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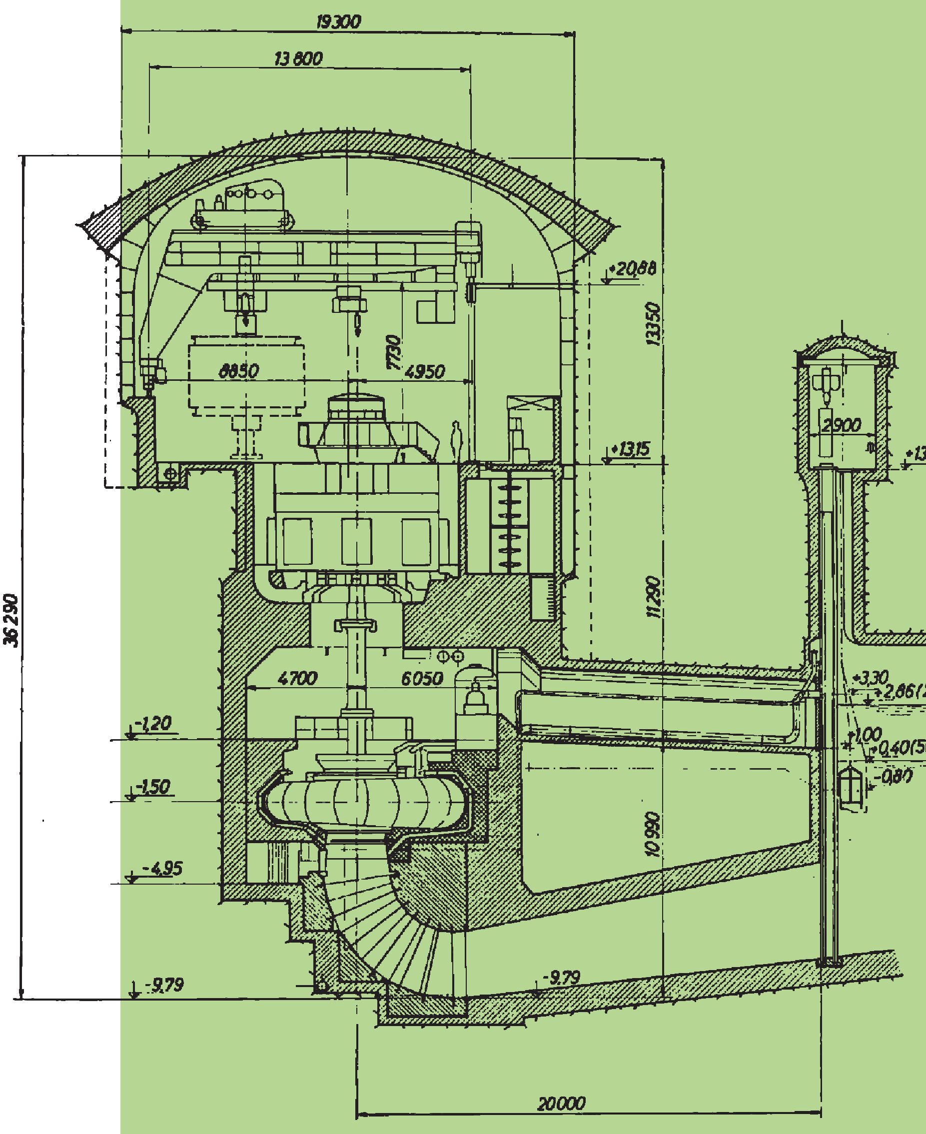

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Modelno podprt sistem za dinamično nastavljanje rezalnih parametrov pri postopku frezanja

A Model-Based System for the Dynamic Adjustment of Cutting Parameters during a Milling Process

Franci Čuš - Uroš Župerl - Edvard Kiker
(Fakulteta za strojništvo, Maribor)

V prispevku je predstavljen modelno podprt mehanizem vodenja, ki z obvladovanjem rezalnih sil zagotavlja stalno kakovost obdelane površine pri postopku oblikovnega frezanja. Sistem z dinamično prilagajanje podajanja in vrtljajev obvladuje hrapavost površine ter rezalne sile na frezalu. Namen izdelave predlaganega mehanizma je poiskati omejitve takšnega načina vodenja, ki s prilagajanjem rezalnih parametrov ohranja stalno rezalno silo. Modelno podprt sistem vodenja je izdelan z razvojno metodo genetskega programiranja (GP). Za določitev empirične povezave med kakovostjo površine in rezalno silo je izdelan načrt preizkusov. Pri vnaprej definirani globini rezanja je preizkusno raziskan vpliv obdelovalnega materiala in rezalnih parametrov (podajanje, globina rezanja) na omenjeno povezavo.

Razvojna metoda GP je uporabljena za izpeljavo izkustvenih povezav med kakovostjo površine in rezalno silo pri obdelavi jekla. Te povezave se nato uporabijo pri izdelavi modelno podprtega sistema za dinamično nastavljanje rezalnih parametrov (SDNRP), v katerem se s krmiljenjem rezalnih sil dviga zahtevana kakovost površine. Rezultati zagotovijo načine za povečanje učinkovitosti postopka z izboljšanjem kakovosti površine, zmanjšanjem posledic spremenljivosti postopka in zmanjšanjem stroškov napak pri opravilih končne obdelave.

(Ključne besede: končno frezanje, rezilni parametri, genetsko programiranje, sistemi vodenja, modelno podprti sistemi)

This paper presents a model-based mechanism of control ensuring the constant quality of the surface finish by controlling the cutting forces during the end-milling process. Using the dynamic adaptation of feeding and speed the system controls the surface roughness and the cutting forces on the milling cutter. The purpose of developing such a mechanism is to find the limitations of this type of control, which maintains a constant cutting force by adapting the cutting parameters. This model-based system of control was developed by the evolutionary method of genetic programming (GP). A drawing of experiments was made in order to determine the empirical correlations between the quality of the surface finish and the cutting force. With the depth of cutting defined in advance the influence of the workpiece material and cutting parameters (feeding, cutting depth) on the abovementioned correlation has been experimentally researched.

The evolution genetic programming method (GP) was applied to derive an empirical relationship for the surface finish and the cutting force values for steel materials. These relationships were applied to develop the proposed evolution simulation model in which the cutting force is adjusted to improve the required surface quality for the end-milling process. The results provide a means for greater efficiency by improving the surface quality, minimizing the effect of the process variability and reducing the error cost during finishing operations.

(Keywords: end-milling, cutting parameters, genetic programming, model-based control)

0 UVOD

Vodenje postopkov frezanja je trenutno v središču pozornosti zaradi potencialnih ekonomskih

0 INTRODUCTION

The control of milling processes is currently receiving a lot of attention due to the potential koristi, povezanih z avtomatizacijo odrezovanja [1]. Deset odstotna dodatna investicija v izboljšanje zmogljivosti sistema vodenja povzroči 10-odstotno povečanje storilnosti frezanja. To pomeni 1000-kratno povrnitev investicije med dobro trajanja stroja [1]. Postopki frezanja so zanimivi z vidika vodenja zaradi težav, kakršne so nelinearnosti, časovno spremenljivi parametri in obraba orodja ([2] in [3]). Nedavno so mnogi raziskovalci preučevali ta problem [4]. Tehnike vodenja, ki so izdelane za postopke obdelave, tradicionalno zahtevajo neki način prilagajanja parametrov ([1] in [5]). Rešitev tega problema je prilagajajoče se vodenje. Prilagajajoče se sisteme vodenja vpeljeta v postopek odrezovanja Stute in Goetz [6]. Najpogosteje uporabljena sistema sta MRAC (modelno referenčno prilagajajoče se vodenje) [7] in STR (samonastavljivo krmiljenje) [8]. MRAC izhaja iz teorije prilagajajočega se vodenja in je pogosto uporabljen zaradi svoje grobosti in zmožnosti odpravljanja motenj. Izdelane so številne oblike sistema MRAC ([9] in [10]). Druga rešitev tega problema so inteligentne nadzorne strategije ([11] in [12]). Pomanjkljivost inteligentnih strategij je v tem, da računanje nevronske mreže in genetskega algoritma terja nekaj časa, kar omejuje odzivnost inteligentnega sistema vodenja.

Kljub začetnim razvojnim težavam je opaziti usmeritev nadgrajevanja računalniško krmiljenih (RK) frezalnih strojev s sodobnimi prilagojenimi sistemi. Zaradi potrebe po povečevanju storilnosti, zmanjševanju stroškov dela, preprečevanju delovnih nezgod, izboljšanju kakovosti obdelave in zmanjšanju človeškega vpliva na postopek se usmeritev avtomatizacije postopka frezanja še stopnjuje.

Za uspešno avtomatizacijo, pri kateri se postopek odvija brez človekovega posredovanja, je treba neprekinjeno spremljati postopek obdelave. To se najpogosteje izvede z merjenjem rezalnih sil, ker te vsebujejo največ informacij o postopku in stanju orodja. Z analizo značilke rezalne sile je mogoče oceniti spremembe v kakovosti obdelane površine [13].

Našteta dejstva so izhodišča za izdelavo modelno podprtega sistema za dinamično nastavljanje in optimiranje rezalnih parametrov (SDNRP). To je prilagajajoči se sistem vodenja, ki z neprekinjenim dinamičnim nastavljanjem rezalnih parametrov nadzoruje rezalno silo in ohranja stalno hrapavost obdelane površine med obdelavo. V okviru raziskave je izdelan simulacijski model, ki

economic benefits associated with automated machining [1]. An additional investment of 10% to increase the capabilities of the control system gives a 10% increase in productivity for the milling operations. Over the lifetime of a machine, this results in a return on investment of 1000 times [1]. Milling processes are interesting from a control perspective due to difficulties such as system nonlinearities, time-varying parameters and tool wear ([2] and [3]). Various investigations have looked at this problem in the recent past [4]. Control techniques that have been developed for machining traditionally require some form of parameter adaptation ([1] and [5]). One solution to this problem is adaptive control. An adaptive control system is introduced in the cutting process by Stute and Goetz [6]. The most frequently used systems are MRAC (Model Reference Adaptive Control) [7] and STR (Self Tuning Regulations) [8]. MRAC, developed from adaptive control theory, is widely used because of its robustness and disturbance-rejection capability. Numerous forms of the MRAC system have been developed ([9] and [10]). Another solution to this problem is a number of intelligent control strategies ([11] and [12]). The drawback of intelligent strategies is that neural-network- and genetic-algorithm-based calculations take time, which limits the response of the intelligent control system.

In spite of the initial difficulties in the development, a trend towards equipping CNC milling machines with modern adaptive systems is clear. Because of the requirements for increased productivity, reduced working costs, the prevention of accidents, improved quality of the milling and a reduced human influence on the process the trend towards automation of the milling process increases.

For effective automation, where the process takes place without human interference, continuous monitoring of the milling process is necessary. Most frequently, this is realised by measuring the cutting forces, because they contain the most information about the process and the tool's condition. By analyzing the cutting force's characteristics it is possible to assess the changes of the quality of the surface finish [13].

The above-mentioned facts are the basis for the development of a model-based system for the dynamic adjustment and optimization of the cutting parameters (SDNRP). This is an adaptive system of control, which controls the cutting force and maintains the constant roughness of the machined surface during milling by a continuous and dynamic adjustment of the cutting parameters. Within the frame of the se uporablja za testiranje stabilnosti in usklajevanje parametrov prilagajajočega se sistema SDNRP - Poglavje 5. SDNRP spreminja svoje odzive kot odgovor na motnje in spremembe v dinamiki postopka odrezovanja.

Po izvedenih simulacijah je sistem SDNRP popolnoma pripravljen in usklajen za uporabo v dejanskem postopku frezanja. Simulacijska shema predlaganega sistema je predstavljena na sliki 3.

1 MODELNO PODPRTO VODENJE POSTOPKA FREZANJA

Na modelu temelječ sistem vodenja vsebuje krmilnik, ki lahko prilagaja svoje delovanje kot odgovor na spremembe dinamike postopka in motnje. Če ostaja rezalna sila nespremenjena med postopkom obdelave, potem tudi kakovost površine ostane nespremenljiva. V prejšnjih raziskavah [14] se pridobi izhajajoča rezalna sila s pomočjo Kistlerjevega merilnika, ki določi tri pravokotne komponente dinamičnih sil: F_x, F_y, F_z. Te sile so izmerjene sproti z uporabo programske opreme LabView. Izmerjeni signali rezalnih sil se uporabijo v modelnem krmilniku pri uravnavanju rezalne sile. Glavni cilj te raziskave je izdelati na genetskem modelu temelječ sistem vodenja, ki lahko reši takšne zahtevne probleme vodenja odrezovanja. Cilj predlaganega sistema vodenja je krmiliti parametre postopka frezanja, to so podajanje in vrtilna frekvenca vretena ter ohranjati rezalno hitrost nespremenjeno, da se sproti dosеže zahtevana vrednost kakovosti površine. Uporabimo frezalni stroj Heller BEA01 v povezavi s krmilnikom podajalnega pogona.

2 RK PODAJALNI SERVO-SISTEM STROJA

Preizkusi so izvedeni na RK frezalnem stroju Heller. To je štiriosni obdelovalni stroj, ki dopušča tri premike vzdolž osi X, Y in Z ter vrtenje palete v vodoravni ravnini. Vgrajeno je računalniško krmilje FAGOR 8040-M. Pogon podajalnih osi je prek krogličnih vodil izveden z izmeničnimi električnimi servomotorji, ki so sinhronizirani s trajnimi magneti. Oznaka servopogona je: Heller S 044/82 8-A20-2220-001/02C. Blokovno shemo (simulacijski model) podajalnega servosistema prikazuje slika 2. Številčne vrednosti stalnic blokovne sheme so prikazane v preglednici 1. Na vhodnem kanalu sistema pride do časovne

research a simulation model for testing stability and harmonizing parameters of the adaptive system (SDNRP), Section 5, has been developed. The SDNRP changes its reactions in response to disturbances and changes in the dynamics of the cutting process.

After the execution of the simulations the system (SDNRP) is fully ready and harmonized for use in a real milling process. The simulation diagram of the proposed system is presented in Figure 3.

1 MODEL-BASED MILLING-PROCESS CONTROL

A model-based control system is a controller that can modify its behaviour in response to a change in the dynamics of the process and the disturbances. If the cutting force is maintained constant during the process of machining, then the surface finish also remains stable. In previous research work [14] the resultant cutting force is obtained using a Kistler force transducer, which provides three orthogonal components of the dynamics forces, F_x, F_y, F_z, and these forces were measured online using LabView software. These measured cutting force signals are used in a model controller to regulate the cutting force. The main objective of this research is to develop a genetic model-based control system that can solve such difficult machining control problems. The objective of the proposed control system is to regulate the milling process' operation parameters, such as the feed rate and the spindle speed, and maintain the constant cutting force to achieve online the required value of the surface finish. A Heller BEA01 milling machine was used in connection with a feed drive controller.

2 CNC MACHINE FEED DRIVE SYSTEM

The tests were carried out on the Heller CNC milling machine. This is a four-axes machine tool allowing three translations along the *X*, *Y* and *Z* axes and rotation of the machine table in the horizontal plane. It is fitted with FAGOR 8040-M CNC controls. The feeding axles are driven through ball screw drives by AC servomotors synchronized with permanent magnets. The servo-drive type is Heller S 044/82 8-A20-2220-001/02C. The block diagram (simulation model) of the feeding servo-system is shown in Figure 2. The numerical values of the constants of the block diagram are presented in Table 1. On the input channel of the system a time delay in the transmission of the zakasnitve pri prenosu ukaza podajanja: to je posledica obdelave ukaznega signala v postopkovnem računalniku (PLK - programljivem krmilju RK sistema). Naloga PLK-ja je, da spremlja stanje zaznaval na stroju in ustrezno logično ustvarja ukaze za uporabnika in del računalniškega krmilja. Prenosna funkcija, ki podaja razmerje med spremembo ukaznega signala podajanja f_c in spremembo dejanske vrednosti podajanja delovne mize f_a ima naslednjo obliko:

command occurs: this is the result of processing the command signal in the processing computer (PLC-programmable controls of the CNC system). The duty of the PLC is to follow up the state of the sensors on the machine and to generate properly and logically the commands for the user and CNC part of the controls. The transfer function stating the relation between the change of the command signal of feeding f_c and the change of the actual value of feeding of the work table f_a has the following form:

$$\frac{f_a(s)}{f_c(s)} = \frac{K_i \cdot K_{ip} \cdot K_t \cdot e^{-s \cdot t}}{J_e \cdot L_a \cdot s^3 + J_e (R_{ra} + K_H \cdot K_{ip}) \cdot s^2 + K_t (K_p \cdot K_{ip} + K_b) \cdot s + K_i \cdot K_t \cdot K_{ip}} \qquad (1).$$

Z vstavljanjem tehničnih stalnic sistema iz preglednice 1 se zgornja prenosna funkcija preoblikuje v:

By entering the technical constants of the system from Table 1 the above transfer function is transformed as follows:

$$\frac{f_a(s)}{f_c(s)} = \frac{497000 \cdot e^{-0.08s}}{(s + 14{,}0) + (s^2 + 155s + 35500)} \qquad (2).$$

Zaradi majhne poenostavite uporabimo za simulacijski model podajalnega servo-sistema naslednjo prenosno funkcijo (sl. 1):

Because of a small simplification the following transfer function is used for the simulation model of the feeding servo-system (Fig. 1):

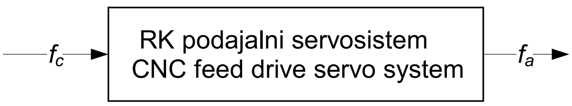
$$\frac{f_a}{f_c} = \frac{14{,}0 \cdot e^{-0{,}08s}}{(s + 14{,}0)} \qquad (3),$$

kjer so:
- t = 8 s: čas zakasnitve,
- f_c: ukaz podajanja [mm/min],
- f_a: dejansko podajanje [mm/min].

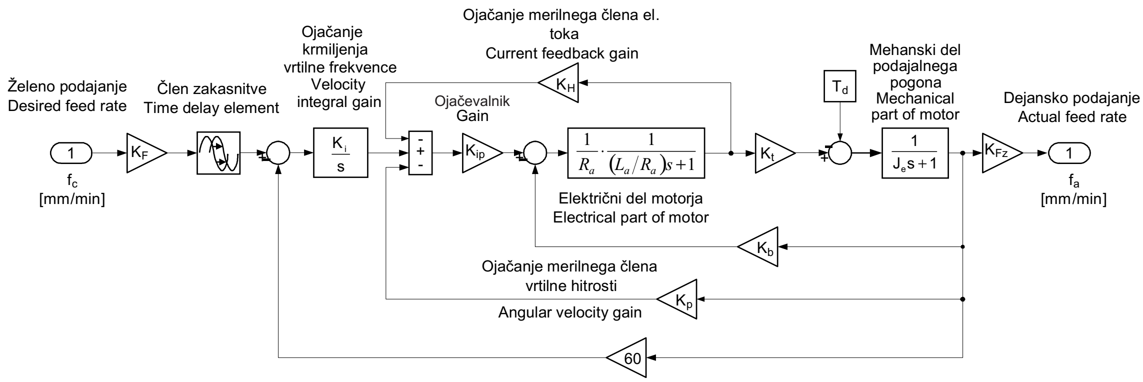
where:
- t = 8 s: time delay,
- f_c: feed rate command [mm/min],
- f_a: actual feed rate [mm/min].

Čas, ki je potreben, da se programljivo krmilje odzove na ukazni signal, se imenuje čas

The time required for programmable controls to respond to the command signal is called the time



Sl. 1. *Model RK podajalnega servosistema*
Fig. 1. *Model of the CNC feed drive system*



Sl. 2. *Blokovna shema podajalnega servosistema*
Fig. 2. *Block diagram of feed drive servo system*

Preglednica 1. *Heller Ltd. Tehnični podatki podajalnega servosistema*
Table 1. *Heller Ltd. Technical data for the feed drive system*

Parameter	Opis /Description	Vrednost/Value
f_c	želeno podajanje (ukaz podajanja) [mm/min] desired feed rate (Feed rate command) [mm/min]	-
f_a	dejansko podajanje [mm/min] actual feed rate [mm/min]	-
ω_c	ukaz kotne hitrosti [rad/min] angular velocity command [rad/min]	-
K_i	ojačanje I-krmilnika vrtilne hitrosti [V/(rad s)] velocity integral gain [V/(rad s)]	8,2
K_p	faktor ojačanja merilnega člena vrtilne frekvence [V/(rad s)] velocity proportional gain [V/(rad s)]	0,4944
V_{ic}	ukaz toka [f] current command [f]	-
K_H	faktor ojačanja - merilnik električnega toka [f/A] current feedback gain [f/A]	0,007
R_{ra}	upor rotorskega navitja [Ω] armature coil resistance [Ω]	0,15
K_t	stalnica vrtilnega momenta [N f m/A] torque constant [N f m/A]	0,165
T_m	stalnica vrtilnega momenta elektromotorja [N f m] electro motor torque gain [N f m]	-
J_e	ustrezna vztrajnost podajalnega pogona [N f m s] equivalent feed drive inertia [N f m s]	0,0146
ω_a	dejanska vrtilna frekvenca gredi motorja [rad/min] actual velocity [rad/min]	-
K_F	količnik ojačanja - vrtilna frekvenca [(rad/s)/(mm/min)] angular velocity gain [(rad/s)/(mm/min)]	0,105
K_{Fz}	ojačanje - podajanje [(mm/min)/(rad/s)] feed rate gain [(mm/min)/(rad/s)]	1,04
V_{if}	dejanski tok - povratna zveza [f] feedback current [f]	-
K_{ip}	proporcionalno ojačanje krmilnika toka current proportional gain	7,5429
L_a	induktivnost rotorskega navitja [mH] armature coil inductance [mH]	1,20
I_q	dejanski električni tok [A] actual current [A]	-
K_b	stalnica EMF – merilni člen hitrosti [V/(rad/s)] back EMF constant - velocity measuring block [V/(rad/s)]	0,38
T_d	vrtilni moment motnje [N f m] disturbance torque [N f m]	-

zakasnitve. Glavni namen SDNRP je ustvariti vrsto ukazov podajanja f_c in vrtilne frekvence n_c ter s tem krmiliti vrednost rezalne sile, tako da bo ta ohranjala želeno stalno kakovost površine.

3 GP-MODELI REZALNIH VELIČIN

Učenje modelov rezalnih veličin je izvedeno z izkustvenimi rezultati, ki so podani v prejšnjih

of the delay. The principal aim of the SDNRP is to generate a series of commands for feeding f_c and the speed of rotating n_c and, thus, to regulate the values of the cutting force so that the latter will maintain the desired constant quality of the surface.

