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Speciality paper

Postopek MPC za nadzor proizvodnih procesov
MPC Process Control Procedure

MARJAN DRUŽOVEC - ADOLF ŠOSTAR - ANDREJ GODINA

Proizvodi in proizvodni procesi so pogosto pod vplivom različnih sprememb, za katere moramo poiskati vzroke in jih odpraviti. Statistične nadzorne karte (SPC) lahko zaznavajo vplive, ki motijo proizvodni proces. V nasprotju z dobrimi rezultati nadzora proizvodnih procesov s statističnimi nadzornimi kartami te z gospodarskega vidika niso zmeraj najustreznejša izbira, posebej pri maloserijskih proizvodnjah. Kot alternativa se ponuja postopek Precontrol, ki pa ima v primerjavi z metodo SPC tudi nekaj pomanjkljivosti. V našem prispevku je podana modifikacija Precontrol, imenovana MPC, ki ohranja pozitivne lastnosti Precontrol in se po učinkovitosti približa SPC.

Ključne besede: procesi proizvodni, nadzor procesov, SPC, Precontrol, karte kontrolne statistične

Product and production processes are always subject to a certain number of variations for which we must discover a reason and correct it. Statistical process control (SPC) charts have the ability to indicate the presence of special causes that upset our processes. In spite of the generally good results in supervising the production processes the statistical control charts are economically not always a very good decision especially in a low series production. Precontrol as a much simpler alternative method has, however some weaknesses in comparison with the SPC. In our paper we present a modification of Precontrol, called the MPC method, which keeps all the benefits of Precontrol with an efficiency which is nearly as that good as of SPC.

Keywords: production processes, process control, SPC, Precontrol, statistical control chart

0 UVOD

Proizvodi in proizvodni procesi so izpostavljeni različnim vplivom, ki so rezultat naključij. Spremembe znotraj stabilnih mej naključnih vzrokov so neizbežne. Če začne proces delovati zunaj določenih stabilnih mej, želimo čimprej podatek o pomiku ali spremembi. Ko imamo indikacijo o pomiku procesa zunaj stabilnih mej ali o spremembi, imamo možnost odkriti vzrok in ga odpraviti.

Statistični nadzor procesov (SPC) spada med temeljna orodja za nadzor proizvodnih procesov, s katerimi zaznavamo motnje v procesih. SPC karte omogočajo vizualno ocenitev procesa glede na njegov položaj μ in raztros σ, kar omogoča zaznavanje, diagnozo in odpravljanje proizvodnih problemov v čim krajšem času. Rezultat je neprestano izboljševanje kakovosti proizvodnje. Nadzor proizvodnih procesov s statističnimi nadzornimi kartami daje v splošnem dobre rezultate, glavne pomanjkljivosti pa so:

- veliki stroški uvajanja zaradi urjenja osebja in vodenja dokumentacije,
- niso primerne v maloserijski proizvodnji, ker majhni vzorci niso ustrezni za statistično oceno raztrosa procesa in njegove pozicije.

Precontrol je alternativni postopek za krmiljenje procesov, ki je v primerjavi z regulacijskimi nadzornimi kartami preprostejša za učenje in zahteva bistveno manj napora za uporabo. Osnova za določitev mej pri krmiljenju procesa sta zgornja in spodnja tolerančna meja, ki ju je določil konstrukter. Za krmiljenje procesa je treba tolerančno območje razdeliti na štiri enaka območja. Srednji dve

0 INTRODUCTION

Products and production processes are always subject to a certain umber of variations as a result of chance alone. Variation within a stable pattern of chance causes is inevitable. If our process begins to operate outside this stable pattern, we want to know about this shift or upset as soon as possible. Once we have an indication of a shift outside a stable pattern of variation, we must discover the reason for the shift and correct it.

