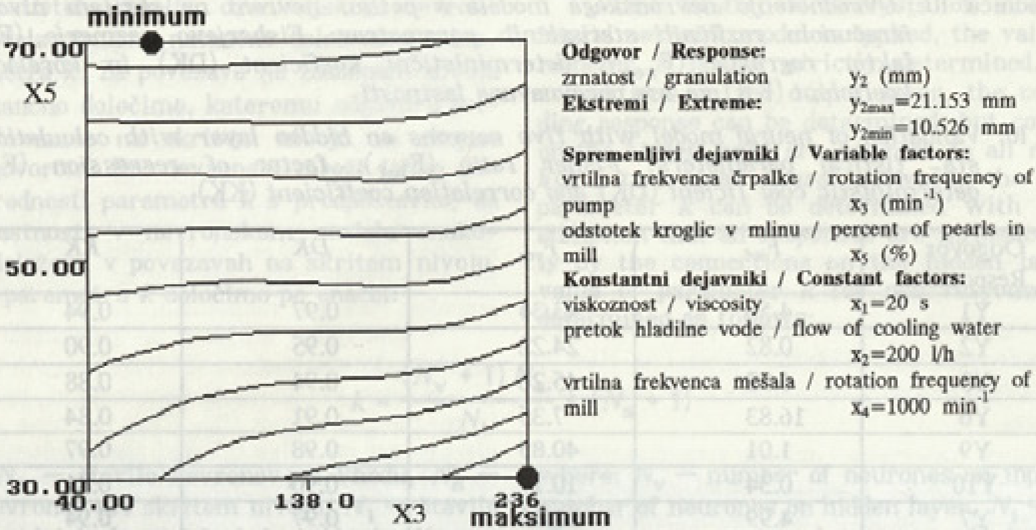
The strategy of the grinding process was determined from a graphical representation of time (Y1), energy consumption (Y3) and granulation of pigment particles (Y2) in dependence on rotation frequency of pump (X3) and percent of pearls in mill (X5). The constant factors were: viscosity at 20 s (X1), flow of cooling water at 200 l/h (X2), and rotation frequency of mill at 1000 min^{-1} (X4). Contours were retrieved from the selected neural model.

At first grinding, the best granulation of particles is achieved when 70 percent pearls are contained in the mill. The area of minimum granulation is in the domain from 40 to 150 revolutions of pump per minute. The consumption of energy and time is smaller if the rotation frequency of the pump is around 150 min^{-1}.



Sl. 3. *Grafična predstavitev odvisnosti porabe energije od vrtilne frekvence črpalke in deleža kroglic v mlinu*

Fig. 3. ***Graphical representation of consumption of energy dependence on rotation frequency of pump and percent of pearls in the mill***



Sl. 4. *Grafična predstavitev odvisnosti zrnatosti delcev od vrtilne frekvence črpalke in deleža kroglic v mlinu*

Fig. 4. *Graphical representation of granulation of particles dependence on rotation frequency of pump and percent of pearls in the mill*

1.6.4 Določitev optimalne strategije mletja

S postopkom načrtovanja preizkusov in uporabe nevronskih mrež v fazi modeliranja smo določili optimalno strategijo mletja s krogličnim mlinom. Mletje bo glede na vse lastnosti potekalo optimalno pri naslednjih vrednostih dejavnikov: viskoznost 20 s, pretok hladilne vode 200 l/h, vrtilna frekvenca črpalke 150 min^{-1}, vrtilna frekvenca mešala 1000 min^{-1} in delež kroglic v mlinu 70 odstotkov. Izračunane vrednosti lastnosti na podlagi nevronskega modela so: čas mletja kilograma mlevne mase (Y1) 95 s/kg, zrnatost delcev po mletju (Y2) 10,7 μm, porabljena energija pri mletju kilograma mlevne mase (Y3) 47 Wh/kg, izhodna temperatura mlevne mase (Y6) 37 °C, masni tok mlevne mase (Y9) 57 kg/h, tlak v mlevni posodi (Y10) 0,9 bar, razlika med vhodno in izhodno temperaturo hladilne vode (Y7) 5,2 K.

Problem optimalne točke je prevelika vrednost za zrnatost (želena je pod 9 μm). Mogoče je, da bomo pri naštetih vrednostih dejavnikov dosegli želeno zrnatost. V preglednici 11 vidimo, da je že negotovost meritve ±2 μm. Če prištejemo še nenatančnost modela, dobimo celo ±3 μm.

Poskusili smo še ugotoviti točko v prostoru dejavnikov z minimalno zrnatostjo. Z genetskim algoritmom [7] smo poiskali želeni minimum v nevronskem modelu. Pri vrednostih dejavnikov:

1.6.4 Determination of optimum strategy of the grinding

The optimum strategy of the grinding process was determined by using the procedure of experimental design and neural networks in a modelling phase. Grinding is optimal for all responses at the values of factors determined as follows: viscosity 20 s, flow of cooling water 200 l/h, rotation frequency of pump 150 min^{-1}, rotation frequency of mill 1 000 min^{-1}, and percent of pearls in the mill 70 %. Simulated values of response calculated from the neural model are as follows: time for milling one kilogram of grinding mass (Y1) 95 s/kg, granulation of particles (Y2) 10.7 μm, energy consumed for milling one kilogram of grinding mass (Y3) 47 Wh/kg, temperature of outflow grinding mass (Y6) 37 0C, flow of grinding mass (Y9) 57 kg/h, pressure in milling vessel (Y10) 0.9 bar, difference between temperature of inflow and outflow cooling water (Y7) 5.2 K.