3 GP-BASED MODELS OF THE CUTTING QUANTITIES

The learning of models for the cutting quantities is effected with experimental results raziskavah ([15] in [16]). Namen modelov je podati funkcionalne odvisnosti med vplivnimi odrezovalnimi parametri: vrtilno frekvenco, hrapavostjo površine in rezalno silo. Za določitev medsebojnih razmerij med vrtilno frekvenco in podajanjem ter rezalno silo in hrapavostjo je uporabljena metoda genetskega programiranja (GP). Pri GP je rezultat matematična formula, sestavljena iz nabora predpisanih opravil. Omenjena metoda bo predstavljena v nadaljevanju.

3.1 Modeliranje GP

V simulacijah se uporabijo GP modeli, ker jih je v simulacijskem paketu Simulink laže preoblikovati v blokovni zapis. Za izdelavo vsakega genetskega modela se uporabi 185 preizkusnih podatkov. Merilni podatek vsebuje vrednost napovedane (modelirane) veličine in pripadajoče vplivne parametre (rezalne parametre). Na podlagi vhodnih in merilnih podatkov ter ob izbranem naboru računskih opravil se ustvarijo modeli: K1, K2, K3, K4, K5=K6. Blokovne sheme najbolj prilagojenih modelov so podane v poglavju 3.2. Izbran je nabor naslednjih osnovnih računskih opravil $\mathscr{F} = \{+, -, *, u^v, \ln\}$ in razlogov $\mathscr{P} = \{2, 2, 3, 2\}$. Množica omejil ($\mathscr{T}$) je podana ob blokovni shemi posameznega modela. Množico omejil običajno sestavljajo vhodni podatki in spremenljivke sistema.

Za določitev modela odrezovanja (K4) je izbrana velikost populacije organizmov M = 1500 in število generacij G = 100. V drugih modelih je M = 850 in G = 100. Uporabljene so standardna genetska opravila reprodukcije, križanja in mutacije. Verjetnost reprodukcije je p_r = 0,15, križanja p_c = 0,5 in mutacije p_m = 0,1. Razvoj modela se ustavi, ko je doseženo predpisano število generacij ali ko je prilagojenost organizma večja od 97 odstotkov.

3.2 Izpeljani GP modeli rezalnih veličin

Pred vsako obdelavo je znana zahtevana kakovost obdelane površine R_a. Spodnja enačba podaja rezalno silo F_d, s katero se doseže in ohranja zahtevana hrapavost površine. Za modelni parameter F_d je po metodi GP izoblikovan naslednji obrazec:

stated in previous researches ([15] and [16]). The purpose of models is to define functional dependences between the influencing cutting parameters: spindle speed, surface roughness and cutting force. The genetic programming (GP) method is used for the determination of mutual relations between the rotating speed and feeding and between cutting force and roughness. In case of GP the result is the mathematical formula consisting of a series of prescribed operations. That method will be presented hereinafter.

3.1 GP Modelling

GP models are used in simulations because, in the simulation package Simulink, they can be more easily transformed into the block recording. A total of 185 pieces of experimental data are used to develop each genetic model. The experimental datum contains the value of the predicted (modelled) quantity and the appurtenant influencing parameters (cutting parameters). On the basis of the input and the experimental data and with a selected series of calculation operations the models, K1, K2, K3, K4, K5 = K6, are generated. The block diagrams of the most adapted models are given in Section 4.2. The series of the following basic calculation operations $\mathscr{F} = \{+, -, *, u^v, \ln\}$ and arguments $\mathscr{P} = \{2, 2, 3, 2\}$is selected. The set of terminals ($\mathscr{T}$) is given in addition to the block diagram of the individual model. Usually, the set of terminals consists of input data and the variables of the system.

The size of the population of organisms, M = 1500, and the number of generations, G = 100, were selected for the determination of the model of cutting (K4). On other models M = 850 and G = 100. The standard genetic operations of reproductions, crossover and mutation were used. The reproduction probability, p_r, was 0.15, the crossover probability, p_c, was 0.5 and the mutation probability, p_m, was 0.1. The development of the model is stopped when the prescribed number of generations is reached or when the fitness of the organism is greater than 97 %.

3.2 Derived GP Models of Cutting Quantities

Prior to any machining the required quality of the surface finish R_a is set. The equation below gives the cutting force F_d with which the required surface roughness is reached and maintained. For the model parameter F_d the following formula was formed according to the GP method:

$$F_d = 293 - \frac{593}{\sqrt{39,37 \cdot R_a}} \quad (4).$$

Za določitev optimalnih rezalnih parametrov sta v uporabi naslednja GP modela:

The following two GP models are in use for the determination of the optimum cutting parameters:

$$f = 25,4 \cdot \left(189 - \frac{5926160}{F^2} \right) \quad (5)$$

$$n = \sqrt{(30064193 - 2,28 \cdot F^3)} \quad (6).$$

Pri tem sta: f - podajanje [mm/min], n - vrtljaji vretena [min^{-1}].

Po zgornjih enačbah se določijo parametri, s katerimi se zagotavlja zahtevana hrapavost površine R_a. Cilj SDNRP je zagotavljati nespremenljivo rezalno silo F. Za simulacijo postopka odrezovanja se uporabi naslednji obrazec (modelni parameter K4).

Where f is the feed rate [mm/min] and n is the spindle speed [min^{-1}].

The parameters with which the required surface roughness R_a is ensured are determined according to the above equations. The objective of the SDNRP is to ensure a constant cutting force F. The following formula (model parameter K4) is used to simulate the cutting process.

$$F = 286,44 - \left(\frac{5,82}{10^{10}} \right) \cdot n^3 - 8973 \cdot \frac{\ln(0,039 \cdot f)}{f} \quad (7).$$

Hrapavost površine se testira po naslednji enačbi:

The surface roughness is tested according to the following equation:

$$R_a = 0,0254 \cdot \left(\frac{593}{293 - F} \right)^2 \quad (8),$$

kjer sta: R_a: hrapavost površine [µm], F: rezalna sila [N].

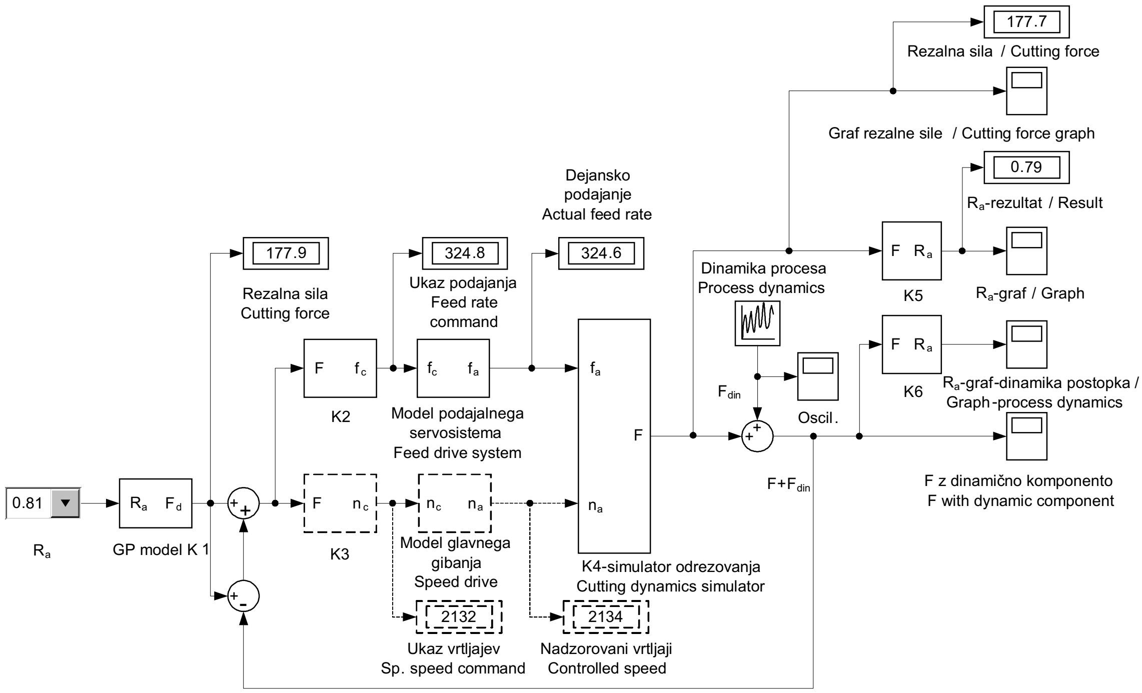
where R_a is the surface roughness [µm] and F is the cutting force [N].

4 SIMULATOR SDNRP

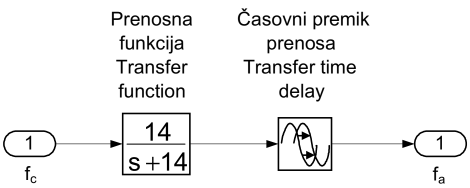
Blokovna shema simulatorja SDNRP je prikazana na sliki 3. Če v blokovni shemi nadomestimo model K4, simulacijski model podajalnega servosistema in model glavnega gibanja obdelovalnega stroja, dobimo usklajen sistem za dinamično nastavljanje rezalnih razmer, ki je pripravljen za takojšnjo uporabo. Sistem s krmiljenjem rezalne sile zagotavlja zahtevano hrapavost površine. Dinamika podajalnega servosistema je podana z enačbo (3). Enačba je izpeljana na temelju določil izdelovalca Heller Ltd. Blokovno shemo prenosne funkcije podajalnega servosistema prikazuje slika 4. Simulacijsko shemo sestavljajo: simulator računalniškega krmilja, simulator podajalnega in glavnega servopogona, simulator odrezovanja, primerjalni blok in modeli, ki določajo medsebojna razmerja med vplivnimi rezalnimi veličinami. Simulacijski modeli dinamike stroja so izdelani na temelju tehničnih določil izdelovalca Heller.

4 SIMULATOR OF SDNRP

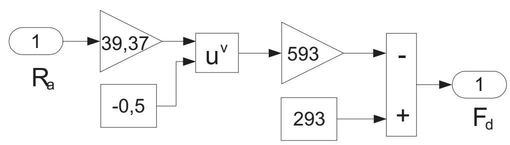
The block diagram of the simulator of the SDNRP is shown in Figure 3. If in the block diagram the model K4, the simulation model of the feed servo-drive and the model of main spindle rotation are replaced by the real machine tool, a harmonized system for the dynamic adjustment of cutting conditions, ready for immediate use, is obtained. The system with regulation of the cutting force ensures the required surface roughness. The dynamics of the feed servo-drive is defined with Equation 3. The equation is derived on the basis of the specifications of the maker, Heller Ltd. The block diagram of the transfer function of the feed servo-drive is shown in Figure 4. The simulation diagram comprises the simulator of CNC controls, the simulator of the feed and main servo-drive, the simulator of the cutting, the reference block and the models determining the mutual relations between the influencing cutting values. The simulation models of the machine dynamics are made on the basis of the technical specifications of the maker, Heller.



Sl. 3. *Blokovna shema sistema za dinamično nastavljanje rezalnih parametrov*
Fig. 3. *Block diagram of the system for dynamic adjusting of the cutting parameters*



Sl. 4. *Prenosna funkcija podajalnega servosistema*
Fig. 4. *Feed-drive servo-system transfer function*



Sl. 5. *Blokovna shema za razmerje hrapavost površine - rezalna sila*
Fig. 5. *Block diagram for the relation surface roughness-cutting force*

V nadaljevanju so podrobno predstavljene prenosne funkcije posameznih elementov SDNRP in pretok signalov med njimi.

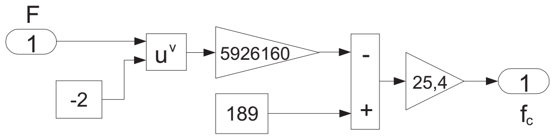
K1: Slika 5 prikazuje prenosno funkcijo, ki podaja odvisnost med želeno hrapavostjo površine in pripadajočo rezalno silo F_d. Prenosna funkcija je podana v obliki blokovne sheme. Modeliranje je izvedeno s standardno zbirko blokov v programskem paketu Matlab 6.5. Uporabljena je množica omejil: $\mathcal{T} = \{R_a, F_d, \mathcal{R}\}$. $\mathcal{R}$ - realna števila na območju od -10 do 10.

K2: Prenosna funkcija za napovedovanje optimalnega podajanja f_c je izpeljana po enačbi (5). Slika 6 prikazuje njeno blokovno shemo. $\mathcal{T} = \{F, f_c, \mathcal{R}\}$.

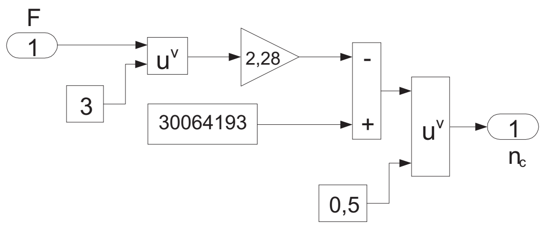
In the following the transfer functions of the individual elements of the SDNRP and the flow of signals between them are presented in detail.

K1: Figure 5 shows the transfer function defining the dependence between the desired surface roughness and the appurtenant cutting force F_d. The transfer function is given in the form of block diagrams. Modelling is effected with the standard set of blocks in the programme package Matlab 6.5. The set of terminals $\mathcal{T} = \{R_a, F_d, \mathcal{R}\}$ is used, where $\mathcal{R}$ is a real number in the interval from -10 to 10.

K2: Transfer function for the prediction of the optimum feeding f_c is derived according to Equation 5. Figure 6 shows its block diagram. $\mathcal{T} = \{F, f_c, \mathcal{R}\}$.



Sl. 6. *Blokovna shema za razmerje rezalna sila - podajanje* f_c
Fig. 6. *Block diagram for the relation cutting force-feed rate* f_c



Sl. 7. *Blokovna shema za razmerje rezalna sila - vrtljaji* n_c
Fig. 7. *Block diagram for the relation cutting force-spindle speed* n_c

K3: Razmerje med rezalno silo F in ukaznim signalom n_c podaja prenosna funkcija, ki je izpeljana po enačbi (4). Prenosna funkcija je prikazana na sliki 7. Njena naloga je neprekinjeno ustvarjati ukazni signal vrtilne frekvence n_c. $\mathscr{T}= \{F, n_c, \mathscr{R}\}$.

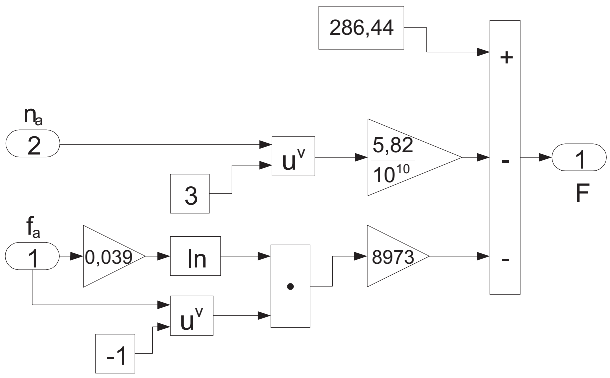
K4: Na sliki 8 je prikazana prenosna funkcija predstavlja simulacijski model postopka odrezovanja. Z blokovno shemo se napoveduje vrednost dejanske rezalne sile na rezilu orodja, in sicer pri danih rezalnih razmerah. $\mathscr{T}= \{n_a, f_a, F, R\}$.

K5, K6: Z blokovno shemo testiramo, ali se simulirana R_a ujema z želeno R_a. Testni postopek prikazuje slika 9. $\mathscr{T}= \{F, R_a, \mathscr{R}\}$.

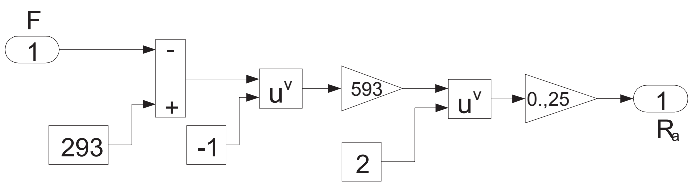
K3: The relation between cutting force F and the command signal n_c is expressed by the transfer function derived according to Equation 4. The transfer function is shown in Figure 7; its purpose is to continuously generate the command signal of the rotating speed n_c. $\mathscr{T}= \{F, n_c, \mathscr{R}\}$.

K4: The transfer function presented in Figure 8 represents the simulation model of the cutting process. Using the block diagram the value of the actual cutting force on the tool cutter with given cutting conditions is predicted. $\mathscr{T}= \{n_a, f_a, F, R\}$.

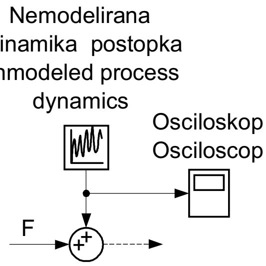
K5, K6: Using the block diagram we can test whether the simulated R_a corresponds to the desired R_a. The test procedure is shown in Figure 9. $\mathscr{T}= \{F, R_a, \mathscr{R}\}$.



Sl. 8. *Simulator postopka odrezavanja*
Fig. 8. *Cutting-process simulator*



Sl. 9. *Blokovna shema za preizkušanje kakovosti površine*
Fig. 9. *Block diagram of surface-finish inspections*



Sl. 10. *Blokovna shema za ustvarjanje dinamične komponente rezalne sile*
Fig. 10. *Block diagram for the generation of the dynamic component of the cutting force*

Med postopkom obdelave se pojavljajo nezaželene vibracije in motnje. Vzroki so: nehomogenost osnovnega materiala, obraba orodja, poškodbe orodja, napake v vodilih in ležajih stroja itn. Z vključevanjem naključnih motenj v simulacijo se testirata stabilnost in grobost predlaganega sistema vodenja. V simulacijskem modelu se ustvarja nemodelirano dinamiko postopka z naključnimi vrednostmi, ki se ujemajo z oscilacijami izmerjenih rezalnih sil. Shema na sliki 10 simulira nemodelirano dinamiko stroja in postopka.

Med simulacijo se na diagramih nadzorne konzole izrisujejo naslednje veličine:
- dejanska hrapavost površine,
- hrapavost površine pri upoštevani dinamiki stroja,
- največja rezalna sila,
- največja rezalna sila z dinamično komponento,
- dejansko podajanje,
- dejanski vrtljaji vretena.

During the machining process undesirable vibrations and disturbances occur. They are caused by inhomogeneity of the base material, tool wear, tool damage, defects in guides and bearings of the machine, etc. By introducing the random disturbances into the simulation the stability and robustness of the proposed control system can be tested. In the simulation model the unmodeled dynamics of the process is generated by random values corresponding to the oscillations of the measured cutting forces. The diagram in Figure 10 simulates the unmodeled dynamics of the machine and the process.

During the simulation the following values are drawn in the diagrams of the control console:
- Actual surface roughness,
- Surface roughness considering the machine-tool dynamics,
- Maximum cutting force,
- Maximum cutting force with the dynamic component,
- Actual feeding,
- Actual spindle speed.

5 POTEK IZVEDBE SIMULACIJE SDNRP

Zmogljivost SDNRP je testirana s simulacijami. Uporabljen je Matlabov simulacijski paket Simulink. Simulacijo sprožimo z nastavitvijo referenčne vrednosti R_a, nato se po modelu K1 napove želena rezalna sila $F_{d.}$ Ko je znana sila F_d, se po modelu K2 in K3 v trenutku izračunajo vrednosti f_c in n_c. Dinamični odziv servosistema na signal f_c je simuliran z blokovno shemo, ki je podana na sliki 2. Prenosni funkciji servosistemov ustvarjata dejansko podajanje f_a in vrtljaje n_a, tako da je po modelu K4 napovedana rezalna sila nespremenljiva. Simulirana R_a se določi s prenosno funkcijo modela K5.

5 THE REALIZATION COURSE OF THE SDNRP SIMULATION

The SDNRP capacity was tested by simulations. For this we used the Matlab simulation package Simulink. The simulation is initiated by the adjustment of the reference value R_a; afterwards the desired cutting force F_d is predicted according to the model K1. When the force F_d is known, the values F_c and n_c are calculated within a moment according to the model K2 and K3. The dynamic response of the servo-system to the signal f_c is simulated by the block diagram given in Figure 2. The two transfer functions of the servo-systems generate the actual feeding f_a and speed n_a, so that the cutting force, predicted according to the model K4, is constant. The simulated R_a is determined by the transfer function of the model K5.

6 PRIMER IZVEDENE SIMULACIJE SDNRP

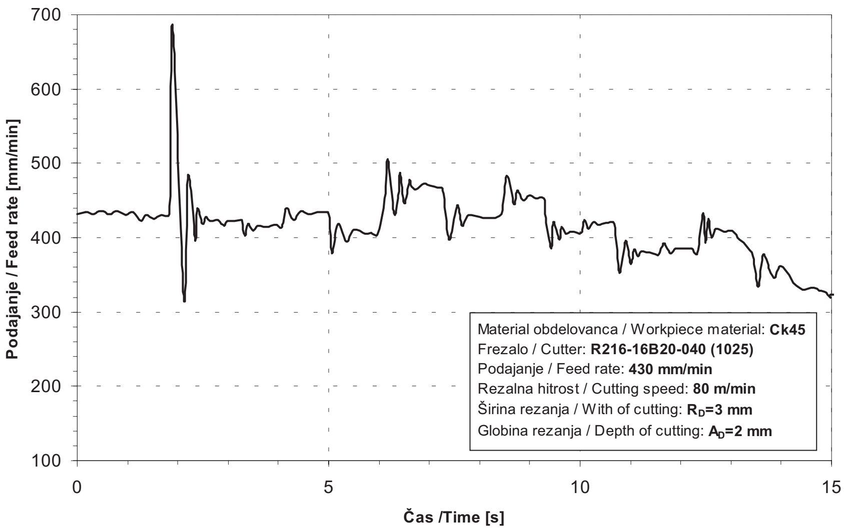
V nadaljevanju je prikazana simulacija št. 5 (pregl. 3), ki je izvedena za material Ck45 in frezalo R216-16B20-040. Izbrana primerjalna hrapavost je 0.81 mm. Začetni optimalni rezalni parametri so določeni z algoritmom PSO (optimizacija, ki oponaša gibanje delcev v velikih jatah) [17]. Podani so v preglednici 2. Rezultat simulacije je prikazan na blokovni shemi slike 4. Začetna vrednost podajanja je 430,4 mm/min. Sistem to vrednost spreminja, dokler ne doseže optimalnega podajanja 324,6 mm/min. Optimalna končna vrtilna frekvenca je 2134 min^{-1}. Dinamično nastavljanje podajanja in vrtilne frekvence je nujno za ohranjanje stalne največje rezalne sile 177,7 N. Rezultat simulacije je hrapavost 0,79 μm, ki je v primerjavi z želeno vrednostjo 0,81 μm sprejemljiva (sl. 16). Potek simulacije je prikazan na slikah 11 in 12. Razvidno je, da se z neprestanim nastavljanjem rezalnih parametrov zagotavlja zahtevana hrapavost pri največji dovoljeni obremenitvi orodja.