Statistical process control (SPC) charts were introduced as one of the fundamental tools for supervising the production processes. These charts have the ability to indicate the presence of special causes that upset the processes. The SPC chart enables visual assessment of a process with regard to its location μ and dispersion σ and so helps to detect, diagnose, and correct production problems in a timely fashion. The result is a substantial improvement in product quality. A supervision of the production processes with statistical control charts yields generally good results. Their main weaknesses are:

- high expenses, especially for training and education of staff and for documentation,
- they are not convenient for low series production because low lot sizes are not an appropriate base for statistical assessment of process dispersion and its location.

Precontrol is an alternative process control method which is much simpler than the SPC; it requires less effort for training and for process control. In this method the specification width for the dimensions of the end products is divided into two equal zones. The middle area is called the

označimo kot "zeleni coni" in obe zunanji kot "rumeni coni". Coni zunaj tolerančnih mej se imenujeta "rdeči coni". Pred začetkom serije potrebujemo vzorec petih izdelkov, med proizvodnjo pa vzorec dveh izdelkov, zajetih v izbranih intervalih. Očitno je, da so za nadzor procesov potrebni manjši vzorci kakor pri SPC. Prednosti v primerjavi s SPC lahko strnemo v naslednje točke:

- preprostejše uvajanje,
- primerna je za manjše serije,
- zahteva manj šolanja izvajalcev,
- manjši investicijski stroški.

V primerjavi s statističnimi nadzornimi kartami pa ima Precontrol naslednje pomanjkljivosti:

- velika verjetnost za uspešen predtek pri procesu, ki za proizvodnjo ni primeren,
- majhna občutljivost na spremembo procesa.

Glede na naštete lastnosti postopka Precontrol bi bilo zaželeno izvesti določene spremembe, ki bi ohranile prednosti in zmanjšale njegove pomanjkljivosti. Obstajajo številne možnosti modificiranja postopka Precontrol, npr. spreminjanje širine pasov in povečanje števila pasov v tolerančnem območju. S tem pa je seveda povezana tudi sprememba postopka izvajanja nadzora. Zato je pri modifikacijah potrebna previdnost, da dobljeni potopek ne bi postal preveč zapleten in bi bila osnovna ideja karte Precontrol, torej preprosta uporaba, izničena. Naša modifikacija postopka Precontrol v postopek MPC je bila izvedena za:

- povečanje občutljivosti na spremembe procesa,
- ohranitev primerljivosti krmiljenja procesa s SPC,
- ohranitev preprostosti osnovne zamisli kakor pri postopku Precontrol.

"green" and the two others the "yellow" zones. The area outside the specification width is called the "red" zone. Before starting the series, five units have to be taken out of the process. During running production two units were taken out in intervals with flexible rhythm. Evidently the Precontrol needs low lot sizes for the process control, as does SPC. The benefits of the Precontrol in comparison with the SPC are:

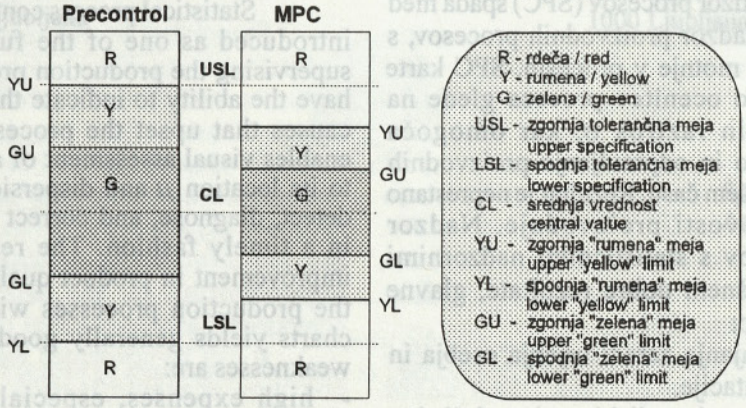
- less effort required for implementation,
- convenient for low series production,
- less training needed for workers,
- lower investment costs.

Precontrol has also some disadvantages compared to SPC:

- the probability of acceptance of the process before starting the series is relatively high if the process is not capable,
- low sensitivity for process variations.