The main problem of the optimum point is too large a value for the granulation of particles. The required value was under the 9 μm. It is possible that the required granulation of particles will be achieved with the selected values of factors. In Table 11 it can be seen that the uncertainty of the experimental data is ± 2μm. If we take into account also the uncertainty of the model we get even ± 3 μm.

We tried to discover the point in the area of factors with the minimum granulation of particles. With a genetic algorithm [7] we determined the requeired minimum in the neural network model. For example, if values for factors were:

Preglednica 11: *Vrednosti eksperimentalnih standardnih odmikov in standardnih odmikov med meritvami ter odgovori iz nevronskega modela*

Table 11: *Values of experimental standard deviations and standard deviations between the experimental data and responses from the neural network model*

	Y1	Y2	Y3	Y6	Y9	Y10	Y7
SD meritve SD of data	11	2	6	2	7	0.6	0.5
SD model SD of model	13	1	9	3	5	0.3	0.6

viskoznost 40 s, pretok hladilne vode 200 l/h, vrtilna frekvenca črpalke 40 min^{-1}, vrtilna frekvenca mešala 1 800 min^{-1} in delež kroglic v mlinu 70% so imele simulirane lastnosti iz nevronskega modela naslednje vrednosti: čas mletja kilograma mlevne mase (Y1) 209 s/kg, zrnatost delcev po mletju (Y2) 5,3 μm, poraba energije pri mletju kilograma mlevne mase (Y3) 200 Wh/kg, izhodna temperatura mlevne mase (Y6) 52 °C, masni tok mlevne mase (Y9) 18 kg/h, tlak v mlevni posodi (Y10) 0,3 bar, razlika med vstopno in izstopno temperaturo hladilne vode (Y7) 12 K.

2 SKLEP

V prispevku je na primeru optimizacije procesa mletja pigmenta s krogličnim mlinom prikazan celoten postopek sodobnega načrtovanja preizkusov. Računalniška podpora je bila uporabljena v vseh korakih izvajanja raziskave, od izdelave načrta preizkusnih točk (program SAS/ADX), zasnove in izvedbe merilnega sistema z avtomatskim zajemanjem izmerkov (program COLOR.BAS), obdelave izmerkov (program Lotus 1-2-3), izdelave linearnih modelov (program EKS) do izdelave modela z nevronsko mrežo (program NEVROGEN).

Rezultat raziskave so linearni modeli in nevronski model procesa. Po analizi linearnih modelov smo določili najvplivnejše dejavnike procesa. Z optimizacijskimi študijami vseh modelov smo določili optimalno strategijo mletja. Modeli ponujajo tudi možnost izdelave nadzornega sistema ali sinteze krmilnega sistema.

Zahvala

Podjetju COLOR iz Medvod in še posebej Nevenki Leskovšek, Voji Jevtiču in mag. Matjažu Kunaverju se zahvaljujemo za podporo pri izvedbi raziskave. Za pomoč pri izvedbi preizkusov pa se zahvaljujemo še Nadi Kršinar in Viliju Luštreku.

viscosity 40 s, the flow of cooling water 200 l/h, pump rotation frequency 40 min^{-1} mill rotation frequency 1800 min^{-1} and the amount of pearls in the mill 70% then the calculated properties or responses from the neural network model had the following values: time for milling a kilogram of grinding mass (Y1) 209 s/kg, granulation of particles (Y2) 5.3 μm, consumption of energy per kilogram of grinding mass (Y3) 200 Wh/kg, temperature of outflow grinding (Y6) 52 °C, flow of grinding mass (Y9) 18 kg/h, pressure in mill (Y10) 0.3 bar, difference between temperature of cooling water on input and output (Y7) 12 K.

2 CONCLUSION

In this contribution, the example of the the complete procedure of the up-to-date experimental design of the optimisation process of grinding colour with a pearl mill was shown. Computer support was present at all steps of implementation of the research, for example in the step of making of the experimental design (SAS/ADX system), planning and execution of the measurement system with the automatic acquisition of data (COLOR.BAS program), treatment of data (Lotus 1-2-3 program), making of linear models (EKS program) and making of a model with the neural network (NEVROGEN program).

The results of the research are linear models and a neural network model of the mill process. With the analysis of linear models, the most important factors of the process were determined. The optimum strategy of the mill process was determined with the optimisation studies of all models. Models give also the possibility of building an instrumentation system or synthesis of a control system.

Acknowledgement

We are grateful to The chemical company COLOR from Medvode, Slovenija for giving support to our research. We would like to thank also Nevenka Leskovšek, Voje Jevtič, and mag. Matjaž Kunaver for the support and many helpful discussions. We wish to thank Nada Kršinar and Vili Luštrek for help during the experimental work.

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Prejeto:
Received: 23.1.1995

Sprejeto:
Accepted: 4.5.1995