6 AN EXAMPLE OF A REALIZED SDNRP SIMULATION

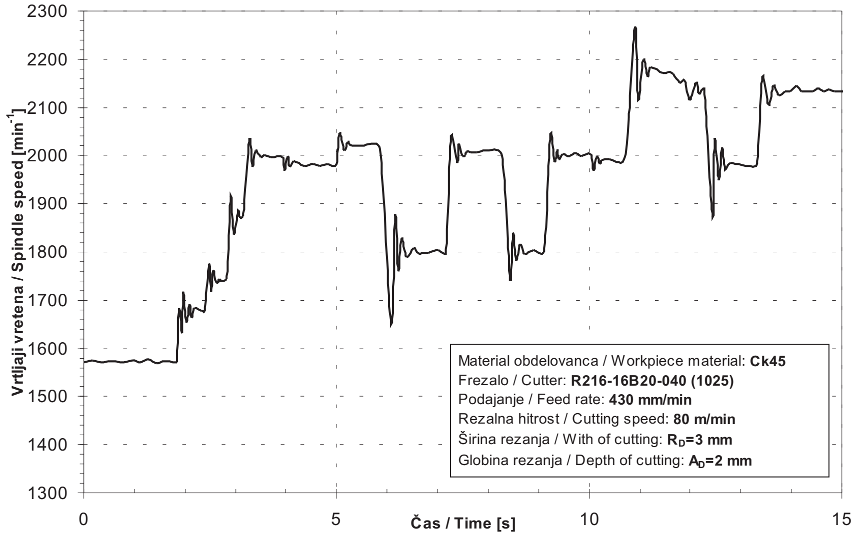
Here we present simulation No. 5 (Table 3), effected for the material Ck45 and the milling cutter R216-16B20-040. The selected reference roughness is 0.81μm. The starting optimum cutting parameters were determined by the PSO (Particle Swarm optimization) algorithm [17]; they are given in Table 2. The simulation result is shown in the block diagram of Figure 4. The initial value of feeding is 430.4 mm/min. The system changes that value until the optimum feeding of 324.6 mm/min is reached. The optimum final spindle speed is 2134 min^{-1}. Dynamic adjustment of the feeding and spindle speed is a prerequisite for maintaining a constant maximum cutting force of 177.7 N. The simulation result is a roughness of 0.79 μm, which is acceptable when compared with the desired value 0.81 μm (Fig. 16). The process of the simulation is shown in Figure 11 and Figure 12. It is clear that with continuous adjusting of the cutting parameters the required roughness is ensured with the maximum allowable tool loading.

Preglednica 2. *Začetne rezalne razmere*
Table 2. *Initial cutting conditions*

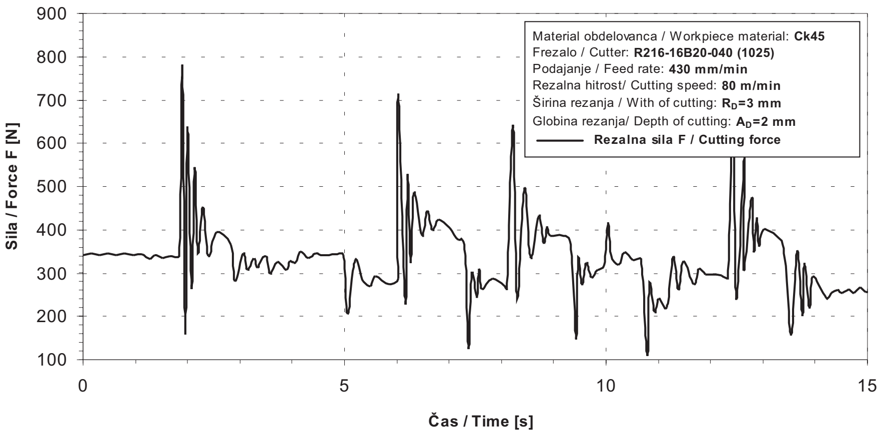
v_c = 80 m/min	R_D = 3 mm
f = 430,4 mm/min	A_D = 2 mm



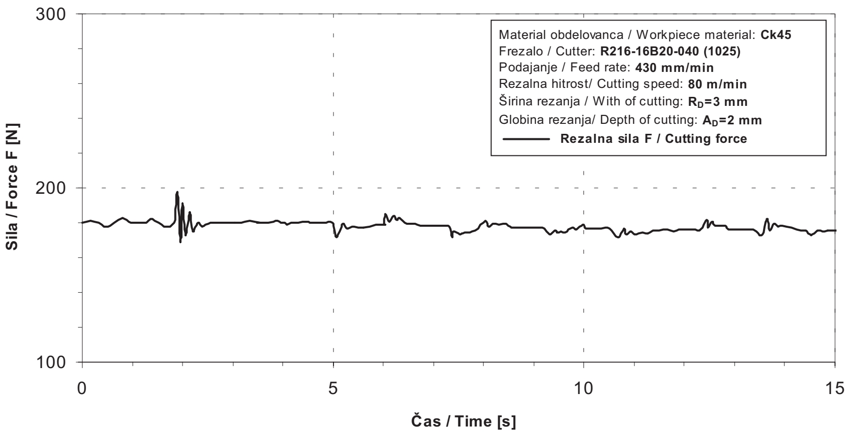
Sl. 11. *Dinamično nastavljanje podajanja med simulacijo*
Fig. 11. *Dynamic adjusting of the feed rate during simulation*



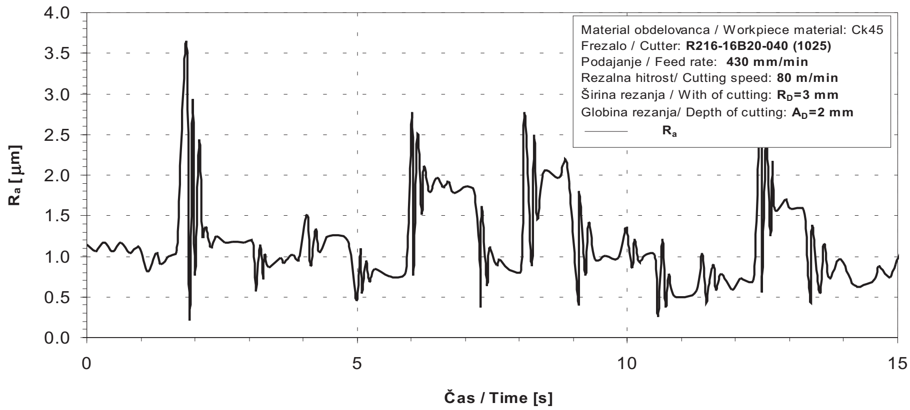
Sl. 12. *Dinamično nastavljanje vrtilne frekvence med simulacijo*
Fig. 12. *Dynamic adjusting of the spindle speed during simulation*



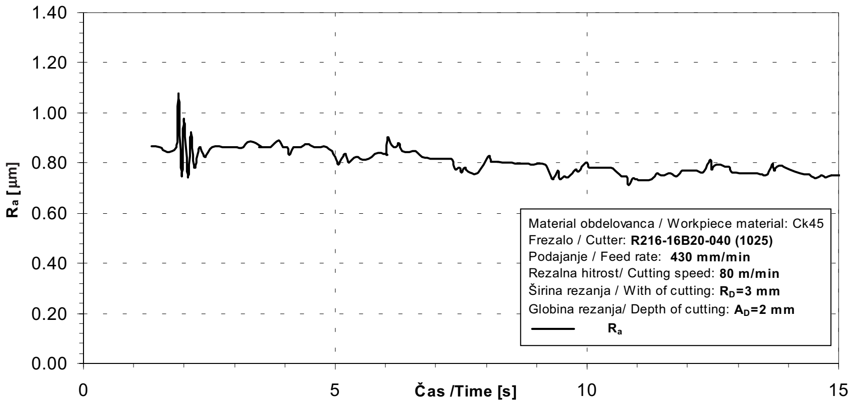
Sl. 13. *Potek rezalne sile brez uporabe SDNRP*
Fig. 13. *The course of the cutting force without the application of SDNRP*



Sl. 14. *Potek rezalne sile pri dinamičnem nastavljanju rezalnih parametrov*
Fig. 14. *The course of the cutting force with dynamic adjusting of the cutting parameters*



Sl. 15. *Hrapavost pred uporabo predlaganega sistema vodenja*
Fig. 15. *Surface roughness before using the proposed control system*



Sl. 16. *Hrapavost po uporabi predlaganega sistema vodenja*
Fig. 16. *Surface roughness after using the proposed control system*

7 ANALIZA REZULTATOV

S simulacijami sta testirani učinkovitost in stabilnost SDNRP pri različnih zahtevah kakovosti površine. Merilo za učinkovitost sistema je razlika med želeno in simulirano R_a. Vhodni podatki so začetni rezalni parametri in želena R_a. V preglednici 3 so podane zahteve in rezultati simulacij.

Izvedenih je 10 simulacij. Rezultati simulacij (pregl. 3) potrjujejo, da je sistem dinamičnega nastavljanja rezalnih parametrov učinkovit pri nadzoru obremenitev orodja in hrapavosti površine. Učinkovit je pri natančni obdelavi; to je še posebej razveseljivo, saj je namenjen za opravila oblikovnega frezanja s paličnimi frezali, kjer so zahteve po kakovosti obdelave ostre. Pri obdelavi, kjer hrapavost preseže 1,1 µm, se odzivnost sistema upočasni. Zmanjša se njegova občutljivost za doseganje želene hrapavosti.

7 ANALYSIS OF THE RESULTS

Using a simulation we can test the efficiency and stability of the SDNRP with different requirements for the surface quality. The criterion for efficiency of the system is the difference between the desired and simulated R_a. The starting cutting parameters and the desired R_a are the input data. In Table 3 the requirements and the results of the simulations are indicated.

Ten simulations were carried out. The simulation results (Table 3) confirm that the SDNRP is efficient in the control of the tool loading and surface roughness. It is also efficient in fine machining; this is a particularly good result, since it is intended for the operations of end milling with shank end mills, where the requirements for the quality of machining are strict. In machining, where the roughness exceeds 1.1 µm, the responsiveness of the system is slowed down and its sensitivity for reaching the desired roughness is reduced.

Preglednica 3. *Preizkusni rezultati simulacij*
Table 3. *Simulation experimental results*

Sim. št.: Sim no.:	Želena hrapavost površine Desired surface roughness R_a [μm]	Začetni rezalni parametri pred simulacijo Initial cutting conditions before simulation			Servo pogonski sistem po 15s Servo drive system after 15s			Dejanska hrapavost površine Produced surface finish R_a [μm]
		F_d [N]	f_c [mm/min]	n_c [min^{-1}]	F [N]	f_a [mm/min]	n_a [min^{-1}]	
1	0,38	161,4	357,12	1974	166,5	264,92	2443	0,50
2	0,51	166,67	379,98	1895	169,9	282,19	2356	0,58
3	0,64	172,1	414,53	1704	173,0	297,94	2272	0,66
4	0,76	176,8	435,26	1563	175,9	313,94	2189	0,74
5	0,81	178,5	430,41	1571	177,7	324,61	2134	0,79
6	0,89	180,9	462,19	1437	178,6	329,95	2108	0,81
7	1,02	184,7	485,14	1377	181,6	350,52	2007	0,91
8	1,14	188,1	507,75	1270	183,9	355,60	1925	0,99
9	1,27	191,2	539,24	1116	185,7	381,25	1880	1,05
10	1,52	196,8	592,58	825	195,2	411,99	1716	1,18

Na sliki 13 je prikazan potek največje rezalne sile brez uporabe SDNRP. V tem primeru ima tudi hrapavost naključna usmeritev (sl. 15). Dinamična komponenta rezalne sile je simulirana z blokovno shemo na sliki 10.

Iz grafov simulacij je razvidno, da lahko na podlagi signalov največje rezalne sile sklepamo o kakovosti obdelane površine. Obe veličini sta medsebojno povezani in imata enake usmeritve. SDNRP zagotavlja stalno hrapavost med vso obdelavo.

Simulacije potrdijo, da je predlagani sistem učinkovit pri zagotavljanju zahtevane hrapavosti in ohranjanju nespremenljive obremenitve stroja. Sistem vodenja se na skok rezalne sile odzove s takojšnjim zmanjšanjem podajanja; iz tega izhaja padec rezalne sile na raven primerjalne vrednosti (sl. 14).

Stalne rezalne obremenitve privedejo do boljše kakovosti površine in preprečijo nezaželene vibracije in povese rezalnega orodja. Izboljšanje kakovosti površine je najbolj opazno pri obdelavi kotov, žepov, utorov in ukrivljenih površin, pri katerih sistem z zmanjšanjem podajanja prepreči nezaželene povese frezala.

Sistem nekoliko slabše sledi hitrim spremembam rezalnih razmer; to je posledica njegove zapletene zgradbe in napak pri modeliranju. Vzrok za počasno odzivnost in

Figure 13 shows the progress of the maximum cutting force without the use of the SDNRP. In this case the roughness has a random trend (Figure 15). The dynamic component of the cutting force is simulated by the block diagram in Figure 10.

The simulation graphs show that on the basis of the signals of the maximum cutting force the quality of surface can be supposed. Both values are mutually related and have identical trends. The SDNRP ensures constant roughness throughout the machining.

The simulations confirm that the proposed system is efficient for ensuring the required roughness and maintaining the constant machine loading. The control system responds to the rise of the cutting force by an immediate reduction of the feeding; as a result, the cutting force drops to the reference value (Figure 14).

Constant cutting loadings lead to a better quality of surface and prevent undesirable vibrations and deflections of the cutting tool. The improvement of the surface quality is most obvious when machining corners, pockets, slots and curved surfaces, where the system prevents undesirable milling cutter deflections by a reduction of the feeding.

The system deals with rapid changes to the cutting circumstances not so well, due to its complex structure and the errors in modelling. The reason for the slow responsiveness and inaccuracy can also be nenatančnost je treba iskati tudi v načinu izgradnje simulacijskega modela podajalnega servosistema. V simulator SDNRP je vključen model podajalnega servo-sistema, ki deluje po poenostavljeni prenosni funkciji (en. (3)). Ta je matematično izpeljana na podlagi določil proizvajalca. S preizkusnim posnetjem dinamike podajalnega servosistema, je mogoče odzivnost sistema močno izboljšati.

Rezultati simulacij nakazujejo naslednje ugotovitve:

- Modelno podprt sistem za dinamično nastavljanje rezalnih parametrov je zmožen nadzorovati rezalno silo v širokem območju rezalnih parametrov.
- Zahtevana hrapavost se doseže s simultanim nastavljanjem podajanja in rezalne hitrosti.
- Sistem je stabilen.
- Signali največjih rezalnih sil so v odvisnosti od hrapavosti površine.
- Največje odstopanje dejanske hrapavosti od izmerjene je 4,1 %.
- Največje odstopanje vodene rezalne sile proti primerjalni je 5,2 %.
- Sistem je najbolj učinkovit pri opravilih natančne obdelave, pri kateri hrapavost površine ne preseže 1,1 μm.

8 POVZETEK

V prispevku je predstavljen modelno podprt sistem dinamičnega nastavljanja rezalnih parametrov. Sistem z dinamičnim prilagajanjem podajanja in vrtljajev obvladuje hrapavost površine ter rezalne sile na frezalu. Med obdelavo spremlja vrednosti največjih rezalnih sil. Soodvisnost med hrapavostjo površine in rezalnimi silami določimo z metodo GP. Za primerjavo so izpeljane z metodo genetskega programiranja še matematična razmerja med vplivnimi rezalnimi veličinami, ki so osnova za izdelavo računalniških simulacij v paketu Simulink.

S simulacijami je potrjena ustreznost in stabilnost sistema vodenja. Dokazano je, da lahko z obvladovanjem rezalnih sil uspešno nadzorujemo hrapavost površine, ki je bistven kazalnik kakovosti postopka. Z ohranjanjem nespremenljive rezalne sile zagotavljamo stalno kakovost obdelane površine.

Na podlagi rezultatov številnih simulacij se odločimo, da preizkusno izvedemo opisan sistem

traced to the manner of the development of the simulation model of the feeding servo-system. The SDNRP simulator incorporates the model of the feeding servo-system, which functions according to the simplified transfer function (Equation 3). The latter is mathematically derived on the basis of the maker's specifications. By experimentally capturing the dynamics of the feeding servo-system it is possible to considerably improve the responsiveness of the system.

The simulation results indicate the following findings:

- A model-based system for dynamically adjusting the cutting parameters is capable of controlling the cutting force over a wide range of cutting parameters.
- The required roughness is reached by simultaneous adjustment of the feeding and cutting speeds.
- The system is stable.
- The signals of the maximum cutting forces correlate with the surface roughness.
- The maximum deviation of the actual from the measured roughness is 4.1%.
- The maximum deviation of the controlled from the reference cutting force is 5.2%.
- The system is most efficient during fine-machining operations, where the surface roughness does not exceed 1.1 μm.

8 CONCLUSION

This paper presents a model-based system for dynamically adjusting cutting parameters. By a dynamic adaptation of the feeding and spindle speed the system controls the surface roughness and the cutting forces on the milling cutter. During machining it follows the values of the maximum cutting forces. The correlation between the surface roughness and the cutting forces is determined by the GP method. Furthermore, mathematical relations between the influencing cutting values, on which the development of the computer simulations in the package Simulink is based, are derived for comparison.

Using simulations the adequacy and stability of the control system are confirmed. It was proved that the surface roughness, which is an important indicator of the process quality, can be successfully controlled by controlling the cutting forces, and by maintaining a constant cutting force a constant quality of surface finish is ensured.

On the basis of the results of numerous simulations we decided to realize experimentally vodenja. Sistem je zasnovan za opravilo oblikovnega frezanja, čeprav ga je mogoče prilagoditi za vse postopke obdelave z odrezovanjem. Primeren je za vključitev v obdelovalne sisteme, ki se uporabljajo v avtomobilski in orodjarski industriji. Odpravlja probleme, ki so povezani z zagotavljanjem kakovosti obdelave, učinkovitosti obdelave in preprečevanjem poškodb orodja.

the described system of control. The system was conceived for the end milling operation, although it can be modified for all processes of machining by cutting. It is suitable for the incorporation into manufacturing systems used in the automobile and tool-making industries. It also eliminates the problems related to the ensurance of the quality of machining, the efficiency of machining and the prevention of tool damage.

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Naslov avtorjev: dr. Uroš Župerl
prof. dr. Franci Čuš
prof. dr. Edvard Kiker
Univerza v Mariboru
Fakulteta za strojništvo
Smetanova 17
2000 Maribor
uros.zuperl@uni-mb.si

Authors' address: Dr. Uroš Župerl
Prof. Dr. Franci Čuš
Prof. Dr. Edvard Kiker
University of Maribor
Faculty of Mechanical Eng.
Smetanova 17
2000 Maribor, Slovenia
uros.zuperl@uni-mb.si

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Razvoj postopkov in naprav za uporabo pri suhem obdelovanju

Process and Apparatus Developments in Dry-Machining Applications

Mustafa Kemal Kulekci
(Mersin University, Turkey)

V prispevku obravnavamo novejši razvoj v postopkih suhega obdelovanja. Pri suhem obdelovanju se izognemo problemom onesnaženja rezalne tekočine, njene odstranitve in nevarnosti za zdravje. Primernost obdelovanca za suho obdelovanje je odvisna od lastnosti materiala. Učinkovitost rezalnega orodja pri suhem obdelovanju je odvisna od lastnosti prevleke. Postopek ima tudi omejitve, ki jih moramo upoštevati: hitro in ponavljajoče se spreminjanje temperature povzroča raztezanje, krčenje ter povečano nevarnost nastanka toplotnih razpok na rezalnem robu. Prisotnost hladiva poveča problem toplotnega pokanja. Pri suhem obdelovanju ostaja orodje vroče in trdno. Med postopkom suhega obdelovanja prevleka prevzame vlogo hladiva pri varovanju rezalnih robov pred obrabo ter zagotavlja zanesljivo odstranjevanje odrezkov. Potrebne so nadaljnje raziskave suhega vrtanja ter pehanja materialov z dolgimi odrezki.

(Ključne besede: suhe obdelave, prevleke, rezilni vložki, življenjska doba orodij)

In this study a recent development in the dry-machining process is discussed. Dry machining eliminates the problems of cutting-fluid contamination, disposal, filtrations and the risk of health problems. The suitability of the workpiece for dry machining depends on the material's properties. The performance of the cutting tool for the dry-machining process depends on the properties of the coating. The process also has a restriction that must be taken into consideration: the rapid, repetitive fluctuations of the temperature lead to expansion, contraction and an increased risk of thermal cracking of the cutting edge. The presence of the coolant exacerbates the thermal cracking problem. Dry machining keeps the tool hot and tougher. During the dry-machining process the coating takes the place of the coolant in protecting the cutting edges from wear and ensures reliable chip evacuation. Additional studies are needed on the dry-drilling and taping process for long chipping materials.

(Keywords: dry machining, coatings, cutting inserts, tool life)

0 INTRODUCTION

Near-dry and dry machining are becoming increasingly popular as ways of reducing production costs, while at the same time protecting the environment [1]. Because of growing concern about pollution and the associated legislation, fluid disposal has become both costly and compulsory for environmental protection. Cutting fluids remove heat, reduce friction, wash away chips, reduce cutting forces and power requirements, improve the dimensional stability of the work part, improve the surface finish and prevent any built-up edge. Coolants are essential in the machining of materials such as aluminium and stainless steels, which tend to adhere to the tool and cause a built-up edge. Cutting fluids also cause some problems, such as odours, health hazards, and loss of their lubrication function with contamination ([2] to [4]). Some 16% of the costs of a machine part are directly attributable to the fluids that are used. Tooling accounts for 4% of the part's costs. Eliminating the coolant reduces the amount of waste dumped in land fills, the amount of airborne material in the factory atmosphere, and the risk of health problems for operators [5].

The transition from the use of coolants to near-dry and dry machining usually depends on the work material. Dry machining eliminates the problems of cutting-fluid contamination, disposal and filtrations. But the process also has a restriction that must be taken into consideration. During dry machining, the tool and the workpiece are subjected to higher temperatures. The friction between the chip, the tool and the workpiece increases during dry machining when processing with a conventional tool, and the adherence tendency of the chip to the tool is higher during dry machining. These negative effects of dry machining shorten the tool life and the stability of the workpiece ([4] and [6]). To overcome these restrictions new coats and coating processes are being developed and tested for dry-machining tools ([7] to [14]).

1 EFFECTS OF DRY MACHINING ON THE CUTTING TOOLS

The important coating properties of the cutting tool are a low coefficient of friction, oxidation resistance, chemical stability against the workpiece material, hot hardness, hardness, ductility, resistance to abrasive wear, crack retardation, and thermo-physical properties. The hardness of the tool material during machining is related to the hot hardness characteristics of the tool material. The hot hardness property usually requires a trade-off in toughness, as hardness and toughness are opposing properties [4]. The hardness characteristics of various tool materials at elevated temperatures are illustrated in Figure 1. In the dry-machining process the coolant is eliminated and the tool reliability is increased. However, the recently developed coated cemented carbide ceramics, cermets, CBN and diamond tools are brittle. These tools chip, fracture and crack during facing and milling operations. Rapid, repetitive fluctuations of the temperature lead to expansion, contraction and increase the risk of the thermal creaking risk of the cutting edge ([16] and [17]). The presence of the coolant exacerbates the thermal cracking problem. Dry machining keeps the tool hot and tougher. The distribution of heat generated during dry machining according to cutting speed is illustrated in Figure 2. In the machining process the high-efficiency machining range is identified according to the time and the cost per piece, as illustrated in Figure 3. Figure 1, 2, and 3 show that there is an optimum temperature limit for economic machining.