According to the listed characteristics of Precontrol it is clear, that a modification is needed which would keep the benefits and eliminate the disadvantages. There are many possibilities for modifying the Precontrol, from changing the width of the zones to increasing the number of the zones. In the latter case the control procedure must be changed. All modifications must be done very carefully so that the new method doesn't become too complicated to fulfil the rudimentary ideas about the simplicity of the Precontrol. Our modification called MPC follows the next goals:

- to increase sensitivity to process variations,
- to sustain the efficiency of the MPC comparable to that of the SPC,
- to sustain the simplicity of the MPC comparable to the Precontrol.



Sl. 1. *Razdelitev con postopkov Precontrol in MPC*
Fig. 1. *Zones for Precontrol and MPC methods*

1 MPC - MODIFICIRAN POSTOPEK PRECONTROL

Pri snovanju postopka MPC je bilo raziskanih precej različnih variant, tudi takšne z večjim številom "barvnih con" znotraj tolerančnega območja. Glede na občutljivost in učinkovitost so bili rezultati zelo dobri. Pomanjkljivost teh variant

1 MPC - MODIFIED PRECONTROL METHOD

To obtain optimum results with the MPC method we have investigated many different modifications of the Precontrol. At first we examined the possibility of increasing the number of zones inside the specification limit. The result was optimistic with regard to sensitivity and efficiency. But the combinatorial possibility as to how units can

je povečanje števila pravil za posege v proces. S tem tretji cilj po preprostosti metode ni bil najbolje izpolnjen. Zato smo se pri snovanju MPC odločili, da kljub nekoliko slabšim rezultatom ohranimo enako število con kakor pri potopku Precontrol. Spremenili smo samo meje con, medtem ko je krmiljenje procesa podobno kakor pri postopku Precontrol.

1.1 Postopek MPC

Za izvajanje MPC je treba tolerančno območje med LSL in USL razdeliti na 6 enakih območij, kakor prikazuje slika 1. Enako kakor pri prej opisanem Precontrolu razglasimo notranja pasova kot "zeleni", sosednja kot "rumeni", celotna pasova na zunanji strani rumenih con pa sta "rdeči coni". Krmiljenje procesa s karto MPC poteka v dveh korakih.

- **Predtek.** Za predtek je treba preveriti 6 zaporednih izdelkov. Če sta veličini največ dveh izdelkov v "rumeni coni" in druge v "zeleni coni", je proces primeren (proces je centriran in raztros je v dovoljenih mejah) in lahko preidemo na proizvodni tek. V nasprotnem primeru proces ni pod nadzorom in je treba izvesti ukrepe za izboljšanje procesa in ponoviti predtek.
- **Proizvodni tek.** Za krmiljenje procesa izberemo dva zaporedna izdelka v izbranih intervalih in izmerjene veličine vnesemo v karto MPC. Proces ustavimo, če je en izdelek v "rdeči coni" ali pa oba v "rumeni". Odpraviti je treba vzrok za nepravilnost in ponoviti predtek. V vseh drugih primerih (nobena v rdeči coni ali vsaj ena v zeleni coni) nadaljujemo s proizvodnim tekom.

1.2 Funkcija operacijske karakteristike

Primernost karte MPC za odkritje premikov v kakovosti procesa prikazuje krivulja operacijske karakteristike (OC) karte. Za ocenitev učinkovitosti kart bomo prikazali krivulje OC za MPC, Precontrol in karte SPC, uporabljene za nadzor procesov.

Predpostavimo, da je indeks primernosti procesa c_p:

$$c_p = \frac{USL - LSL}{6\sigma} \tag{1}$$

znan in konstanten. Če se srednja vrednost procesa premakne z nadzorne vrednosti, npr. s srednje vrednosti CL na novo vrednost:

$$\mu = CL + d \cdot (USL - LSL)/2 \tag{2},$$

je verjetnost, da bo vzorec x v "zeleni" coni Pg in v "rumeni" Py za MPC in Precontrol:

$$Pg = P\{GL \le x \le GU\}$$
$$Py = P\{YL \le x \le YU\} - Pg \tag{3},$$

pri čemer sta GL, GU spodnja in zgornja "zelena" meja, YL in YU pa spodnja in zgornja "rumena"

occupy the zones also increased on account of the higher number of the zones. Because of this the aim of improving simplicity of the MPC method was only partially fulfilled. Finally, in spite of the slightly worse result, we decided to keep the three zones to account for simplicity. We changed the zone limits, while the procedure remained much the same as for the Precontrol.