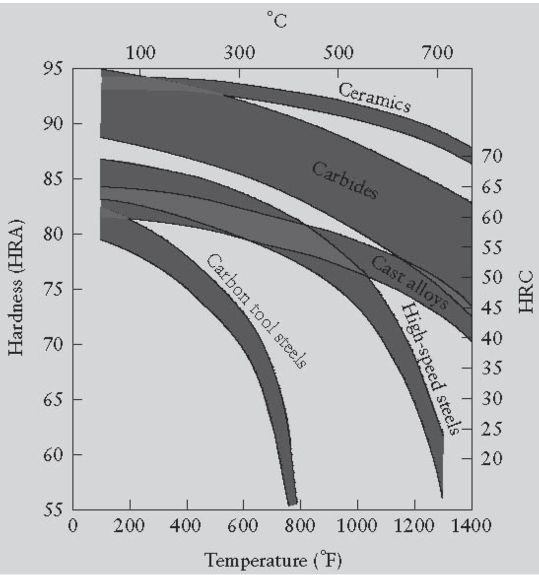

Fig. 1. *Hardness characteristics of cutting tool materials, at elevated temperature [15]*

2 DEVELOPMENTS IN TOOLS FOR DRY MACHINING

In the dry-machining procedure the unwanted effects of temperature on the tool can be compensated by selecting a harder grade insert. Selecting an insert with a larger nose radius can be used to improve the feed-dependent surface finish. An increase in temperature lowers the hardness, while at the same time increasing the toughness of the cutting edge, as seen in Figure 1. During a facing operation of a cylindrical workpiece, the tool cuts with a constant rpm and a variable surface speed. Using coolant as the cutting tool moves from the outer side to the centre of the face of the part causes the temperature of the cutting edge to decrease. Fluctuations in temperature change the stress state of the tool, which is effective during the thermal cracking of the tool [17]. Dry machining in similar conditions will give better results in terms of tool life. The cutting speed, feed and depth of the cut are the factors that control the metal removal rate during turning. These parameters determine the tool life. An increase of 50% in the cutting-speed feed and the depth of the cut results in a decrease of the tool life by 90%, 50% and 10% respectively [19]. On the other hand, increasing the depth of the cut is not an option for near-net-shape part production. Consequently, increasing the feed rate and decreasing the cutting speed have a positive impact on tool life. The disadvantage of this approach is a deterioration of the surface finish. The selection of

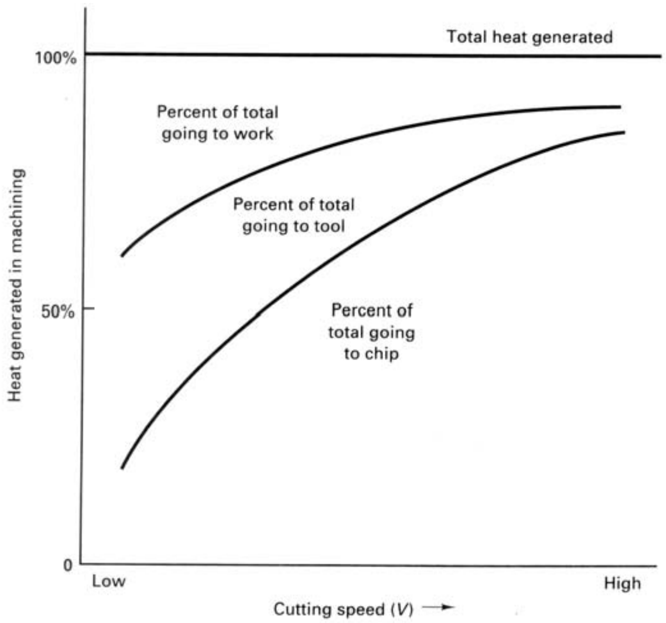

Fig. 2. *Distribution of heat generated in dry machining according to cutting speed [18]*

a tool that has a larger nose radius will compensate for this deterioration. Increasing the cutting edge, the rake angle and adjusting the lead angles decreases the friction and the temperature. Under certain conditions where lubrication is needed, such as drilling, grooving, parting off, the machining of stainless steels and high-temperature alloys, minimum-quantity lubrication (MQL), which consists of a drop or droplets of oil suspended in compressed air, must be used. During the dry drilling and taping of long chipping materials, premature tool replacement or expensive waste because of tool failure are common problems. The extreme temperatures that develop at the cutting edges are the main source for such problems because the tool becomes more susceptible to wear and fracture. The deformed hot chips, which may weld to the tool and form built-up edges, also greatly impair the reliability ([5] and [20]). Recently produced tools with new coatings combine a harder and soft coating and provide effective chip evacuation without any conventional lubrication. The hard layer is a titanium aluminium nitride (TiAlN) coating, while the soft lubricant layer is tungsten carbide/carbon (WC/C), a coating of medium hardness and a low coefficient of friction, as seen in Figure 4.c. The combination of these coating layers results in an improved chip flow, while generating a lower coefficient of friction ([5], [8] and [14]). This coating combines the advantages

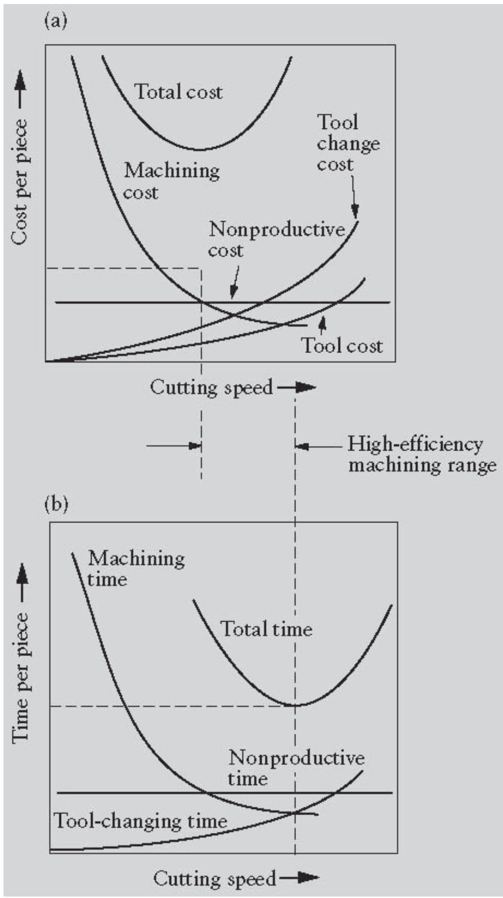

Fig. 3. *Cost per piece (a), and time per piece (b) in high efficiency machining [15]*

of an extremely hard and thermally stable TiAlN coating with the sliding and lubricating properties of the outer WC/C coating. During the dry-machining process the coating takes the place of the coolant to protect the cutting edges from wear, while simultaneously ensuring reliable chip evacuation. These lubricious coatings reduce the generation of heat by decreasing the amount of friction. Coatings such as molybdenum disulfide and tungsten carbide-carbon have low coefficients of friction and can lubricate the cutting action. These coatings are soft and have a relatively poor tool life. To compensate for this limitation, these coatings are often used with hard under-layers such as titanium carbide, titanium aluminium nitride, aluminium oxide or some combination of these. Diamond-like carbon (DLC) coatings are the first kind of coating for the dry machining of aluminium alloys [22]. The surface of a DLC coating is exceptionally smooth and has an extremely low friction coefficient, 0.05 to 0.2 μ, for aluminium alloys. DLC coatings are based on the same carbon chemistry as diamond and graphite and feature an amorphous structure that provides a high hardness and good lubrication ([10] and [21]). The lubrication properties of DLC coatings improve the chip versus uncoated inserts. The DLC coating reduces the cutting temperature and the cutting force by 25% and 50%, respectively [22]. DLC coatings give reasonable results in low-silicon aluminium and in finishing/semi-finishing milling applications. Keiichi et al. compared a DLC-coated insert with an uncoated tool in the machining process for aluminium materials. They report that as a result of a lower heat generation the chips from the DLC-coated insert were about 1.5 times the length of those from the uncoated insert [10] and [21]. Hanyu H. et al. produced a 1-μm surface roughness of the diamond coating on cutting edges and flutes of drills using a chemical vapour deposition (CVD) technique. In the study using dry cutting conditions an aluminium alloy including 12% silicon was drilled with different tools. The numbers of holes were 94, 731 and 3080 for the non-coated, conventionally diamond coated and fine-crystallized smooth diamond-coated drills, respectively. The increase in the number of holes for the fine-crystallized smooth diamond-coated tool is explained by the difference in the friction and the anti-sticking properties [2].

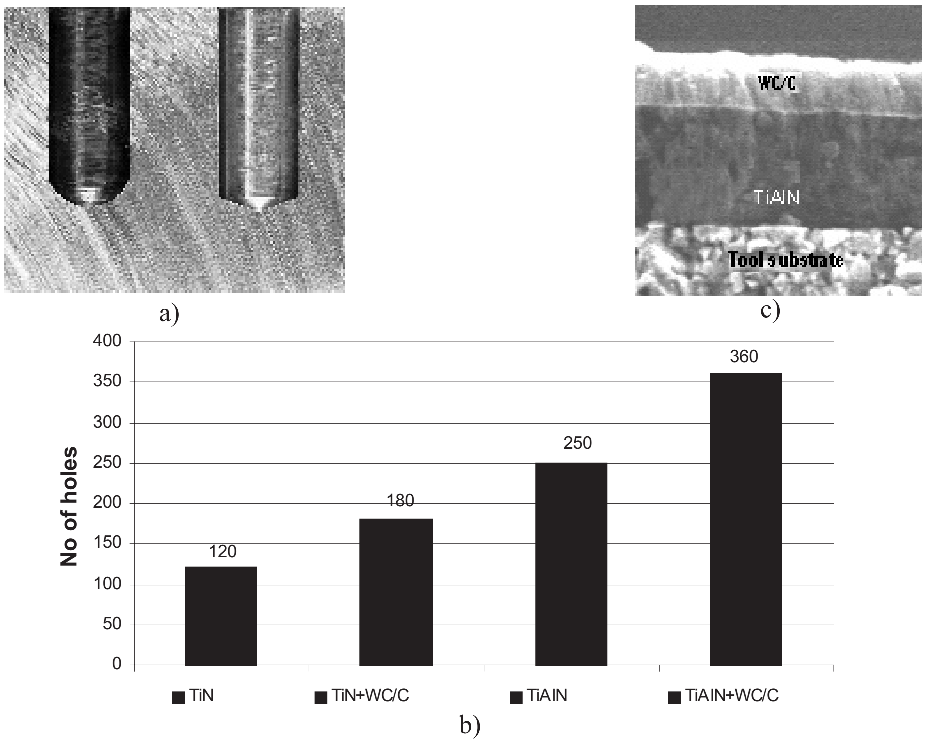

Fig. 4. a) *Surface quality after the same number of drilled holes: TiAlN (left), and TiAlN+WC/C (right), b) Coating performance in dry machining, c) SEM cross-section of the TiAlN+WC/C [5]*

3 DRY MACHINING OF COMMON METALLIC MATERIALS

The suitability of the workpiece for dry machining depends on the material properties, and in some cases the fluids may be undesirable, for example, where there is a risk of contamination. The cutting fluids stain the part or contaminate it.

Cast iron and alloyed steel. Cast iron and alloyed steel materials are relatively easy to dry machine and conduct heat well, allowing the chips to carry away most of the generated heat.

Low-carbon steel. Low-carbon steel becomes more adhesive as the carbon content falls. Newly developed tools may be used to prevent welding. The key variables for the dry machining of nonferrous materials are achieving a higher spindle speed, improving the chip-ejection geometry and the design.

Aluminium alloys. Aluminium alloys can be dry machined because of the relatively low cutting temperatures. Sharp edges and highly positive rake angles make it possible to solve the welding problem of the chips. When dry machining aluminium alloys at high speeds, recently developed TiAlN+WC/C, DLC or diamond-like-film-coated PCD tools can be used.

Stainless steels. At the machining temperature stainless steels are sticky and have a propensity to cause build-up along the cutting edge, leading to a poor surface finish.

Nickel and chromium based alloys. During the machining of nickel- and chromium-based alloys a higher temperature is generated, which must be taken into consideration in the dry-machining process. These materials require tools that have better lubrication and hot hardness properties.

Titanium. The properties of titanium prevent it from being dry machined. Titanium is also sticky at higher temperatures, has a low thermal conductivity and a low flash point. Consequently, the chips do not carry the heat away and the workpiece can get hot enough to ignite and burn [23].

Magnesium. Magnesium can be dry machined, but there is a risk of burning of the workpiece because of the lower flash point. Magnesium use in industrial application is expanding and it may be “the metal of the future”; this is because it has high strength, light weight, a good damping capacity and can be formed to a near-net shape fairly easily. The dry-machining process might be an important technique for solving technological problems in the use of magnesium. Magnesium chips are a fire hazard and they react with water in the coolant and form magnesium hydroxide. This reaction releases hydrogen, which is dangerous and makes the water in the coolant harder. The quality of the wetted magnesium chips (magnesium hydroxide) deteriorates, so the recycling of the chips can be a problem.

4 PROBLEMS IN DRY MACHINING

The main problems associated with dry machining are related to heat. Deformation occurs earlier, thereby reducing the tool life. Another problem associated with dry machining is the instability in the workpiece size, caused by the increasing temperature. Without coolant the temperature of the tool, the tool holder, the machine components and the workpiece increases and the size of the workpiece changes [4]. To eliminate these effects the contact time between the tool and the workpiece must be reduced. For applications that require several operations, planning the order of the operations reduces the temperature. Using an insert, which has the appropriate chip groove, makes it possible to remove the chip with the minimum deflection or deformation. Minimising the deformation during the machining reduces the generated temperature [14]. By minimizing the depth of the cutting in the finishing process it is possible to lower the temperature of the cut. During dry machining precautions must also be taken to prevent chip breakage and evacuations. The chips at a high temperature are more ductile than their cooler counterparts, so chip breaking becomes more difficult in higher-temperature regimes. The tools that are designed with a versatile chip groove control the stringy chips and eliminate this problem. However, in dry machining the hot chips can remain in the cutting region, heating up the workpiece, the tool and the machine. Overheating results in work hardening and serious geometrical and dimensional flaws in the finished part. Gravity may be used to remove the chip from the cutting region. The chips can fall on a conveyor if the tools are used vertically or diagonally upward [22]. Increasing the cutting speed in the drilling operations forces the chips to leave the hole more quickly and reduce the heat in the cutting region and so increase the tool’s life.

5 RESULTS

During the dry-machining process optimisation of the tool and the workpiece is needed to identify the parameters of the cutting speed, the depth of cut and the feed rate. The performance of the cutting tool for the dry-machining process depends on the properties of the coating. The feed rate can be increased, while the cutting speed is decreased during dry machining for a defined material-removal rate. Success during dry machining requires a methodical approach to control the heat produced in the process.

Any advances in dry machining will enhance the industrial applications of magnesium and magnesium alloys, which have a good strength/density ratio. The presence of the coolant exacerbates the thermal cracking problem of the cutting tool. Dry machining keeps the tool hot and tougher. During the dry drilling and taping of long chipping materials, premature tool replacement or expensive waste because of tool failure are common problems. Additional studies are needed on drilling and taping. The combination of TiAlN+WC/C coating layers results in an improved chip flow and a low coefficient of friction during dry machining. In the dry machining process the coating takes the place of the coolant to protect the cutting edges from wear and ensure reliable chip evacuation. Molybdenum disulfide, diamond-like carbon (DLC) and tungsten carbide-carbon (WC/C) coatings are lubricious coatings and have low coefficients of friction. In the dry-machining processes special precautions must be taken to remove the chips from the cutting zone.

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Author's Address: Dr. Mustafa Kemal Kulekci
Mersin University
Faculty of Tarsus Technical Education
33480 Tarsus, Turkey
mkkulekci@mersin.edu.tr

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Toplotno-gospodarsko optimiranje toplovodnega sistema: Parametrična raziskava vpliva pogojev sistema

The Thermo-Economic Optimization of Hot-Water Piping Systems: A Parametric Study of the Effect of the System Conditions

Hasan Karabay
(Kocaeli University, Turkey)

V prispevku smo predstavili toplotno-gospodarsko metodo optimiranja toplovodnega sistema. Metoda temelji na drugem zakonu termodinamike. Sočasno, ob upoštevanju eksergijske razgradnje zaradi trenja in eksergijske izgube zaradi toplotnih izgub in stroškov delovanja, smo določili optimalni premer cevi in debelino izolacije, medtem ko smo stroške cevovoda in izolacije obravnavali kot investicijo. S parametrično raziskavo smo predstavili vpliv masnega pretoka, letni čas obratovanja, amortizacijsko dobo ter temperaturo vode. Rezultati kažejo, da na optimalni premer cevi najbolj vpliva masni pretok. Letni čas obratovanja, amortizacijska doba in temperatura vode so odločilni vplivi pri izbiri primerne debeline izolacije.

(Ključne besede: toplovodni sistemi, optimiranje, eksergijska razgradnja, eksergijske izgube)

A thermo-economic optimization method for a hot-water distribution pipe is presented. The method is based on the second law of thermodynamics. Both the optimum pipe diameter and the insulation thickness are determined simultaneously, considering exergy destruction due to friction and exergy loss due to heat losses as the operation cost, while the piping and insulation costs are considered as an investment. The effect of mass flow rate, annual operation time, depreciation period and water temperature on the optimum pipe diameter and insulation thickness are presented with a parametric investigation. The results show that the mass flow rate dominates the optimum pipe diameter. The annual operation time, depreciation period and water temperature are the decision parameters for the optimum insulation thickness.

(Keywords: hot water networks, optimizations, exergy destruction, exergy loss)

0 INTRODUCTION

Hot-water network systems distribute thermal energy from a central source to residents; these are widely used in district and geothermal heating systems. They are also like the arteries of nearly all industrial applications. This is why hot-water networks should be designed carefully, in order to be able to operate the systems efficiently. The heat and pressure losses must be decreased to save energy, and also the investment and operation costs of the piping system must be as low as possibility to save money.

A literature review shows that there are a few methods for piping techniques. The classical piping techniques have been presented in various text books and handbooks ([1] to [3]). The classical piping techniques can be easily applied to a hot-water network layout, but they are not suitable for present-day requirements, as they consider only the fluid flow aspects.

A design procedure has been developed by Jones and Lior [4] that involves solar-heating-system piping and water-storage tanks. Their optimization method considers cost minimization with the first law of thermodynamics and fluid-flow aspects. Another method presented Wepher et al. [5], for selecting the optimum pipe size and insulation thickness, is based on the minimization of the total cost of piping and insulation capital and operation costs using the second law of thermodynamics. A bleeder steam line was presented as a case study.

Wechsatol et al. ([6] and [7]) proposed a design procedure involving the optimum geometric layout of schemes of hot-water distribution over an area. In these studies, investment and operation costs, exergy costs, lifetime and operation time of the system and other economic aspects were not considered. Lorente et al. [8] included the effect of the exergy in the design procedure used by Wechsatol et al.

In a recent study, four different thermo-economic techniques for the optimum design of hot-water piping systems were compared [9]. A simultaneous determination of the pipe diameter and the insulation thickness based on a thermo-economic optimization with the second law of thermodynamics method was recommended for use in design studies.

In this paper the aim is to study and present the parameters affecting the system conditions, such as the mass flow rate, the annual operation time, the depreciation period and the fluid temperature on the decision variables.

1 THERMODYNAMIC MODEL FOR PIPE FLOW

The thermodynamic model based on the second law will be summarized as follows. The details can be found in [9]. A schematic representation of the insulated pipe segment is shown in Fig. 1. It is a long straight conduit segment, installed above the ground in an environment at a temperature and pressure (T_{out}, P_{out}) that are identical to those of the dead state. The assumptions are a constant environmental temperature for T_{out} and constant thermodynamic properties at an appropriate mean temperature. The pipe segment consists of a stainless-steel pipe, insulation material and a galvanized steel cover sheet. Hot water is pumped through the conduit; the thermodynamic variables at the entrance and the exit of the conduit segment are as shown in Fig. 1.

Assuming the pumping energy is very small in comparison to the energy transported through the pipe segment, the hot-water exit temperature, T_{exit}, from the pipe is [10]:

$$T_{exit} - T_{out} = (T_{\sup} - T_{out})\ e^{-\Gamma_1 \Gamma_2} \quad (1)$$

with:

$$\Gamma_1 = \left(\frac{2\pi}{\begin{array}{l}(1/r_{in}h_{in}) + (1/k_{pipe})\ln(r_{pipe}/r_{in}) + \\ (1/k_{ins})\ln(r_{out}/r_{pipe}) + (1/r_{out}(h_{out}+h_{rad}))\end{array}} \right) \quad (2)$$

$$\Gamma_2 = \left(\frac{L}{\dot{m}C_p} \right) \quad (3),$$

where the convection heat-transfer coefficient inside pipe, h_{in}, and the convection and radiation heat transfer coefficients outside pipe, h_{out} and h_{rad}, are calculated as [10]:

$$\frac{h_{in}\,D_{in}}{k} = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \quad (4)$$

$$h_{rad} = \frac{\sigma\varepsilon(T_{ms}^4 - T_{ms}^4)}{T_{ms} - T_{out}} \quad (5)$$

$$\begin{array}{l} h_{out} = 11.58\left(1/D_{out}\right)^{0.2}\left[2/\left(T_{ms}+T_{out}\right)\right]^{0.181} \\ \left(T_{ms}-T_{out}\right)^{0.266}\left(1+0.7935\,V_{wind}\right)^{0.5} \end{array} \quad (6).$$

Eq. (6) is valid for turbulent air flow and L/D_{out} >10. It is a general equation of the ASTM Standard C680 for computer calculations [11]. The mean outside surface temperature, T_{ms}, is calculated iteratively in Eqs. (5) and (6).

Assuming a constant heat capacity at the arithmetic mean temperature, the heat loss is calculated as:

$$\dot{Q}_{loss} = \dot{m}C_p(T_{\sup} - T_{exit}) \quad (7).$$

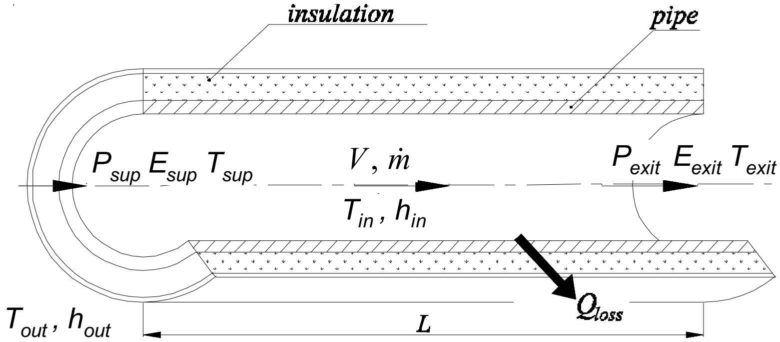

Fig. 1. *Pipe segment and definition of various parameters*

The pumping power is:

$$\dot{W}_p = \frac{\dot{m}\,\Delta P}{\rho\,\eta_p} \qquad (8),$$

where ΔP is the pressure drop through the pipe, which is calculated using the Darcy-Weisbach equation:

$$\Delta P = \left(f\frac{L}{D} + \sum \xi \right) \rho \frac{V_m^{\ 2}}{2} \qquad (9).$$

Here f is the Darcy–Weisbach friction factor, which is evaluated using the Colebrook correlation [12]. ξ is the pressure-loss coefficient of the fittings. The numerical values of ξ are evaluated as suggested in [2].

The exergy destruction due to friction is [13]:

$$\dot{E}_{des} = \frac{T_{out}}{T_m}\dot{W}_p \qquad (10).$$

Here, $T_m=(T_{sup}+T_{exit})/2$ is the mean water temperature.

The exergy flow in the pipe is [13]:

$$\dot{E} = \dot{m}C_p\left[(T - T_{out}) - T_{out}\int_{Tout}^{T}\frac{dT}{T} \right] \qquad (11).$$

The difference between the exergy supplied, $\dot{E}_{\sup}$ plus $\dot{W}_p$, and the exergy at the exit, $\dot{E}_{exit}$, will be the exergy loss from the pipe segment:

$$\dot{E}_{loss} = \dot{E}_{\sup} + \dot{W}_p - \dot{E}_{exit} \qquad (12).$$

1.1 The objective function

Exergy destruction due to friction and exergy loss due to heat losses are considered as operation costs, while the piping and insulation costs are considered as investment. Using a similar method in [5], the objective function can be written as:

$$\dot{C}_{tot} = \dot{Z}_{pipe} + \dot{Z}_{ins} + c_{el}\dot{E}_{des,p} + c_e\dot{E}_{loss} \qquad (13),$$

where c_{el}, c_e are the specific exergy costs for the electrical energy and the hot water.

The unit exergy cost of the hot water in a boiler, c_e, is calculated in a similar way to [3]:

$$c_e = \frac{c_f\dot{E}_f + \dot{Z}_b}{\dot{E}_{\sup} - \dot{E}_{ret}} \qquad (14).$$

Here, c_f is the energy cost of the fuel. $\dot{E}_f$ is the annual fuel exergy flow rate. $\dot{Z}_b$ is the cost of capital annualized over the boiler lifetime and the cost of operation and maintenance. $\dot{Z}_b = (CRF + \varsigma)C_b$, $CRF = i/(1-(1+1)^{-n})$ is the capital recovery factor, ς (= 0.01) is a coefficient that accounts for part of the fixed operation and maintenance cost and C_b is the total capital cost of the boiler. $(\dot{E}_{\sup} - \dot{E}_{ret})$ is the hot-water supply and return exergy flow rates added in the boiler.

The capital costs of the pipe and the insulation segment annualized over its lifetime and the annual cost of the operation and maintenance are given in [3]:

$$\dot{Z}_{pipe} = (CRF + \varsigma)C_{pipe} \qquad (15)$$

$$\dot{Z}_{ins} = (CRF + \varsigma)C_{ins} \qquad (16),$$

where C_{pipe} and C_{ins} are the total cost of the pipe and the insulation, which are evaluated according to the data given in [14], based on US currency as follows:

$$C_{pipe} = (1.308032 + 0.54011\, m_{pipe} + 1.4933x10^{-5}\ m_{pipe}^2)L_{pipe} \qquad (17)$$

$$C_{ins} = (11.156 + 299.308 e_{ins} - 471.830\ e_{ins}^2)A_{ins,surf} \qquad (18)$$

here, m_{pipe} is the pipe mass per length for any diameter, e_{ins} is the insulation thickness, $A_{ins,surf}$ is the insulation surface area. Eq. (17) is valid for 1.22 to 248 kg/m and Eq. (18) is valid for 10 to 240 mm of insulation thickness.

Finally, Eq. (13) is referred to as *the objective function*. It can be minimized through either analytical or numerical methods. In any case it is necessary to define the decision variables for each pipe segment. The decision variables are taken as the pipe diameter and the insulation thickness.

In practice, above-ground installation is not usual, most of the pipes in district-heating networks are installed under the ground. If an underground application is considered, the digging and burying costs should be included in the objective function as new investment parameters. Since these new cost terms may vary significantly from one application region to another, this parametric study is conducted only for above-ground installation.

2 SOLUTION PROCEDURE

In the present study the minimization of the objective function was obtained with a numerical method using a computer code written in FORTRAN. The computer code was written in a general form that can optimize the whole network. In this study the calculations are presented only for a pipe segment. The code obtains the minimum value of Eq. (13) for a pipe segment utilizing all the available defined pipe diameters and insulation thickness. For the parametric study, the inner diameter of the pipe in the computations varies from 100 mm to 1000 mm. The thickness of the pipe was assumed to be 1 % of the pipe diameter. The insulation thickness varies from 0 to 150 mm.

3 PHYSICAL AND FINANCIAL PARAMETERS

The validation of the objective function Eq. (13) for a single pipe was carried out using the same piping system as shown in Fig. 1. The fixed parameters are as follows: pipe segment length, L = 100 m; water supply temperature, T_{sup} = 100 °C; water return temperature to boiler, T_{ret} = 80 °C; ambient temperature, T_{out} = 10°C; and the mass flow rate, $\dot{m}$ =25 kg/s. The economic and financial parameters are as follows: annual interest rate, i = 6%; depreciation period, n = 20 years; and annual operation time, t = 3500 h/year. The energy costs: natural gas was used as a base fuel with c_f = 3.90 \$/GJ, with a lower heating value of the fuel H_u = 0.0495 GJ/kg and assuming a boiler efficiency of η_b = 0.9. The exergy cost is calculated from Eq. (14) as c_e = 18.60 \$/GJ. The electricity price: electricity is assumed to be c_{el} = 26.11 \$/GJ. The thermo-physical parameters: the conductivities of the pipe and the insulation materials were assumed to be k_{pipe} = 54 and k_{ins} = 0.045 W/mK, respectively. The emissivity of the insulation jacket was ε = 0.26. The range of the fluid velocity was 0.3 m/s to 6.3 m/s.

4 DISCUSSION OF RESULTS

Fig. 2 shows the cost as a function of the pipe's inside diameter with the cost components. The mass flow rate in the pipe is assumed to be 25 kg/s. The total cost of the pipe at the optimum point is 0.19 \$/hour. The optimum insulation thickness is 73 mm. The optimum pipe diameter is 158 mm. As can be seen in the figure the determining parameter of the total costs is the cost of the frictional loss. The other parameters being almost linear functions, increasing with the pipe's diameter. For $D > D_{opt}$ the cost of the heat loss and the insulation are significantly higher than the costs of the pipe and the pressure loss. At the optimum point the heat loss cost is about 40 %, the insulation cost is 35 %, the frictional loss cost is 15 % and the pipe cost is 10 % of the total cost.

Figures 3 to 6 show the effect of the system conditions on the decision variables. For simplicity and a better comparison the results in these figures are presented in a non-dimensional form. The parameters in these plots are non-dimensionalized as $(\phi - \phi_{fix})/\phi_{fix}$. Here, ϕ is the parameter being investigated and ϕ_{fix} represents the fixed or reference value of ϕ. The ϕ_{fix} values are the optimum values mentioned in Fig.2.

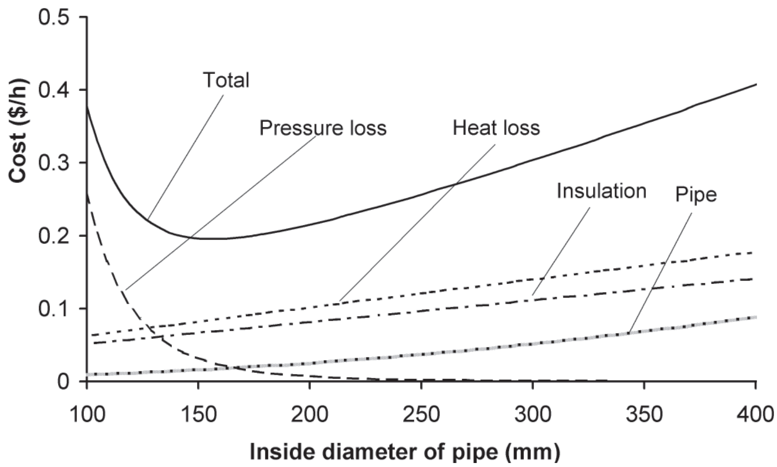

Fig. 2. *Variation of costs with pipe inside diameter for e_{opt}=73 mm*

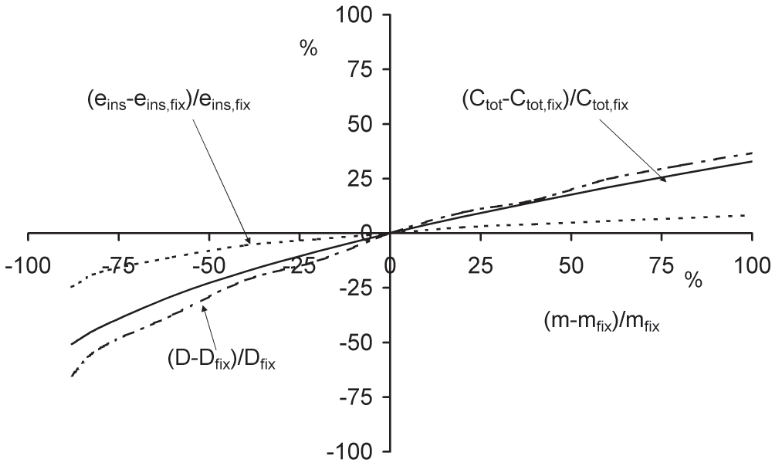

Fig. 3. *Effect of the mass flow rate on the decision variable:* m_{fix}*=25 kg/s,* D_{fix}*=158 mm,* $e_{ins,fix}$*=73mm,* $C_{tot,fix}$*=0.19 \$/hour*

Fig. 3 shows the non-dimensional variations of the total cost, the optimum pipe diameter and the insulation thickness with the non-dimensional mass flow rate. The mass flow rate $\dot{m}$ altered from 5 to 50 kg/s, and the pipe diameter, insulation thickness and the total cost for the optimum conditions were obtained using Eq.(13) for each mass flow rate. The parameters shown in the figure are non-dimensionalized using the related ϕ_{fix} values, which are the optimum values of Fig.2. The results in Fig.3 show that the mass flow rate is the determining parameter for the optimum pipe diameter and the total cost. The effect of mass flow rate on the optimum insulation thickness is less significant, compared to the other parameters. This is an important outcome for the designer. Consider a tree-shaped hot-water distribution network. If the flow in the pipe in this network is divided equally into two branches, the flow rate in the new branches will be 50% of the main pipe and the non-dimensional optimum pipe diameter of the new branches reduces about 29%. The non-dimensional total cost for new pipes is reduced by about 24%. However, the non-dimensional insulation thickness is reduced by only 9%. As a result, this figure suggests that the pipe diameters in the considered hot-water distribution-network system should be reduced satisfactorily, from the energy plant to the end user. But the insulation thickness should not be changed too much. In addition, the ratio of the pipe diameter of the branches to the main pipe diameter is about 0.707, which agrees well with the value reported in [6].

Fig. 4 shows the effect of the annual operation time on the total cost, the optimum pipe

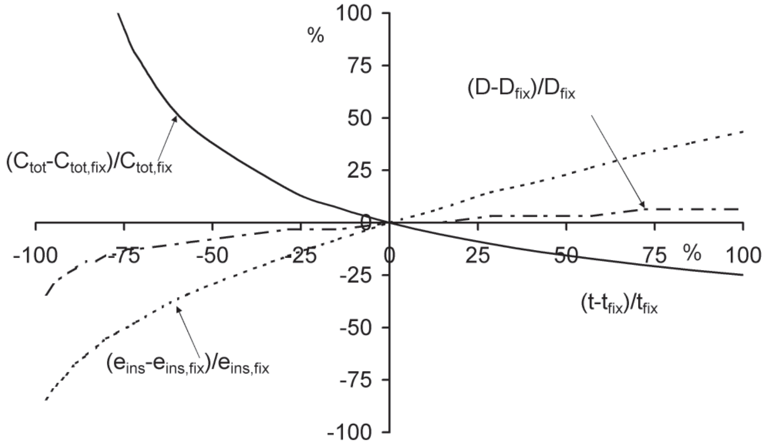

Fig. 4. *Effect of the annual operation time on the decision variables:* t_{fix}*=3500 hours/year,* D_{fix}*=158 mm,* $e_{ins,fix}$*=73mm,* $C_{tot,fix}$*=0.19 \$/year*

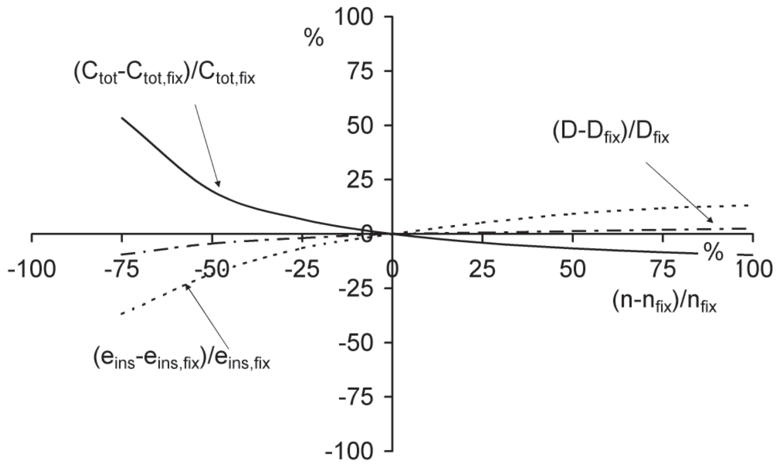

Fig. 5. *Effect of the depreciation period on the decision variables:* n_{fix} *= 20 years,* D_{fix} *= 158 mm,* $e_{ins,fix}$ *= 73mm,* $C_{tot,fix}$ *= 0.19 \$/year*

diameter and the insulation thickness. A longer annual operation time reduces the total cost of the conduit, which is as expected. The insulation thickness is affected significantly by the annual operation time. However, the effect of the annual operation time on the pipe diameters is less significant. For a prearranged hot-water distribution network, if the annual operation time of the system is extended by 100%, the optimum pipe diameter increases by about 5%. However, the optimum insulation thickness for the new system rises by about 40%. This shows that the annual operation time influences the heat-loss cost and the insulation cost significantly. The designer should be careful when specifying the annual operation time, which dominates the insulation thickness drastically.

Fig. 5 shows the effect of the depreciation period on the decision variables. The effect of the depreciation period is less significant with respect to the optimum pipe diameter. The heat-loss cost is more crucial than the frictional loss. The insulation thickness increases by about 15% when the depreciation period is extended by 100%.

Fig. 6 shows the effect of the water-supply temperature on the decision variables. Here, the supply temperature was altered from 50°C to 200°C. The water-supply and return temperature difference is assumed to be 20°C. The effect of the pressure variation with hot-water temperature on the pipe's thickness was ignored. Referring to Fig. 6, a higher fluid temperature increases the heat loss and the insulation thickness, which raises the total cost of the conduit. The pipe diameter is reduced slightly by a temperature rise, which causes a reduction in the heat-transfer area.

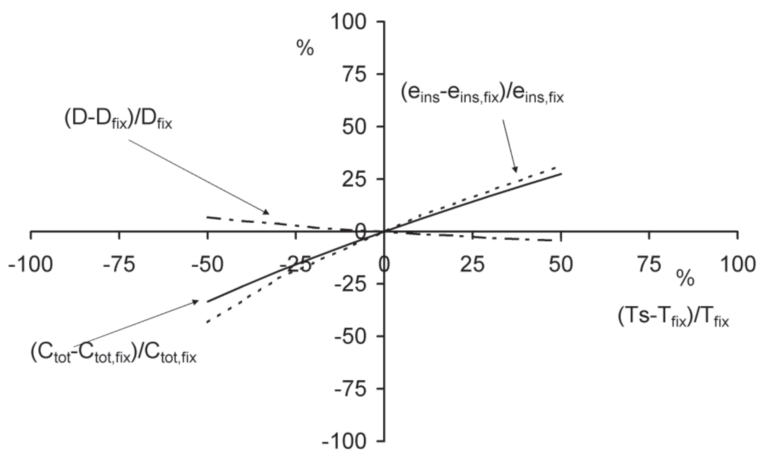

Fig. 6. *Effect of the water supply temperature on the decision variables:* T_{fix} *= 100 °C,* D_{fix} *= 158 mm,* $e_{ins,fix}$ *= 73mm,* $C_{tot,fix}$ *= 0.19 \$/year*

5 CONCLUSIONS

In this study the effect of the hot-water piping-system conditions on the decision variables is investigated with a thermo-economic optimization method based on the second law of thermodynamics. Important parameters, such as the ambient conditions, the interest rate, the fuel and electricity prices, and the thermo-physical parameters, were assumed to be the same and constant for the calculations. The main results obtained in this study can be summarized as follows:

- The results for the optimized pipe show that heat-loss cost, including the insulation cost, is about 75% of the total cost. The effect of the frictional cost and the pipe cost on the total costs is about 25%. The priority in the piping-design techniques for a hot-water delivery system should be on the heat-transfer calculation rather than the pressure-drop calculations.
- The mass flow rate is a determining parameter for the optimum pipe diameter. There is a secondary effect of the mass flow rate on the insulation thickness.
- The annual operation time is a determining parameter for the insulation thickness. The insulation thickness increases significantly when the annual operation time increases. The effect of the annual operation time on the pipe diameter is less significant.
- The effects of the depreciation period on the decision variables are similar to the annual operation time, but they are less significant. Heat-loss and insulation costs are more important parameters affecting the optimum values of the total cost of the hot-water piping network over the lifetime of the system.
- For an optimization study the fluid temperature is also an important parameter. A higher fluid temperature increases the heat loss, which requires a higher insulation thickness. There is a less significant effect of the fluid temperature on the pipe diameter.

Finally, the system conditions have a strong effect on the optimum values of the design parameters. Therefore, one should start to design the hot-water distribution network by specifying the precise amount of capacity, annual operation time, depreciation period and fluid temperature. For an existing hot-water network, any increase in the capacity by adding new users or changing the system parameters and keeping the pipes unchanged might affect the system's efficiency in a negative way.

6 NOMENCLATURE

C	\$	cost
c	\$/kJ	specific cost
$\dot{C}$	\$/s	cost rate
C_p	kJ/kgK	heat capacity
CRF		capital recovery factor
D	m	diameter
$\dot{E}$	kJ/s	exergy flow rate
e	m	thickness
f		friction coefficient
h	W/m^{2}K	convective heat-transfer coefficient
h_{rad}	W/m^{2}K	radiative heat-transfer coefficient
i		annual interest rate
k	W/mK	conductivity
L	m	pipe length
$\dot{m}$	kg/s	mass flow rate
n	year	depreciation period
P	Pascal	pressure
Pr		Prandtl number
$\dot{Q}$	kJ/s	heat flow rate
Re		Reynolds number
r	m	radius
T	K	temperature
T_{ms}	K	mean outside-surface temperature
t	h/year	annual operation time
V	m/s	velocity
$\dot{W}_p$	kJ/s	pumping power
Z	\$	capital cost
$\dot{Z}$	\$/s	capital cost rate

Greek letters

ε		surface emissivity
η		efficiency
ϕ		exergy efficiency
ρ	kg/m^3	density
σ		Stefan-Boltzmann constant
ξ		pressure loss coefficient

Subscripts

b	boiler
des	destruction
e	exergy
el	electricity
$exit$	exit value
f	fuel
in	inside, inner value of conduit

ins	properties of insulation	*pipe*	properties of pipe
m	mean value	*rad*	radiative
opt	optimum value	*ret*	return value
out	outside, outer value of conduit	*sup*	supply value
p	pumping	*tot*	total value

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Author's Address: Dr. Hasan Karabay
Kocaeli University
Engineering Faculty
41300, Kocaeli, Turkey
hkarabay@kocaeli.edu.tr

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Parametrična analiza Stirlingove soproizvodne enote na biomaso za uporabo v hišni tehniki

A parametrical Analysis of a Biomass Stirling Cogeneration Unit for Use in Housing

Uroš Stritih - Gregor Zupan - Vincenc Butala
(Fakulteta za strojništvo, Ljubljana)

Pričujoči prispevek predstavlja enoto za soproizvodnjo toplotne in električne energije (STE) na lesno biomaso za preskrbo z energijo v stanovanjskih hišah. Stirlingov motor je uporabljen kot sredstvo za soproizvodnjo toplotne in električne energije, za katero je bila narejena termodinamična analiza. Termodinamične vrednosti so izračunane matematično, za simulacijo pa je napisan računalniški program. Izdelana je parametrična analiza termodinamičnih vrednosti glede na učinkovitost Stirlingovega motorja. Moč motorja se lahko spreminja s količino delovnega plina, kar zahteva zbiralnik. Ker je učinkovitost motorja odvisna samo od zgornje in spodnje temperature v motorju, bi bila v primeru popolne regeneracije izohorne toplote, električna učinkovitost Stirlingovega motorja enaka učinkovitosti Carnotovega postopka.

(Ključne besede: Stirlingov motor, biomasa, parametrične analize, učinkovitost)

This paper presents a combined heat and power (CHP) unit using wood biomass to provide an energy supply for housing. The Stirling engine is used as a CHP-producing technology for which a thermodynamic analysis was carried out. The thermodynamic values were mathematically calculated and a computer program for the CHP simulation was written. A parametrical analysis of different combinations of thermodynamic values with respect to the efficiency of the Stirling engine was made. The power of the engine can be changed by the quantity of the working gas, which requires a reservoir. We concluded that if all the isochoric heat were regenerated, the electrical efficiency would be equal to Carnot's efficiency, since it depends only on the upper and lower temperatures in the engine.