1.1 MPC procedure

The elementary division of the specification width between upper specification USL and lower specification LSL for MPC is into six equal intervals (Fig. 1). The "green" zone occupies the middle two intervals and the "yellow" zone occupies the adjacent two intervals, as presented in figure 1. The two outside intervals and the whole area outside the specification limits present the "red" zone. MPC control procedure is described by the following steps.

- **Trial run**. Before starting the series, six successive units have to be taken out of the process. In case that at the most two units are inside the "yellow" zone, while all other units are inside the "green" zones, the process is accepted as quality capable (distribution is narrow and centred). So, it is possible to change over to production run procedure. If more than two units lie in the yellow or even the red zone, the machine should be checked and adjusted, and the trial run repeated.
- **Production run**. During running production two units have to be taken out at intervals with a flexible rhythm. The process is stopped if two units are red, red and yellow, or both yellow. The cause for this deviation has to be removed and the trial run must be repeated. In all other cases (none unit in red zone, and at least one unit in green zone) the production run procedure is continued.

1.2 The Operating-Characteristic Function

The ability of the MPC chart to detect shifts in process quality is described by their operating characteristic (OC) curves. To estimate efficiency we present these OC curves for MPC, Precontrol and SPC charts used for on-line control of the process.

Consider the process-capability index c_p:

$$c_p = \frac{USL - LSL}{6\sigma} \tag{1}$$

known and constant. If the mean shifts from the in-control value, say CL (centre line) to another value:

$$\mu = CL + d \cdot (USL - LSL)/2 \tag{2},$$

the probability of the sample x inside the "green" zone Pg and "yellow" zone Py for MPC and Precontrol is:

$$Pg = P\{GL \le x \le GU\}$$
$$Py = P\{YL \le x \le YU\} - Pg \tag{3},$$

where GL, GU are lower and upper "green" limits, YL and YU are lower and upper "yellow" limits.

meja. Enačbo (3) lahko zapišemo kot:

We may write eq. (3) as:

$$Pg = \Phi\left(\frac{GU-\mu}{\sigma}\right) - \Phi\left(\frac{GL-\mu}{\sigma}\right)$$
$$Py = \Phi\left(\frac{YU-\mu}{\sigma}\right) - \Phi\left(\frac{YL-\mu}{\sigma}\right) - Pg \quad (4).$$

Funkcija $\Phi(.)$ je standardna normalna kumulativna distribucijska funkcija:

Function $\Phi(.)$ denotes the standard normal cumulative distribution function:

$$P\{x \le a\} = \Phi\left(\frac{a-\mu}{\sigma}\right) = \int_{-\infty}^{a} \frac{1}{\sigma\cdot\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \cdot dx \quad (5).$$

Ker je iz (1):

Considering (1):

$$(USL - LSL)/2 = 3 \cdot c_p \cdot \sigma \quad (6),$$

lahko zapišemo sredjo vrednost μ iz (2) kot:

the mean μ in (2) is:

$$\mu = CL + 3 \cdot d \cdot c_p \cdot \sigma \quad (7),$$

"barvne" meje za MPC so potem:

the "colour" limits for MPC are:

$$GU_M = CL + 1/3 \cdot (USL - LSL)/2 = CL + c_p \cdot \sigma$$
$$GL_M = CL - 1/3 \cdot (USL - LSL)/2 = CL - c_p \cdot \sigma$$
$$YU_M = CL + 2/3 \cdot (USL - LSL)/2 = CL + 2 \cdot c_p \cdot \sigma \quad (8),$$
$$YL_M = CL - 2/3 \cdot (USL - LSL)/2 = CL - 2 \cdot c_p \cdot \sigma$$

za postopek Precontrol pa:

and the colour limits for Precontrol are:

$$GU_P = CL + 1/2 \cdot (USL - LSL)/2 = CL + 1.5 \cdot c_p \cdot \sigma$$
$$GL_P = CL - 1/2 \cdot (USL - LSL)/2 = CL - 1.5 \cdot c_p \cdot \sigma$$
$$YU_P = CL + (USL - LSL)/2 = CL + 3 \cdot c_p \cdot \sigma \quad (9).$$
$$YL_P = CL - (USL - LSL)/2 = CL - 3 \cdot c_p \cdot \sigma$$