(Keywords: Stirling engines, biomass, parametrical analysis, efficiency)

0 UVOD

Energetska oskrba v gospodinjstvih in industriji se običajno zagotavlja z nakupom električne energije iz javnega elektroenergetskega sistema in lastnim pridobivanjem toplote iz goriva, nabavljenega pri dobavitelju goriva. V zadnjem času se pa kot izbirna možnost pokrivanja energetskih potreb pojavlja soproizvodnja toplotne in električne energije. Z rastjo cen fosilnih goriv na svetovnih trgih, povečevanjem okoljevarstvene zavesti ter uvajanjem novih tehnologij zgorevanja goriv postaja lesna biomasa pomemben vir za pridobivanje tako toplotne kakor tudi električne energije. Soproizvodnja z uporabo biomase je torej izbirna možnost za

0 INTRODUCTION

The energy supply for households and industry is usually ensured by buying electrical energy from the public electrical energy system, while purchasing fuels from fuel suppliers provides one's heating. Recently, an alternative method for covering energy needs has appeared, called combined heat and power (CHP) generation. With the rise in the prices of fossil fuels on world markets, increased environmental consciousness, and the introduction of new fuel-combustion technologies, wood biomass is becoming an important means of acquiring both thermal and electrical energy. CHP using biomass is therefore an alternative option for soproizvodnjo toplotne in električne energije. Biomasa kot gorivo je sestavljena iz različnih prvinskih virov in je lahko uporabljena neposredno, ali pa je spremenjena v drugotno gorivo skozi različne tehnološke postopke. Lesna biomasa je po navadi uporabljena samo za proizvodnjo toplote, pri čemer je smotrno kurilni napravi prigraditi hranilnik toplote [1].

Soproizvodnja toplotne in električne energije na mikro ravni je eden od glavnih načinov za doseganje razpršene proizvodnje. Znotraj mikro soproizvodnega sistema ločimo hišno in nehišno skupino. Prva skupina, s 3 kW_e ali manj, je oblikovana tako, da se prilagaja potrebam stanovanja, druga skupina pa je lahko uporabljena za večstanovanjske stavbe, manjše hotele ali za manjše plavalne bazene.

Prednosti hišne soproizvodnje (HSE) pred ločeno proizvodnjo energije so: večja energijska učinkovitost, približanje proizvodnje uporabniku, zmanjšanje negativnih vplivov na okolje in povečanje zanesljivosti energijske oskrbe stavbe. Hišna soproizvodna enota se običajno izbere na pokrivanje toplotnih potreb stanovanjske hiše. Odvisno od vrste gradnje in velikosti stavbe običajno zadošča HSE moči med 5 in 15kW_t. Ker je hišna soproizvodnja blizu uporabniku, ni izgub energije med prenosom.

Stirlingovi motorji v primeru soproizvodnje toplotne in električne energije so bili tema številnih študij. Ö Ercan Ataer [2] je v svoji študiji predstavil razporeditev temperature plina vzdolž regeneratorskega bata in stene valja za kompresijski in ekspanzijski polovični krog. L. Berrin Erbay in Hasbi Yavuz [3] sta analizirala Stirlingov toplotni stroj pri največji moči; njuna analiza je vključevala politropno ekspanzijo in politropno kompresijo. Erich Podeser [4] je predstavil proizvodnjo električne energije iz biomase z uporabo Stirlingovega motorja; motor je bil konstruiran za razpršeno proizvodnjo električne energije za podeželske vasi, kjer električna omrežja niso dobro razvita. Ö. Ercan Ataer in H. Karabulut [5] sta analizirala hladilnik, ki deluje po Stirlingovem načelu. Analiza je vključevala termodinamično analizo motorja s kotom 90° med regeneratorskim in delovnim batom. Evgueniy Entchev in ostali [6] so v letu 2003, za dva različna sistema, analizirali delovanje mikrosistema Stirlingovega motorja za soproizvodnjo toplotne in električne energije.

1 STIRLINGOV KROŽNI POSTOPEK

Stirlingov motor (sl. 1) temelji na zaprtem krožnem postopku, pri katrem je delovni plin

heat and power production. Biomass is made up of various primary sources, either used directly or converted into secondary fuels via various technological processes. Wood biomass is usually used for heat production only, in which case a thermal storage unit should be combined with a biomass boiler [1].

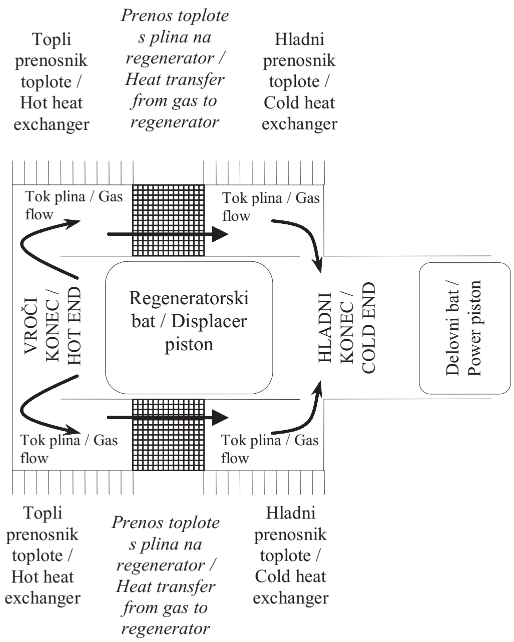
Micro-scale CHP is one of the main ways of achieving decentralized power production. There are two categories of micro-CHP: house and non-house uses. The first category of 3 kW_e or less is for a single household's needs, while the second category is for multi-story residential buildings, small hotels, and small swimming pools.

The advantages of house CHP compared to the separate production of heat and power are: the saving of primary energy, the higher electrical efficiency, the bringing of energy production closer to users, the reduction of the negative impact on the environment, and the increase in the certainty of energy supply. The house CHP unit is usually dimensioned to cover the heat needs. A CHP unit of heat power between 5 and 15 kW is usually enough for the house category. Because house CHP brings energy production closer to the users, there is no energy loss during the transmission.

Stirling engines, as an example of a heat and power production unit, have been the subject of a number of studies. Ö Ercan Ataer [2] presented the gas temperature distribution along the displacer and cylinder wall for a compression and expansion half-cycle. L. Berrin Erbay and Hasbi Yavuz [3] analyzed a Stirling heat engine under maximum power conditions; their analysis included polytropic expansion and polytropic compression. Erich Podeser [4] presented electricity production from a biomass Stirling engine; the engine was designed for decentralized electricity production in rural villages, where the electricity network is not well developed. Ö Ercan Ataer and H. Karabulut [5] analyzed a refrigerator that operates on the Stirling-cycle, including a thermodynamic analysis of the engine with an angle of 90° between the displacer and the power piston. Evgueniy Entchev et al. [6] estimated the operation of a micro-system for CHP production for two different systems in 2003.

1 STIRLING CYCLE

The Stirling engine (Fig. 1) is based on a closed circular process, where the working gas is alternately



Sl. 1. *Beta izvedba Stirlingovega motorja [7]*
Fig. 1. *Beta configuration of a Stirling engine [7]*

izmenično komprimiran v hladnem valju in ekspandiran v vročem valju. Prednost Stirlingovega motorja v primerjavi z motorji z notranjim zgorevanjem je v tem, da toplota ni dovedena krožnemu postopku z zgorevanjem goriva znotraj valja, ampak je prenesena skozi prenosnik toplote. Toplota, ki nastane z zgorevanjem goriva, se prenese delovnemu plinu skozi topli prenosnik toplote. Toplota, ki se ne spremeni v delo, se prenese ohlajevalni vodi skozi hladni prenosnik toplote. Ker je Stirlingov motor zaprt sistem, se kot delovno sredstvo lahko uporabi bolj primeren plin od zraka. Najbolj uporabljeni plini so helij, vodik in dušik.

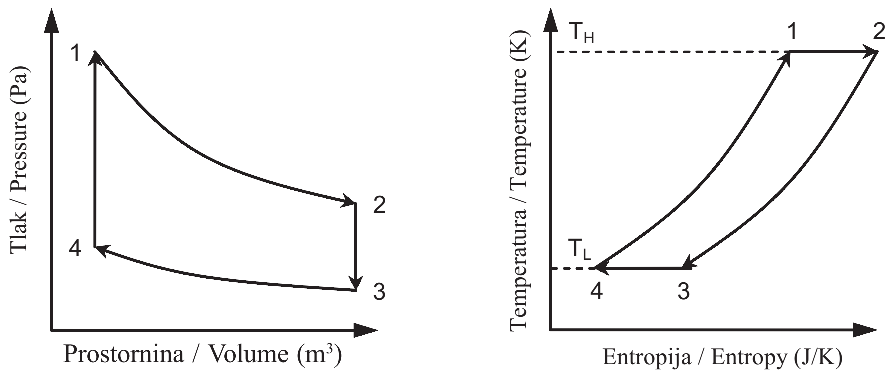
Motorji, ki delujejo na način Stirlingovega postopka, so najbolj učinkoviti toplotni stroji, ki so se kadarkoli zgradili [7]. Kot motor lahko deluje na katerikoli toplotni vir, vključno na sončno ogrevanje. Glede na lego valjev ločimo naslednje tri tipe Stirlingovih motorjev: alfa, beta in gama.

V idealnem Stirlingovem motorju se odvijajo štirje ločeni termodinamični postopki. Ti postopki so prikazani v diagramu tlaka v odvisnosti od prostornine ter temperature v odvisnosti od entropije (sl. 2). V idealnem Stirlingovem motorju se vpliv prostornine prenosnikov toplote, regeneratorja in prenosnih poti zanemari.

compressed in a cold cylinder and expanded in a hot cylinder. The advantage of a Stirling engine compared to an internal combustion engine is that heat is not supplied to the circular process with fuel combustion taking place inside cylinder, rather it is transferred from outside through the heat exchanger, like a steam boiler. Heat originating from the fuel combustion is transmitted to the working gas through a hot heat exchanger. Any heat not transformed into work on the engine shaft is delivered to cooling water in the cold heat exchanger. Because it is a closed system, more a appropriate working gas than air can be utilized in the Stirling engine. The most utilized gases are: helium, hydrogen, and nitrogen.

Engines working on the Stirling-cycle principle are the most effective heat engines that have ever been built [7]. As engines they can operate on any kind of heat source including solar. There are three different types of Stirling engines, depending on the position of the cylinders: alpha, beta, and gamma.

Four separate thermodynamic processes are performed in an ideal Stirling engine. Those processes are shown in graphs of pressure versus volume and temperature versus entropy (Fig. 2). In an ideal Stirling-cycle, the influence of the volume of heat exchangers, regenerators, and transport is ignored.



Sl. 2. *Termodinamični postopki v idealnem Stirlingovem motorju*
Fig. 2. *Thermodynamic processes in an ideal Stirling engine*

2 MATEMATIČNI MODEL

Čisto delo Stirlingovega motorja se določi z uporabo krožnega integrala tlaka po prostornini. Ker je neto delo, delo enega kroga, ki ga opravi motor, moramo za določitev električne moči integral tlaka glede na prostornino pomnožiti še s frekvenco gibanja delovnega bata v motorju:

2 MATHEMATICAL MODEL

The **net work output** of a Stirling engine can be evaluated by considering the cyclic integral of pressure with respect to volume. Because the net work output is the work output of one cycle made by the engine, the integral of the pressure with respect to volume should be multiplied by the frequency of the power piston motion in the engine:

$$P = \nu \cdot \int p \cdot dV \qquad (1).$$

Za izračun integrala upoštevamo delo, ki se opravi med izotermno ekspanzijo in porabi med izotermno kompresijo. Med izohornima preobrazbama se ne opravi in ne porabi nič dela. Na ta način lahko oblikujemo končno enačbo za moč:

To evaluate the integral we need only consider the work done during the isothermal expansion and used during the isothermal compression, since there is no work done or used during the isochoric processes. Thus, the final equation for power can be formulated as:

$$P = m \cdot R \cdot \ln \varepsilon \cdot \Delta T \cdot \nu \qquad (2),$$

kjer sta ε kompresijsko razmerje (V_2/V_1 in V_3/V_4), ΔT pa temperaturna razlika med zgornjo T_H in spodnjo T_L temperaturo.

Toplotni tokovi v Stirlingov motor in iz njega se izračunajo z upoštevanjem integrala temperature glede na entropijo:

where ε corresponds to the compression ratios (V_2/V_1 and V_3/V_4) and ΔT is the temperature difference between T_H and T_L.

Heat flows into and out of the Stirling engine can be evaluated by considering the integral of the temperature with respect to entropy:

$$\dot{Q} = \nu \cdot \int T \cdot dS \qquad (3).$$

Toplotni tok prehaja v motor pri izohorni kompresiji ter izotermni ekspanziji. Z uporabo prvega glavnega zakona termodinamike se lahko zapiše končna enačba za toplotni tok v motor:

Heat flow passes into the engine during the isochoric compression and isothermal expansion. Using the laws of thermodynamics, the final equation for heat flow into the engine can be formulated as:

$$\dot{Q}_{in} = m \cdot \nu \cdot \left(c_v \cdot \Delta T + R \cdot T_H \cdot \ln \varepsilon \right) \qquad (4).$$

Po analogiji dovedenega toplotnega toka lahko določimo odvedeni toplotni tok. Toplota zapušča motor pri izohorni ekspanziji ter izotermni kompresiji:

The equation for heat flow out of the engine can be formulated by analogy with heat flow into the engine. Heat is thus rejected from the engine during the isochoric expansion and isothermal compression:

$$\dot{Q}_{out} = m \cdot \nu \cdot \left(c_v \cdot \Delta T + R \cdot T_L \cdot \ln \varepsilon \right) \quad (5).$$

Učinkovitost katerega koli toplotnega stroja je določena kot razmerje pridobljenega dela in vložene toplote:

The **efficiency** of any heat engine is defined as the ratio of the work output and the heat input:

$$\eta = \frac{P}{\dot{Q}_{in}} = \frac{R \cdot \ln \varepsilon \cdot \Delta T}{c_v \cdot \Delta T + R \cdot T_H \cdot \ln \varepsilon} = \frac{\ln \varepsilon \cdot \Delta T \cdot (\kappa - 1)}{\Delta T + T_H \cdot \ln \varepsilon \cdot (\kappa - 1)} \quad (6).$$

Eksergija toplotnih tokov je odvisna od temperature pri kateri toplota prehaja meje sistema. Višja ko je temperatura prehajanja toplote, večja je njena eksergija:

The **exergy of heat the flows** depends on the temperature that the heat passes at a boundary of the system. The higher the temperature, the higher its exergy:

$$E_{\dot{Q}} = \nu \cdot \int_A^B \left(1 - \frac{T_e}{T} \right) \cdot dQ. \quad (7).$$

Eksergija dovedenih toplotnih tokov je sestavljena iz eksergije toplotnega toka med izohorno kompresijo ter izotermno ekspanzijo:

The exergy of the supplied heat flow consists of the exergy of the heat flow during the isochoric compression and isothermal expansion:

$$E_{\dot{Q}_{in}} = m \cdot \nu \cdot \left\{ c_v \cdot \left[\Delta T - T_e \cdot \ln \left(\frac{T_H}{T_L} \right) \right] + \left[R \cdot T_H \cdot \ln \varepsilon \cdot \left(1 - \frac{T_e}{T_H} \right) \right] \right\} \quad (8).$$

Eksergija odvedenih toplotnih tokov je sestavljena iz eksergije toplotnega toka med izohorno ekspanzijo in izotermno kompresijo:

The exergy of the heat flow out of the engine consists of the exergy of heat flow during the isochoric expansion and isothermal compression:

$$E_{\dot{Q}_{out}} = m \cdot \nu \cdot \left\{ c_v \cdot \left[-\Delta T - T_e \cdot \ln \left(\frac{T_L}{T_H} \right) \right] + \left[R \cdot T_L \cdot \ln \left(\frac{1}{\varepsilon} \right) \cdot \left(1 - \frac{T_e}{T_L} \right) \right] \right\} \quad (9).$$

Eksergija masnega toka biomase je odvisna od količine vlage v gorivu, ker je kurilnost biomase enaka kurilnosti gorljivih snovi samo v primeru, ko je gorivo absolutno suho. Za vse preostale vrednosti količine vlage v gorivu je kurilnost biomase manjša od kurilnosti gorljivih snovi za uparjalno toploto vode:

The **exergy of the mass flow of biomass** depends on the moisture content of the fuel since the net caloric value of the biomass is equal to the net caloric value of combustible substances only in the case where the fuel is absolutely dry. For all the remaining values for the moisture content of the fuel, the net caloric value of biomass is less than the net caloric value of the combustible substances by an amount equal to the heat of vaporization of water:

$$E_{\dot{m}_b} = \dot{m}_b \cdot H_{cs} = \dot{m}_b \cdot \left(H + r \cdot w \right) \quad (10).$$

Eksergijska učinkovitost je določena kot količnik med eksergijo, dobljeno iz sistema, ter med eksergijo, ki je dovedena sistemu:

The **exergy efficiency** is defined as the quotient of exergy obtained from the system and the exergy that is supplied to the engine:

$$\xi = \frac{E_{out}}{E_{in}} = \frac{E_{\dot{Q}_{out}} + P}{E_b} \quad (11).$$

Tlačna stanja v Stirlingovem motorju so določena za vsako stanje posebej z naslednjo enačbo:

The **pressure conditions** of the Stirling engine are defined for each state by the following equation:

$$p_i = \frac{m \cdot R \cdot T_i}{V_i} \qquad (12).$$

Srednji tlak v motorju pa se izračuna kot aritmetično povprečje posameznih tlačnih stanj:

The medium pressure in the engine is calculated as the arithmetical mean of the individual pressure states:

$$p_m = \frac{\sum_{i=1}^{n} p_i}{n} \qquad (13).$$

3 RAČUNALNIŠKI PROGRAM

Simulacija STE je sestavljena iz treh delov in je narejena z uporabo računalniškega programa Microsoft Excel. Podatki so vstavljeni v program v prvem delu. Ti podatki vsebujejo lastnosti delovnega plina in ohlajevalnega sredstva oz. sredstva za ogrevanje hranilnika toplote. Poleg tega ti podatki vsebujejo tudi parametre Stirlingovega motorja, to so delovna prostornina motorja, kompresijsko razmerje, zgornja in spodnja temperatura v motorju, masa delovnega plina in kurilnost biomase.

Rezultati simulacije, dobljeni iz matematičnega modela, so predstavljeni v drugem delu računalniškega programa. Izračunan je toplotni tok v motor pri izohornem in izotermnem postopku. To je zahtevani toplotni tok za doseganje zgornje temperature v motorju. Glede na ta toplotni tok je izračunan masni pretok biomase za doseganje zahtevanega toplotnega toka v motor oz. za doseganje zgornje temperature v motorju. Izgube pri zgorevanju in prenosu toplote skozi topli prenosnik toplote so upoštevane pri učinkovitosti kurilne naprave. Izračunan je tudi toplotni tok iz motorja pri izohornem in izotermnem postopku za ogrevanje sredstva hranilnika toplote. Predpostavljen je 100-odstotni prenos toplote na sredstvo za ogrevanje hranilnika toplote. To pomeni, da je predpostavljen toplotni tok na sredstvo za ogrevanje hranilnika toplote brez izgub. Eksergiji toplotnih tokov v Stirlingov motor in iz njega sta izračunani za izohorni in izotermni postopek. Preostali rezultati, kakor so električna energija, dobljena iz sistema, električna učinkovitost motorja za primer brez regeneracije toplote kakor tudi za primer popolne regeneracije toplote in toplotna ter eksergijska učinkovitost motorja, so prav tako podani v tem delu računalniškega programa.

Tlačna stanja so izračunana v tretjem delu računalniškega programa in temeljijo na enačbi

3 COMPUTER PROGRAM

A simulation of the CHP unit consists of three parts and was made using the computer program Microsoft Excel. The data are entered into the program in the first part. These data concern the properties of the working gas and the cooling fluid or the fluid for heating the thermal storage, in addition to the Stirling engine's parameters, such as the working volume of the engine, the compression ratio, and the highest and the lowest temperature in the engine. The mass of the working gas and the net caloric value of the biomass are also given in this part.

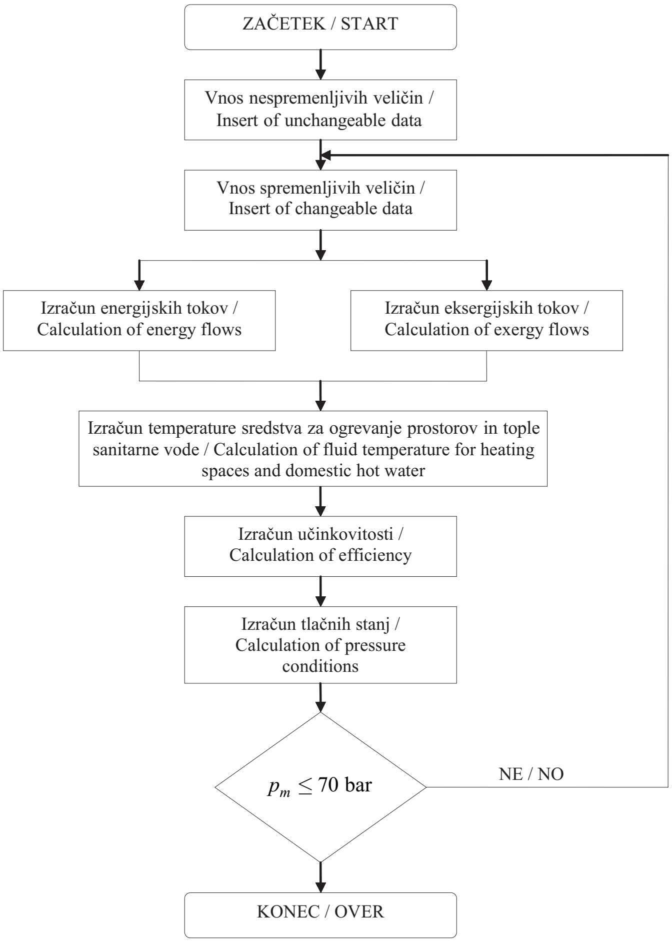
The results of the simulation obtained from the mathematical model are presented in the second part of computer program. Heat flow into the engine over the isochoric and isothermal process is calculated. This is the required heat flow for reaching the upper temperature in the engine. With regard to this heat flow, the mass flow rate of biomass required to reach the heat flow into the engine or the upper temperature in the engine is defined. Losses during combustion and the heat transfer through the hot heat exchanger are also considered in the efficiency of the boiler. Further heat flow out of the engine over the isochoric and isothermal process for heating the fluid for heating the thermal storage is calculated. A total of 100% heat transfer to the fluid for heating the thermal storage is presumed. This means that the heat transfer to the fluid for heating the thermal storage is performed without losses. The exergies of the heat flows into and out of the engine are calculated for both the isochoric and isothermal processes. Other results, like the electrical energy obtained from the system, the electrical efficiency of the engine for cases without heat regeneration as well as complete heat regeneration, and heat and exergy efficiency of the engine, are also given in this part.

Pressure states are calculated in the third part of the program on the basis of the equation of state. The medium pressure in the engine is defined as stanja. Srednji tlak v motorju je določen kot aritmetično povprečje posameznih tlačnih stanj.