Glede na (7) do (9) zapišemo (4) za MPC:

According to (7) to (9) we write (4) for MPC as:

$$Pg_M = \Phi(c_p - 3 \cdot d \cdot c_p) - \Phi(-c_p - 3 \cdot d \cdot c_p)$$
$$Py_M = \Phi(2 \cdot c_p - 3 \cdot d \cdot c_p) - \Phi(-2 \cdot c_p - 3 \cdot d \cdot c_p) - Pg_M \quad (10)$$

in za postopek Precontrol:

and for Precontrol as:

$$Pg_P = \Phi(1.5 \cdot c_p - 3 \cdot d \cdot c_p) - \Phi(-1.5 \cdot c_p - 3 \cdot d \cdot c_p)$$
$$Py_P = \Phi(3 \cdot c_p - 3 \cdot d \cdot c_p) - \Phi(-3 \cdot c_p - 3 \cdot d \cdot c_p) - Pg_P \quad (11).$$

Tako lahko izračunamo verjetnost uspešnega predteka Pt_M za MPC in Pt_P za Precontrol:

Now, we can compute the probability of a successful trial run Pt_M for MPC and Pt_P for Precontrol:

$$Pt_P = (Pg_P)^5$$
$$Pt_M = (Pg_M)^6 + 6 \cdot (Pg_M)^5 \cdot Py_M + 15 \cdot (Pg_M)^4 \cdot (Py_M)^2 \quad (12)$$

in nadaljevanje procesa P_M za MPC in P_P za Precontrol:

and also the probability of a successful process run P_M for MPC and P_P for Precontrol:

$$P_M = (Pg_M)^2 + 2 \cdot Pg_M \cdot Py_M$$
$$P_P = (Pg_P)^2 + 2 \cdot Pg_P \cdot Py_P \quad (13).$$

Verjetnost uspešnega procesa pri SPC je:

The probability of a successful run for SPC is:

$$P_{SPC} = P\{LCL \le \bar{x} \le UCL\} = \Phi\left(\frac{UCL-\mu}{\sigma/\sqrt{n}}\right) - \Phi\left(\frac{LCL-\mu}{\sigma/\sqrt{n}}\right) \quad (14).$$

Ker sta pri SPC zgornja in spodnja kontrolna meja:

$$UCL = CL + 3 \cdot \sigma/\sqrt{n}$$
$$LCL = CL - 3 \cdot \sigma/\sqrt{n} \quad (15),$$

lahko (14) zapišemo kot:

$$P_{SPC} = \Phi\left(3 - 3 \cdot \sqrt{n} \cdot c_p \cdot d\right) - \Phi\left(-3 - 3 \cdot \sqrt{n} \cdot c_p \cdot d\right) \quad (16),$$

kjer je n število enot v vzorcu.

Oglejmo si uporabo enačb (10) do (13) in (16) na primeru izračuna verjetnosti odkritja premika na novo vrednost $\mu = CL + d \cdot (USL - LSL)/2$ pri prvem vzorcu. Pt_M, Pt_P, P_M, P_P in P_{SPC} so verjetnosti, da premika ne odkrijemo (napaka β). Krivulja OC prikazuje napako β glede na velikost premika d za različne karte.

1.3 **Analiza MPC**

Za ocenitev učinkovitosti predteka in proizvodnega teka so na slikah 2 in 3 podane krivulje operacijskih karakteristik. Diagrami na slikah podajajo verjetnosti, da bo proces označen kot ustrezen za posamezne premike vrednosti μ med srednjo vrednostjo CL in zgornjo toleranco USL. Velikost premika je določena z vrednostjo veličine d, ki se giblje med 0 in 1.