Podatke iz Joanneum Research [4] smo uporabili z namenom, da se preveri pravilnost delovanja simulacije. Namen njihovega projekta je bilo oblikovanje, konstruiranje in delovanje Stirlingovega motorja, ki je ogrevan z dimnimi plini, ki nastanejo pri zgorevanju biomase. Motor je bil oblikovan samo za laboratorijske raziskave. Uporabljen delovni plin je bil zrak, ker je cenejši od helija in povsod na voljo. Njihova 25-odstotna učinkovitost motorja je bila preverjena pri 3,2 kW moči in je malo manjša od naše. Vsi naši rezultati so bili dobljeni z uporabo njihovih podatkov. Spremembe parametrov so predstavljene v naslednjih diagramih. Eksperimentalno preverjena področja so označena s križcem, ali pa je kar cel stolpec označen drugače. Algoritem računalniškega programa je prikazan na sliki 3.

the arithmetical medium of the individual pressure states.

Data from Joanneum Research [4] is used in order to authenticate the correctness of the operation. The goals of their project were the design, construction and operation of the Stirling engine, which is heated by the flue gas of a biomass furnace. The engine was designed only for laboratory research. Air was used as the working gas because it is cheaper than helium and available everywhere. A shaft power of 3.2 kW at a coefficient of performance of 25 % was verified, which is a little bit lower than our findings. All our data were obtained using their data. The changes of the parameters are presented in the following diagrams. Experimentally verified areas are marked with a cross or the whole columns are marked differently. An algorithm of the computer program is shown in Fig. 3.



Sl. 3. *Algoritem računalniškega programa*
Fig. 3. *Algorithm of the computer program*

4 PARAMETRIČNA ANALIZA

Prva analiza, ki je bila za nas zanimiva, je, kako se električna učinkovitost spreminja od vrste plina v motorju (sl. 4). Vzeti plini za simulacijo so bili: zrak, acetilen, amoniak, helij in vodik. Plini na sliki so razporejeni v vrstnem redu od plina z najnižjo (zrak) do plina z najvišjo plinsko konstantno (vodik).

Po predvidevanjih naj bi se električna učinkovitost močno spreminjala v odvisnosti od plinske konstante; pri zraku najnižja, pri vodiku najvišja električna učinkovitost. S slike 4 pa je razvidno, da je najvišja električna učinkovitost pri heliju in ne pri vodiku ter da ni najnižja učinkovitost pri zraku temveč pri acetilenu. Razlog je v razmerju specifične toplote plina pri stalnem tlaku in specifične toplote plina pri nespremenljivi prostornini (κ), kar je lepo prikazano v enačbi (6).

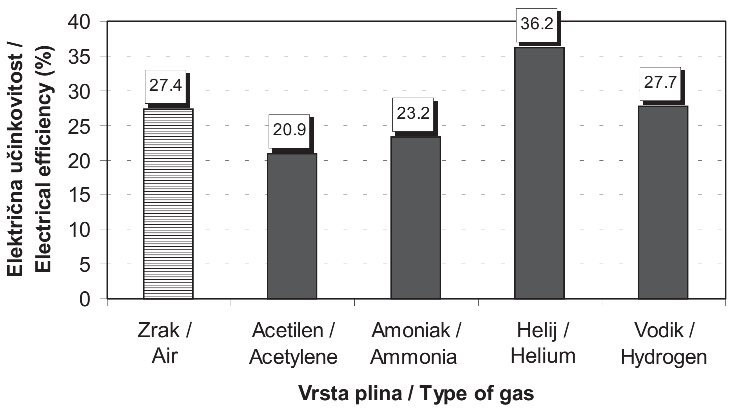
Po predvidevanjih pa se spreminja srednji tlak v motorju, ki je odvisen samo od specifične plinske konstante (sl. 5). Uporaba helija kot delovnega sredstva v motorju po sliki 4 daje najvišjo električno učinkovitost v enakih razmerah. S slike 5 pa je razvidno, da se pri uporabi helija srednji tlak povzpne prek 370 bar. Tega pa za ostale uporabljene parametre v naši simulaciji konstrukcija motorja ne bi zdržala. Pri uporabi vodika kot delovnega sredstva pa bi se srednji delovni tlak zvišal kar na prek 735 bar. To pomeni, da delovni plin ne more biti preprosto zamenjan s plinom z višjo učinkovitostjo. Potrebno je, da so tlačna stanja preračunana preden zamenjamo plin v motorju. Če izračun nakazuje, da so tlačna stanja nesmiselna, zamenjava delovnega plina ni mogoča.

4 PARAMETRICAL ANALYSIS

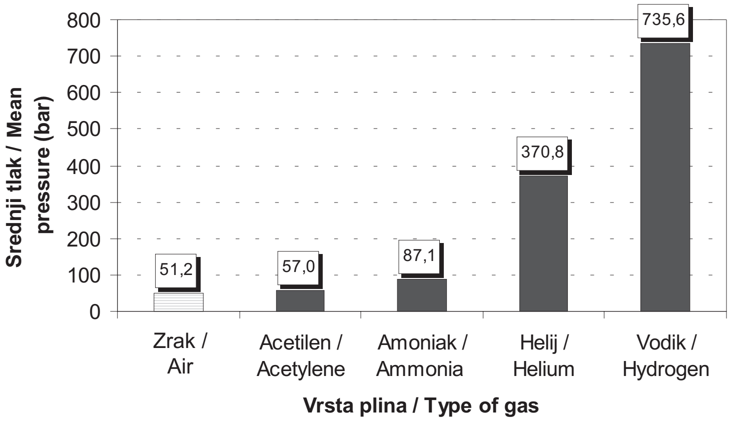
The first analysis was the dependence of the electrical efficiency on the type of gas in the engine (Fig. 4). Air, acetylene, ammonia, helium, and hydrogen were used in the simulation. The gases in Fig. 4 are arranged from the gas with the lowest specific gas constant (air) to the gas with the highest (hydrogen).

We expected that the electrical efficiency would depend on the specific gas constant: thus, air should have the lowest electrical efficiency and hydrogen the highest. However, Fig. 4 shows that the highest electrical efficiency is actually found with helium and not with hydrogen, while the lowest efficiency is not with air but with acetylene. This is due to the ratio of the specific heat capacity of the gas at constant pressure with the specific heat capacity of the gas at constant volume (κ), which is seen from Equation 6.

The medium pressure in the engine changed according to our expectations, since it depends only on the specific gas constant (Fig. 5). Using helium as the working gas in the engine gives the highest electrical efficiency under equal conditions according to Fig. 4. However, Fig. 5 shows that when using helium the medium pressure in the engine exceeds 370 bar and at that pressure the engine would collapse. If we were to use hydrogen as the working gas in the engine, the medium pressure in the engine would exceed 735 bar. This means that the working gas cannot be simply replaced with a gas that has a higher efficiency. It is necessary to calculate the pressure conditions before the gas is replaced in the engine. If the calculation indicates that the pressure conditions are not reasonable, a replacement of working gas in not possible.



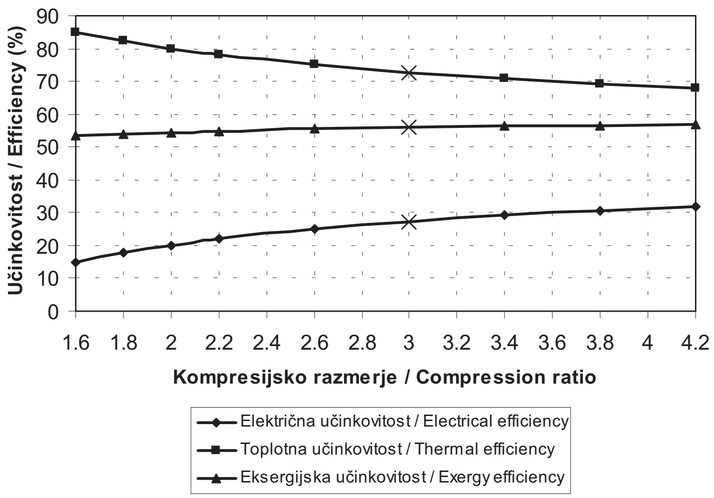
Sl. 4. *Vpliv plina na električno učinkovitost*
Fig. 4. *Influence of gases on the electrical efficiency*



Sl. 5. *Vpliv plina na srednji tlak v motorju*
Fig. 5. *Influence of gases on the mean pressure*

Pri spreminjanju kompresijskega razmerja se v naši simulaciji spreminja samo zgornja mrtva prostornina in s tem gib bata, večja prostornina pa ostaja ves čas stalna. Ker se torej pri višanju kompresijskega razmerja delovna prostornina motorja veča, zgornja mrtva prostornina motorja pa manjša, dosežemo tudi višje tlačno stanje po koncu izotermne kompresije. Pri višjem tlaku pa je za vzdrževanje stalne temperature v motorju potreben večji toplotni tok. Ker je pri izotermni kompresiji nižja temperatura kakor pri izotermni ekspanziji, je pri enaki spremembi kompresijskega razmerja potreben manjši odvedeni toplotni tok, kakor je dovedeni. Ker je torej sprememba pri dovedenem toplotnem toku večja kakor pri odvedenem toplotnem toku, iz sistema pridobimo več dela in s tem večjo moč

Changing the compression ratio changes only the upper non-zero volume and the movement of the piston; however, the larger volume remains constant at all times. With a rise in the values of the compression ratio, the working volume of the engine increases and the upper non-zero volume decreases. Thus, a higher pressure condition is reached at the end of the isothermal compression. Keeping a constant temperature in the engine at a higher pressure requires a higher heat flow into the engine. Because there is a lower temperature during the isothermal compression than during the isothermal expansion, a lower heat flow out of the engine than into the engine is required when there is a constant change in the compression ratio. Since there is a greater increase of heat flow into the engine than heat flow out of the engine, more work and, consequently, more power comes out of



Sl. 6. *Sprememba učinkovitosti v odvisnosti od kompresijskega razmerja*
Fig. 6. *Efficiency change as dependent on compression ratio*

motorja. S slike 6 je lepo razvidno, da se z večanjem kompresijskega razmerja električna učinkovitost povečuje, toplotna pa zmanjšuje. Za čim večjo električno učinkovitost je torej treba imeti čim višje kompresijsko razmerje, ki pa je zaradi konstrukcijskih lastnosti materialov navzgor omejeno.

Slika 7 prikazuje odvisnost posameznih učinkovitosti od zgornje temperature v motorju. Črta s kvadratki pomeni idealno električno učinkovitost, ki bi bila dosežena v primeru popolne regeneracije toplote. Pri naših podatkih, s temperaturo 1273 K, bi imeli s popolno regeneracijo toplote, električno učinkovitost prek 72 odstotkov. Najnižja črta na sliki pomeni električno učinkovitost brez regeneracije toplote. Vse električne učinkovitosti se z višanjem temperature dvigajo, toplotna učinkovitost pa se z višanjem temperature zniža.

Slika 8 prikazuje odvisnost učinkovitosti od spodnje temperature v motorju. Črta s kvadratki pomeni idealno učinkovitost, ki pa se z višanjem temperature znižuje.

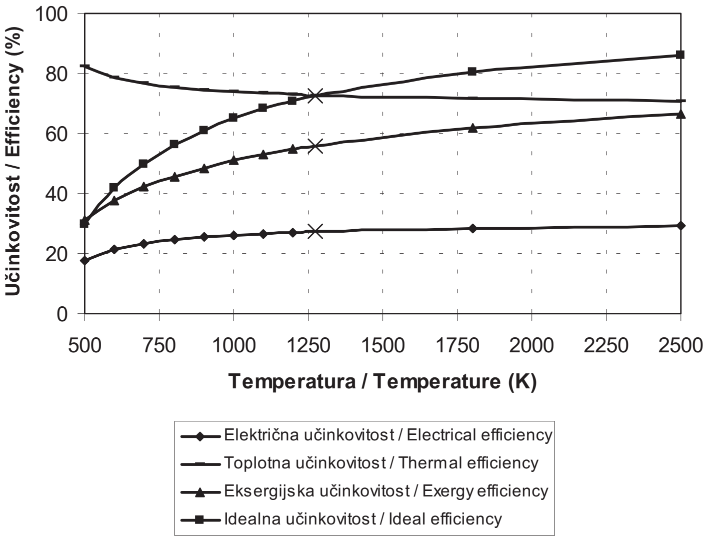
S slik 7 in 8 lahko ugotovimo, da dobimo višjo učinkovitost, če imamo spodnjo temperaturo v motorju čim nižjo, zgornjo temperaturo pa čim višjo. Vendar pa je to zaradi omejitev težko doseči. Navzgor smo omejeni z vzdržljivostjo materialov ter z možnostjo dovoda toplote v sistem; imeti moramo dovolj vroče ostanke zgorevanja ter veliko vrednost prehoda

the system. Fig. 6 shows an increase in the electrical efficiency and a decrease in the thermal efficiency with increasing compression ratios. A higher electrical efficiency requires a higher compression ratio, although the upper limit of the compression ratio is constrained due to the constructional properties of the materials.

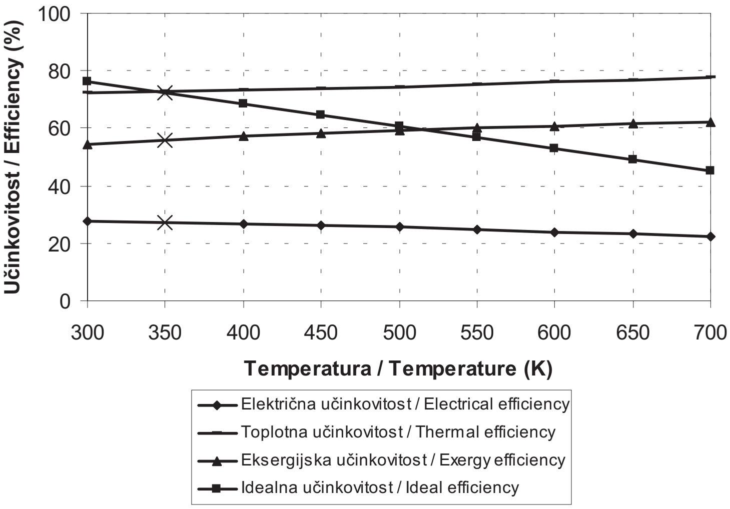
Fig. 7 shows the efficiencies versus the upper temperature in the engine. The curve with little squares represents an ideal electrical efficiency, which would be reached if we had perfect heat regeneration. For our data with a temperature of 1273 K, the electrical efficiency would exceed 72 % if there were perfect heat regeneration. The lowest curve in Fig. 7 represents the electrical efficiency without heat regeneration. All the electrical efficiencies increase with the rising temperature, while the thermal efficiency falls with the rising temperature.

Fig. 8 shows the dependence of the efficiencies on lower temperatures in the engine. The curve with little squares represents an ideal efficiency, which falls with rising temperature.

Figs. 7 and 8 show that a higher efficiency is obtained if the lower temperature in the engine is as low as possible and the upper temperature in the engine is as high as possible. This is difficult to achieve, for a number of reasons. There are upper temperature limits imposed by the constructional properties of materials and the potential heat supply, e.g., the products of combustion should be hot enough, the heat transfer



Sl. 7. *Učinkovitost v odvisnosti od zgornje temperature v motorju*
Fig. 7. *Efficiencies as dependent on the upper temperature*



Sl. 8. *Učinkovitost v odvisnosti od spodnje temperature v motorju*
Fig. 8. *Efficiencies as dependent on the lower temperature*

toplote in veliko površino prenosnika toplote. Omejeni pa smo tudi navzdol. Pri prenizki temperaturi je prenos toplote na ogrevalno sredstvo nemogoč zaradi prenizke temperaturne razlike med spodnjo temperaturo v motorju in temperaturo sredstva za ogrevanje hranilnika toplote.

5 SKLEP

Ugotovili smo, da je za hišno tehniko (do 100 kW toplotne moči) zelo primerna izvedba Stirlingov motor, saj se Rankinov postopek uporablja za višjo raven (do 1 MW) za daljinsko ogrevanje, medtem ko se parni postopek uporablja za nekaj več MW v večjih elektrarnah.

Ugotovili smo, da moč Stirlingovega motorja za soproizvodnjo toplotne in električne energije lahko povečamo s temperaturno razliko med vročim in hladnim koncem motorja, s kompresijskim razmerjem ter z vrsto in maso plina. Temperaturno spremembo je težko veliko povečati, ker je zgornja temperatura v motorju odvisna od temperature ostankov zgorevanja, od velikosti toplotne prehodnosti toplega prenosnika toplote, ki je odvisna od materiala, ter končno od vzdržljivosti materialov (tesnila). Spodnja temperatura v motorju pa je precej odvisna od temperature in pretoka sredstva, ki hladi hladni konec motorja. Sprememba kompresijskega razmerja ni mogoča. Kompresijsko razmerje je treba določiti pri konstruiranju motorja, ker je odvisno od geometrijske oblike motorja

coefficient should be large enough, and the size of the heat exchanger big enough. There are also lower temperature limits. At too low a temperature the heat transfer to the fluid for heating the thermal storage may become impossible due to a too low temperature difference between the lower temperature in the engine and the temperature of the fluid for heating.

5 CONCLUSION

We have found that the Stirling engine is a suitable technology for power production in housing (up to 100 kW of heat power), while the ORC (Organic Rankine Cycle) process is better suited to higher level power production (up to 1 MW) as in district heating, and the steam process is best used for the largest power stations (more than 1 MW).

The power of the Stirling engine for CHP can be increased by creating a higher temperature difference between the hot and cold ends of the engine, by changing the compression ratio, the type of gas, and the mass of the working gas. The temperature difference cannot be changed infinitely since the upper temperature in the engine depends on the temperature of the products of combustion, on the heat-transfer coefficient of the hot heat exchanger, which in turn depends on the material, and finally on the properties of the construction material (packing). The lower temperature in the engine depends on the temperature and flow of the fluid that cools the cold end of the engine. Changing the compression ratio for a given engine is not (prostornina motorja, velikost batov, gibna prostornina). Večjo moč motorja si zagotovimo tudi z uporabo drugega plina, ki ima drugačno razmerje specifičnih toplot plina. Zelo primerna je uporaba helija, ker daje, v nasprotju z uporabo vodika, poleg večje moči motorja tudi veliko višjo električno učinkovitost. Motor pa mora biti, zaradi konstrukcijskih lastnosti materialov, izdelan za določen plin in zato sprememba plina v posameznih motorjih ni mogoča. Je pa med delovanjem mogoča sprememba količine plina. Sprememba količine plina ne vpliva na učinkovitost motorja, pač pa na njegovo moč oz. na pridobljeno delo iz motorja. S spreminjanjem količine plina v Stirlingovem motorju, kakor tudi pri temperaturni spremembi, se spreminjajo tudi tlačne razmere v motorju. Zato je treba že pri konstruiranju motorja določiti, kateri plin bo uporabljen, kakšni sta zgornja in spodnja temperaturna meja in za kakšne toplotne moči bo motor oz. soproizvodna enota namenjena.

Z upoštevanjem popolne regeneracije toplote daje po enačbah Stirlingov motor, teoretično učinkovitost enako učinkovitosti Carnotovemu postopku. Popolna regeneracija toplote ni mogoča, ker bi moral biti tok plina skozi regenerator zelo počasen, da bi tam oddal vso svojo toploto. Pridobljeno delo iz motorja je odvisno od njegove hitrosti; večja ko je hitrost, več dela pridobimo oz. večja je moč motorja pri enaki učinkovitosti. Prav tako pa zaradi mrtvih prostornin plin nikoli v celoti ne poteka skozi regenerator. Zato je popolna regeneracija mogoča samo teoretično, dejansko pa se regenerira le majhen del. Tudi gibanje batov ne more biti prekinjeno, zato ne dosegamo popolnih izotermnih in izohornih preobrazb. To in še mnogo drugih stvari daje dejansko električno učinkovitost veliko nižjo od idealne.

possible. The compression ratio is set at the time the engine is constructed, since it depends on the geometry of the engine (volume of the cylinders, size of pistons, bore times stroke). Higher power can be obtained by using different gases with different specific heat capacities. Using helium produces not only more power but also a higher electrical efficiency in comparison to hydrogen. Due to the constructional properties of materials, the engine must be made for a defined gas, so any change in gas for an individual engine is not possible. However, a change in the quantity of gas is possible during operation, which influences the power of the engine but not its efficiency. By varying the quantity of gas and the temperature, the pressure conditions in the engine are also changed. Because of this, the type of gas and the upper and lower temperature limits, as well as the heat needs of the engine or house CHP units, should be defined during the engine's construction.

By assuming complete (100%) heat regeneration, the Stirling engine has a theoretical efficiency equal to the Carnot efficiency. In reality, complete heat regeneration is not possible, since the gas flow rate through the regenerator would have to be very slow in order to release all of its heat. The work gained from the engine depends on its speed: the higher the speed, the more work is acquired or the higher the power of the engine at equal efficiency. However, the total volume of gas never goes through the regenerator due to non-zero volumes. Complete heat regeneration is, therefore, only possible theoretically, and only a small part is regenerated in reality. Finally, since the piston motion cannot be discontinuous, the isothermal and isochoric processes are never perfect. What this means is that the actual efficiency is much lower than the theoretical efficiency.

6 OZNAČBE
6 NOMENCLATURE

specifična toplota pri stalni prostornini	c_v	J/kg.K	specific heat capacity at constant volume
eksergija	E	J	exergy
kurilnost	H	J/kg	net caloric value
razmerje specifičnih toplot	κ		ratio of specific heat capacities
masa	m	kg	mass
masni tok	$\dot{m}$	kg/s	mass flow rate
moč	P	W	power
tlak	p	Pa	pressure
toplota	Q	J	heat

toplotni tok	$\dot{Q}$	W	heat flow
uparjalna toplota	r	J/kg	heat of vaporization
specifična plinska konstanta	R	J/kg.K	specific gas constant
entropija	S	J/K	entropy
temperatura	T	k	temperature
prostornina	V	m^3	volume
količina vlage v gorivu	w	kg/kg	moisture content of the fuel
Indeksi			**Subscripts**
biomasa	b		biomass
gorljive snovi	cs		combustible substances
okolje, elektrika	e		environment, electricity
visok	H		high
določeno stanje	i		certain state
doveden	in		supplied
nizek	L		low
srednji	m		medium
število stanj	n		number of states
izločen	out		extracted

7 LITERATURA
7 LITERATURE

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Naslov avtorjev: dr. Uroš Stritih
Gregor Zupan
prof. dr. Vincenc Butala
Univerza v Ljubljani
Fakulteta za strojništvo
Aškerčeva 6
1000 Ljubljana
uros.stritih@fs.uni-lj.si
gregor.zupan@fs.uni-lj.si
vincenc.butala@fs.uni-lj.si

Naslov avtorjev: Dr. Uroš Stritih
Gregor Zupan
Prof. Dr. Vincenc Butala
University of Ljubljana
Faculty of Mechanical Engineering
Aškerčeva 6
1000 Ljubljana, Slovenia
uros.stritih@fs.uni-lj.si
gregor.zupan@fs.uni-lj.si
vincenc.butala@fs.uni-lj.si

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Analiza poznavanja in uporabe metod presoje investicijskih projektov v strojništvu

Analysis of the Knowledge and the Use of Investment Project Evaluation Methods in the Field of Mechanical Engineering

Igor Pšunder - Nadja Ferlan
(Fakulteta za gradbeništvo, Maribor)

Raziskave, ki so jih opravili v ZDA in Veliki Britaniji, nakazujejo, da se je z razmahom osebnih računalnikov in elektronskih preglednic razširila tudi uporaba metod presoje investicijskih projektov, ki temeljijo na razobrestovanju (diskontiranju) denarnih tokov. Vendar teoretična spoznanja o teh metodah razlagajo, da metode vsebujejo veliko omejitev, katerih nepoznavanje lahko vodi do napačnih rezultatov ter tudi do napačnih sklepov presoj investicij in investicijskih projektov.