Na sliki 2 so podani grafi verjetnosti uspešnega predteka MPC in Precontrol za procese s faktorjem primernosti $c_p = 1$, $c_p = 1{,}33$, $c_p = 1{,}66$ in $c_p = 2$. Iz diagramov je razvidno, da je za centrirane procese pri karti MPC verjetnost, da bodo sprejeti, nekoliko večja kakor pri uporabi Precontrol. Pri necentriranih procesih je verjetnost sprejetja pri obeh kartah približno enaka.

Krivulje operacijskih karakteristik za SPC, MPC in Precontrol za proizvodni tek za procese s faktorjem primernosti $c_p = 1$, $c_p = 1{,}33$, $c_p = 1{,}66$ in $c_p = 2$ so prikazane na sliki 3. Krivulja za SPC podaja primer, ko je za statistični nadzor procesa v vzorcu pet kosov. S slike je razvidno, da je karta MPC bistveno bolj primerljiva s SPC kakor postopek Precontrol.

Since the upper and lower control limits are:

we may write (14) as:

where n is the number of units in the sample.

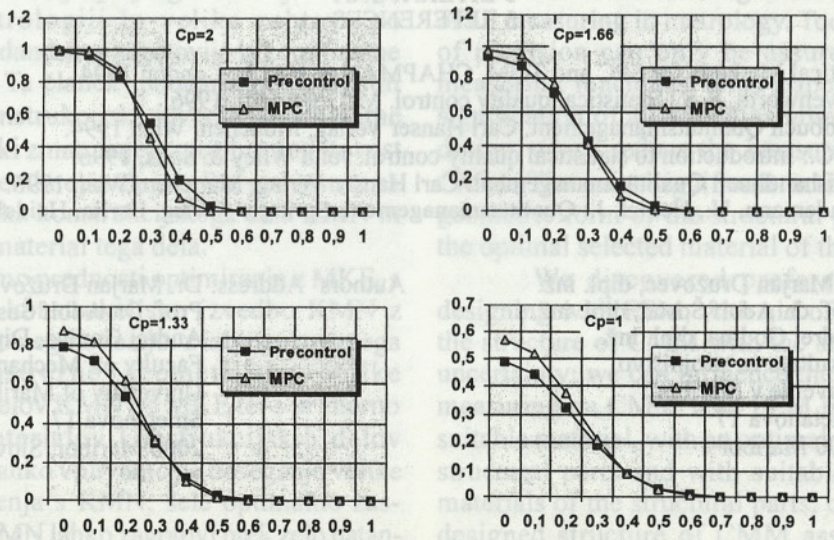
To illustrate the use of Equations (10) to (13) and (16) suppose we wish to determine the probability of detecting a shift to $\mu = CL + d \cdot (USL - LSL)/2$ on the first sample following the shift. The Pt_M, Pt_P, P_M, P_P and P_{SPC} are the probabilities of not detecting such a shift, also called β-risk. The OC curve for the different charts plots the β-risk against the magnitude of shift d.

1.3 **Analysis of MPC**

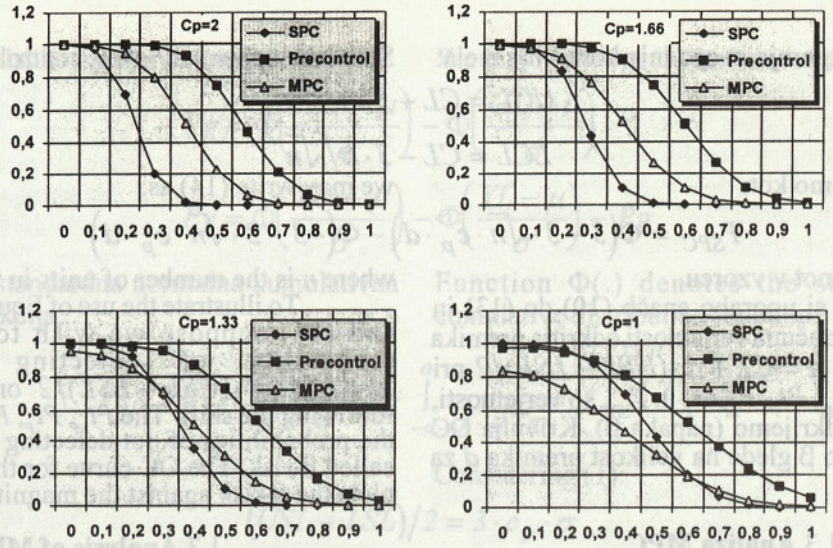
Some operating characteristic curves to estimate the efficiency of the trial run and of production runs are presented in Figures 2 and 3. The graphs in the figures present the probabilities that the process will be accepted as quality capable for different process shifts of mean μ between central line CL and upper specification USL, while d has a value of between 0 and 1.

The graphs in Figure 2 present the probability of acceptance for MPC and Precontrol in a trial run for processes with process capability index $c_p = 1$, $c_p = 1.33$, $c_p = 1.66$ and $c_p = 2$. According to the graphs the probability of acceptance for centred processes using MPC is a little greater than when using Precontrol. Meanwhile the probability of acceptance for shifted processes is nearly equal for both methods.

The operating characteristic curves for SPC, MPC and Precontrol in production run are presented in Figure 3 for processes with capability index $c_p = 1$, $c_p = 1.33$, $c_p = 1.66$ and $c_p = 2$. The example for SPC is based on five units per sample. The graphs clearly show that the MPC method is much more comparable to SPC than is the Precontrol.



Sl. 2. *Krivulje operacijske karakteristike za predtek*
Fig. 2. *Operating characteristic curves for trial run*



Sl. 3. *Krivulje operacijske karakteristike za proizvodni tek*
Fig. 3. *Operating characteristic curves for production run*

2 SKLEP

Preizkušanje MPC in Precontrol karte z uporabo računalnika je po pričakovanju popolnoma potrdilo teoretične rezultate in pričakovanja pri uporabi na različnih procesih. Iz krivulj operacijskih karakteristik na slikah 2 in 3 je razvidno, da daje MPC boljše rezultate od Precontrol. Ugotovitve v zvezi z uporabnostjo karte MPC lahko strnemo v naslednjih točkah:

- Karta MPC ohranja vse prednosti, ki smo jih omenili za Precontrol.
- Njena glavna pomanjkljivost je velika verjetnost za uspešen predtek pri procesu, ki ni primeren.
- Glavna prednost karte MPC v primerjavi s Precontrol se pokaže pri proizvodnem teku. Verjetnost sprejetja necentriranih procesov je pri uporabi MPC mnogo manjša kakor pri uporabi Precontrol.
- Učinkovitost karte MPC je primerljiva s SPC.

2 CONCLUSION

The results of computer testing of MPC and of Precontrol completely confirm the theoretical calculations and expectations for different processes. From the operating characteristic curves in Figures 2 and 3 it is evident that the MPC is more convenient than Precontrol. Statements about applicability of the MPC method are:

- MPC method preserves all the above mentioned advantages of the Precontrol.
- Its main imperfection is a high probability of acceptance of non-capable processes in trial run.
- The main advantage of the MPC with regard to the Precontrol is evident in production run. The probability of acceptance of the non-centred processes is much lower for MPC than for Precontrol.
- Efficiency of MPC is comparable to SPC.

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Naslov avtorjev: dr. Marjan Družovec, dipl. inž.
prof. dr. Adolf Šostar, dipl. inž.
Andrej Godina, dipl. inž.
Fakulteta za strojništvo
Univerze v Mariboru
Smetanova 17
2000 Maribor

Authors' Address: Dr. Marjan Družovec, Dipl. Ing.
Prof. Dr. Adolf Šostar, Dipl. Ing.
Andrej Godina, Dipl. Ing.
Faculty of Mechanical Engineering
University of Maribor
Smetanova 17
2000 Maribor, Slovenia

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