V pričujočem prispevku prikazujemo rezultate raziskave, ki smo jo opravili med projektnimi vodji v slovenskih podjetjih. V raziskavi smo preučevali lastna mnenja anketirancev o uporabi metod presoje investicijskih projektov in poznavanju njihovih pomanjkljivosti, pri čemer smo v raziskavo vključili tako metode, ki temeljijo na razobrestovanju denarnih tokov, kakor tudi enoobdobne metode presoje investicij in investicijskih projektov. V analizi rezultatov smo ločeno obravnavali stanje na področju strojništva ter ga primerjali s preostalimi tehničnimi ter drugimi (netehničnimi) vedami.

Z raziskavo smo ugotovili, da strokovnjaki, ki se ukvarjajo s presojo investicijskih projektov in imajo izobrazbo s področja strojništva, pogosteje uporabljajo metode presoje investicijskih projektov, ki temeljijo na razobrestovanju denarnih tokov, kakor strokovnjaki drugih tehničnih smeri, vendar približno enako pogosto kakor strokovnjaki ekonomskih in sorodnih smeri. Ugotoviti je tudi mogoče, da strokovnjaki strojniške smeri izobrazbe nadpovprečno dobro poznajo pomanjkljivosti metod presoje investicijskih projektov, vendar jih kljub temu le polovica pozna večkratno notranjo (interno) donosnost, ki je v teoriji najpogosteje opisovana pomanjkljivost metode notranje donosnosti in le slabi dve tretjini popačenost rezultata zaradi neupoštevanja časovne zapadlosti plačil pri metodi časa vračila sredstev.

(Ključne besede: strojništvo, investicijski projekti, evalvacije, pretok denarja)

Research done in the USA and the UK has shown that, with the increased use of computers and electronic spreadsheets, the use of these investment project evaluation methods that are based on discounted cash flow has increased. However, theoretical findings about these methods show that they have numerous limitations, and ignorance of these limitations can lead to false results as well as false conclusions about investments and investment projects.

This paper shows the research results acquired from project managers of Slovene companies. Their personal opinions about investment project evaluation methods and knowledge of the methods' faults were studied in the research. Methods based on discounted cash flow as well as single-period methods of investment evaluation and investment projects were used. During the analysis of the results the situation in the field of mechanical engineering was treated separately and compared with other technical and non-technical sciences.

Research has shown that experts dealing with investment project evaluation who have a degree in the field of mechanical engineering more often use discounted cash-flow methods for investment project evaluation than do experts of other technical sciences, but approximately as often as experts in economics and similar sciences. We were able to conclude that experts with education in mechanical engineering are more than usually familiar with the flaws in investment project evaluation methods, but at the same time, only half of them know the multiple internal rate of return, which is the most commonly mentioned fault of *the internal rate of return method. Only one-third of experts are familiar with result deformation due to a disregard for the time component of payments in the payback period method.*

(Keywords: mechanical engineering, investment projects, evaluation, cash flow)

0 UVOD

Raziskave, ki so jih opravili konec preteklega stoletja, nakazujejo, da se je z razmahom osebnih računalnikov razširila uporaba metod presoje investicij in projektov, ki temeljijo na razobrestovanju (diskontiranju) denarnih tokov, med katerimi velja izpostaviti predvsem metodo notranje donosnosti (IRR) in metodo čiste sedanje vrednosti (NPV). Klammer in Walker [1] navajata, da se je v ZDA "uporaba razobrestovanja povečala z 19 odstotkov leta 1960 do 57 odstotkov leta 1970", v raziskavi pa nadalje ugotavljata, da se je uporaba razobrestovanja v letu 1980 zvišala do 75 odstotkov pri projektih, ki zadevajo razširjanje sedanjih zmogljivosti. Podobno piše Pike [2] za Veliko Britanijo, in ugotavlja, da se je uporaba metod notranje donosnosti ali čiste sedanje vrednosti v velikih podjetjih v Veliki Britaniji med leti 1975 in 1986 zvišala z 58 na 84 odstotkov, uporaba izključno metode notranje donosnosti s 44 na 75 odstotkov, uporaba izključno metode čiste sedanje vrednosti pa z 32 na 68 odstotkov. Zanimivo je, da Ho in Pike [3] v raziskavi iz leta 1996, v kateri preučujeta informacijski sistem presoje investicij (ISPI - CABIS), ugotavljata precej podobne deleže in pišeta, da "odgovori kažejo, da so podjetja najbolje seznanjena z metodami razobrestovanja, na primer čisto sedanjo vrednostjo in notranjo donosnostjo: 74,8 % uporabnikov CABIS-a jih redno uporablja". Na podlagi rezultatov pričujočih raziskav lahko povzamemo, da ni mogoče sklepati o bistvenih spremembah v pogostosti uporabe sodobnih metod presojanja investicij in investicijskih projektov po osemdesetih letih prejšnjega stoletja, obenem pa Puxty in Dodds [4], na podlagi rezultatov raziskave McIntyrea in Coulthursta [5], opozarjata na velike razlike v uporabi metod razobrestovanja denarnih tokov med velikimi in srednje velikimi podjetji.

Omenjene raziskave so odprle vprašanje o uporabi metod evalvacije projektov v Sloveniji, kamor – zaradi relativne majhnosti podjetij – rezultati navedenih raziskav, ki so jih opravili med velikimi podjetji, niso neposredno prenosljivi. Pri raziskavi smo poseben poudarek namenili strokovnjakom s področja strojništva ter podjetjem, katerih pretežna dejavnost je strojništvo, saj so

0 INTRODUCTION

Research done at the end of last century shows that with the increased use of computers, the use of discounted cash-flow methods for investments and projects' evaluation has increased. Among these methods, the internal rate of return method (IRR) and the net present value method (NPV) were the most common. Klammer and Walker [1] state that in the USA, "the use of discounting grew from 19 % in 1960 to 57 % in 1970", and their research establishes that the use of discounting in 1980 grew to 75 % in projects dealing with the expansion of existing capacities. Similar conclusions for the UK are drawn by Pike [2], who established that the use of the internal rate of return method or net present value method in large UK companies grew from 58 % to 84 % between 1975 and 1986; the exclusive use of the internal rate of return method grew from 44 % to 75 % and the exclusive use of net present value grew from 32 % to 68 %. It is interesting that Ho and Pike [3] in their 1996 analyses of CABIS (capital budgeting information systems) established very similar percentages, so they concluded that "the summary of responses shows that firms are most familiar with discounting methods such as net present value/internal rate of return: 74.8 % of CABIS users always use it". Based on the results of these research projects we can establish that it is not possible to conclude that there have been any essential changes in the frequency of use of investment evaluation methods and investment project evaluation methods since the 1980s. At the same time Puxty and Dodds [4], based on the research results of McIntyre and Coulthurst [5], stress the major differences in the use of discounting cash flow methods between large and medium-sized companies.

The above-mentioned research has raised questions about the use of project evaluation methods in Slovenia, where – owing to the relatively small size of Slovene companies – the results of such research conducted on large companies are not directly transferable. Throughout our research, special stress was placed on experts with education in mechanical engineering and companies who deal mostly with mechanical projekti na področju strojništva pogosto investicijske narave, njihov obseg razmeroma velik, narava denarnih tokov pa zaradi občasnih večjih vzdrževalnih del spremenljiva, tako da lahko metode razobrestovanja denarnih tokov, predvsem metoda notranje donosnosti, izražajo neverodostojne rezultate.

V raziskavi smo obravnavali enoobdobne in večobdobne metode oziroma metode razobrestovanja denarnih tokov. Med enoobdobnimi smo zajeli metodo časa vračila sredstev in metodo tekoče donosnosti, pri metodah dikontiranja denarnih tokov pa smo se omejili na metodo čiste sedanje vrednosti, indeks čiste sedanje vrednosti, metodo notranje donosnosti in metodo prilagojene (modificirane) notranje donosnosti. Pri analizi poznavanja pomanjkljivosti smo se osredotočili na metodo časa vračila sredstev med enoobdobnimi metodami in na metodo notranje donosnosti med metodami razobrestovanja denarnih tokov, saj tema dvema avtorji pripisujejo največ pomanjkljivosti.

Na pasti navidezne preprostosti uporabe in pomanjkljivosti razumevanja metod presoje investicijskih projektov opozarjajo številni avtorji; Lumby in Jones [6] se osredotočata predvsem na pomanjkljivosti metode notranje donosnosti, ki izvirajo iz njene polinomske zasnove:

- na večkratno notranjo donosnost,
- na neobstoječo notranjo donosnost in
- v povezavi z metodo čiste sedanje vrednosti tudi neobstoječo pozitivno čisto sedanjo vrednost ob hkratni enolični notranji donosnosti.

Vse naštete pomanjkljivosti se, če se pojavijo, izrazijo v napačnih ali vsaj v neenoličnih rezultatih (napovedih), Holmes [7] pa še dodatno opozarja na problem možnosti nasprotnih rezultatov (napovedi) metod notranje donosnosti in čiste sedanje vrednosti, kadar metode uporabljamo pri primerjanju dveh vzajemno izključujočih se projektov. Mauboussin [8] izpostavlja še napake, ki izvirajo iz neustreznih vstopnih podatkov, ki jih analitiki uporabljajo pri presoji investicij, kakor na primer prekratko predvideno investicijsko obzorje ali neustrezni stroški kapitala, vendar te napake presegajo področje raziskave, ki smo jo opravljali, zato jih posebej ne bomo obravnavali.

Iz prej omenjenih raziskav je mogoče razbrati, da metoda časa vračila sredstev sodi med najbolj uporabljane. Tudi pri tej metodi pa se lahko porajajo napačne razlage rezultatov, ki izvirajo iz njene matematične zasnove. V prvi vrsti gre med pomanjkljivostmi poudariti značilnost vseh

engineering, because projects in the field of mechanical engineering are often investment-based, their scope is relatively wide, and the nature of cash flow changes owing to occasional maintenance work. Therefore, discounting cash-flow methods, especially the internal rate of return method, could produce non-credible results.

We covered single-period as well as multi-period or discounted cash-flow methods in the study. Among single-period methods, we dealt with the payback-period method and the accounting rate of return method, and among discounted cash-flow methods we dealt with the net present value method, the net present value index, the internal rate of return method and the modified internal rate of return method. When analyzing the deficiencies of the methods, we focused on the payback period method among single-period methods and on the internal rate of return method among discounted cash-flow methods, since authors ascribe the most deficiencies to these methods.

Numerous authors point out the misleading simplicity in the use of investment project evaluation methods and lack of understanding of their use; Lumby and Jones [6] focus mainly on flaws in the internal rate of return method that result from its polynomial foundation:

- on multiple internal rate of return,
- on non-existent internal rate of return,
- in connection with the net present value method, also a non-existent positive net present value along with an existent internal rate of return.

All these faults are, if they appear, expressed in false or at least inexact results (indications). Holmes [7] discusses the additional problem of the potential for conflicting results (indications) when using methods of internal rate of return and net present value when these methods are used when comparing two mutually exclusive projects. Mauboussin [8] stresses the faults that result from inadequate incoming data used by analysts in investment evaluations, such as the forecast horizon being anticipated too short or inadequate capital costs. Since these faults exceed the scope of our research, we have not dealt with them in detail.

From the aforementioned research we can conclude that the payback period method belongs among the most commonly used methods. The false interpretations of results that appear with this method arise form its mathematical structure. In the first place we should point out a characteristic enoobdobnih metod, da ne upoštevajo različnega časovnega dospevanja plačil ter da temeljijo na izmišljenem povprečnem donosu reprezentativnega obdobja. Vir [9] piše, da je mogoče zanesljivo uporabljati metodo časa vračila sredstev šele ob upoštevanju modela tržnega ravnovesja.

Zaradi pomanjkljivosti metod presoje investicijskih projektov, katerih posledica je lahko tudi napačna presoja in odločanje, smo v raziskavi posebno poglavje namenili poznavanju teh pomanjkljivosti.

1 PODROČJE RAZISKAVE IN METODOLOGIJA

Raziskovalni okvir

Namen raziskave, izvedli smo jo med strokovnjaki, ki se ukvarjajo z investicijami v slovenskih podjetjih, je bil ugotoviti raven poznavanja in uporabe metod presoje investicij, pri čemer se pri razlagi rezultatov osredotočamo na tiste, ki zadevajo strokovnjake s področja strojništva oziroma na podjetja, katerih pretežna dejavnost je strojništvo. Poznavanje in uporabo metod presoje investicij med strokovnjaki s področja strojništva oziroma med podjetji, katerih pretežna dejavnost je strojništvo, smo primerjali s poznavanjem in uporabo istih metod med strokovnjaki preostalih tehniških, naravoslovno-matematičnih ter drugih ved. Poleg poznavanja in (pogostosti) uporabe metod evalvacije projektov so nas zanimale tudi odvisnosti med smerjo izobrazbe in poznavanjem metod presoje investicijskih projektov ter med stopnjo izobrazbe in poznavanjem ter uporabo obravnavanih metod. Na podlagi primerjave ravni znanja med strokovnjaki s področja strojništva in drugih sorodnih ved ter širše smo sklepali o izdatnosti izobraževanja na posameznih strokovnih področjih.

Vzorec in zbiranje podatkov

Podatke smo zbirali z anketiranjem. Vzorec je obsegal 44 podjetij, ki so pokrajinsko pokrivala vso Slovenijo. Strojniško izobrazbo je imelo 18,2 % vprašanih in 11,4 % jih je bilo zaposlenih v podjetjih, katerih pretežna dejavnost je strojništvo. Izmed anketirancev s strojniško izobrazbo jih je bila večina (37,5 %) zaposlenih v podjetjih, katerih pretežna dejavnost je strojništvo, ostali pa v gradbeništvu – okrog 25 % – energetiki in

of all single-period methods: that they do not consider differences in payment maturities and that they are based on the fictive average income for a representative period. Source [9] says that the payback period method can be reliable only when we consider the market equilibrium model.

Owing to the flaws in the project investment evaluation methods, which can also lead to false judgements and decisions, one part of our research concentrates on the knowledge about those flaws.

1 RESEARCH AREA AND METHODOLOGY

Research frame

The goal of the research conducted among experts dealing with investments in Slovene companies was to establish the level of knowledge and the use of investment evaluation methods while, during the interpretation of results, focusing on those results which concern experts from the field of mechanical engineering and companies whose main activity is mechanical engineering. We compared the knowledge and use of investment evaluation methods among experts in the field of mechanical engineering and among companies whose main activity is mechanical engineering with the knowledge and use of the same methods among experts in technical, natural, mathematical and other sciences. Besides the knowledge and (frequency of) use of the project evaluation methods, we were also interested in any relation between the field of education and knowledge of investment project evaluation methods, and between the level of education and the use of the methods in question. Based on a comparison between the level of knowledge of experts in the field of mechanical engineering and other related and also non-related sciences, we reached conclusions about the effectiveness of the education in a particular field.

Sample and data gathering

We gathered data using questionnaires. The sample included 44 companies, representing all the Slovene regions. A total of 18.2 % of people involved in the research have education in the field of mechanical engineering and 11.4 % work in companies whose main activity is mechanical engineering. Among people with an education in mechanical engineering, most (37.5 %) work in companies whose main activity is mechanical engineering; the rest (around 25 %) work in construction, while the percentage of engineers working komunali ter metalurgiji, kjer so bili deleži okrog desetinski.

Dobri dve tretjini (34,1 %) preostalih anketiranih je imelo izobrazbo drugih tehničnih smeri (gradbeniška, elektrotehniška), še dobri dve odstotni točki več (36,4 %) pa je bilo strokovnjakov ekonomske ali družboslovne izobrazbe. Okrog desetina je bilo anketirancev z drugih področij (matematika, kemija in geodezija).

Anketni vprašalnik je bil sestavljen v obliki uporabe spleta. Udeleženci so bili povabljeni k odgovarjanju po elektronski pošti. Odziv je bil 11,7 odstoten.

Vprašalnik je bil sestavljen iz treh sklopov. V prvem smo poizvedovali po dejstvih o izpolnjevalcu (starost, spol, stopnja in smer izobrazbe, delovno mesto, dejavnost in velikost podjetja ipd.). V drugem delu smo poizvedovali o mnenjih anketirancev o lastnem poznavanju in pogostosti uporabe enoobdobnih metod presoje investicijskih projektov, h katerim smo uvrstili dve, ki ne upoštevata časovne vrednosti denarja (čas vračila sredstev, tekoča donosnost), ter o poznavanju in pogostosti uporabe metod razobrestovanja denarnih tokov, torej tistih, ki časovno razsežnost denarja upoštevajo, med katerimi smo se omejili na metodo čiste sedanje vrednosti, metodo notranje donosnosti, indeks čiste sedanje vrednosti in metodo prirejene notranje donosnosti. V zadnjem sklopu smo povpraševali o mnenjih anketirancev o lastnem poznavanju pomanjkljivosti metod presoje investicijskih projektov. Pri tem smo se med enoobdobnimi metodami omejili na pomanjkljivosti metode časa vračila sredstev, med metodami razobrestovanja denarnih tokov pa na metodo notranje donosnosti.

Analiza podatkov

Z anketo pridobljene podatke smo sistematizirali in statistično analizirali. Izračunali smo odvisnosti poznavanja metod in pomanjkljivosti le-teh od posameznih spremenljivk. Za analizo povezanosti smo uporabljali kazalce negotovosti (osnovni kazalnik χ^2, Pearsonov koeficient negotovosti in popravek negotovosti).

2 REZULTATI

Analiza uporabe metod presoje investicij je v skladu s pričakovanji pokazala, da večina podjetij pri svojem delu uporablja tako metode razobrestovanja denarnih tokov kakor enoobdobne

in the field of energetics, environmental engineering and metallurgy is around 10 %.

Among the respondents to the questionnaire, over two-thirds (34.1 %) had an education in other technical sciences (construction, electrical engineering), and 36.4 % were experts with an economics or social science education. Around one-tenth the questionnaire respondents had an education in other fields (mathematics, chemistry, and geodesy).

The questionnaire was in the form of an internet application. The people answering the questionnaire were asked to submit it by e-mail. A total of 11.7 % of the questionnaires were returned.

The questionnaire had three parts. The questions in the first part dealt with the personal data of the person answering the questionnaire (age, sex, education degree level, position, field of activity and size of the company, etc.). The second part was composed of questions about their opinion of their knowledge and frequency of use of single-period investment project evaluation methods, among which we selected two that do not consider the time value of money (payback period, accounting rate of return). With the questions about the knowledge and the frequency of use of discounting cash-flow methods, which means the methods that do consider the time value of money, we focused on the net present value method, the internal rate of return method, the net present value index, and the modified internal rate of return method. The last part of the questionnaire consisted of questions about the respondents' opinions of their own knowledge of the flaws in investment project evaluation methods. Among the single-period methods, we focused on the faults of the payback period method; among the discounting cash flow methods, we focused on the internal rate of return method.

Data analysis

The data acquired from the questionnaires were systematised and analysed statistically. We calculated the dependence of method and faults knowledge from individual variables. For the analysis of dependence, we used contingency indicators (elementary indicator χ^2, Pearson's contingency coefficient and the correction of contingency).

2 RESULTS

The analysis of investment evaluation method use showed, as anticipated, that most companies use discounting cash-flow methods as well as single-period methods. Most companies, metode. Največ podjetij za presojanje investicij uporablja metodo časa vračila vloženih sredstev – več ko tri četrtine (77,3 %), med metodami razobrestovanja denarnih tokov pa se največkrat uporablja metoda čiste sedanje vrednosti (70,45 %), ki ji sledi metoda notranje donosnosti z manj ko 70-odstotnim deležem. Razmeroma skromna pa je uporaba metode prirejene notranje donosnosti (manj kot 30 %), kar gre pripisati zamudnemu izračunavanju, predvsem pa manjši splošni prepoznavnosti te metode, saj je po navedbah ne pozna polovica strokovnjakov s strojniško izobrazbo.

Uporaba enoobdobnih metod presoje investicijskih projektov in poznavanje njihovih pomanjkljivosti

Rezultati raziskave potrjujejo domnevo, da so enoobdobne metode v podjetjih v Sloveniji še vedno zelo priljubljene. Iz izsledkov raziskave uporabe enoobdobnih metod presoje investicijskih projektov glede na strokovno smer izobrazbe pokažejo, da je več ko 80 odstotkov anketirancev s strojniško izobrazbo odgovorilo, da v podjetjih, v katerih so zaposleni, za ugotavljanje upravičenosti in uspešnosti investicij uporabljajo enoobdobne metode, približno enako pa so te metode razširjene med anketiranci z ekonomsko ali družboslovno izobrazbo, ki tvorita pretežni del razreda "preostale smeri". Med strokovnjaki drugih tehničnih smeri in matematično-naravoslovnih smeri so te metode manj razširjene, kar podrobneje prikazujemo v preglednici 1.

Med enoobdobnimi metodami se največkrat uporablja metoda časa vračila sredstev, še posebej med strojniki in med ankenitranci "preostalih smeri" izobrazbe, saj jo kot analitsko orodje uporablja kar 87,5 % strokovnjakov navedenih smeri, s čimer bistveno presegajo povprečje, ki

more than three-quarters (77.3 %), use the payback period method for investment evaluation. Among the discounting cash flow methods, the net present value method is most commonly used (70.45 %), followed by the internal rate of return method, with a percentage of less than 70 %. There is relatively little use of the modified internal rate of return method (less than 30 %), most probably due to the time-consuming calculations and especially due to low general recognition of this method, since only half the experts with mechanical engineering educations are familiar with it.

Use of single-period investment project evaluation methods and knowledge of their faults

Research results confirm the hypothesis that single-period methods are still very popular in Slovene companies. The results of the research on the use of single-period investment project evaluation methods according to the field of education show that more than 80 % of people with a mechanical engineering education answered that the companies for which they work use single-period methods to determine the justification and success of investments. The answers of people with an education in economics or social science (forming the majority of the "other sciences") were approximately the same. Among experts in other technical sciences and mathematical-natural sciences, these methods are less common. Table 1 shows detailed results on the use of the single-period investment project evaluation methods.

Among the single-period methods, the most commonly used is the payback period method, especially among mechanical engineers and people with education in other sciences – 87.5 % of experts in these other sciences use this method as an analysis tool, and in this way exceed the average frequency

Preglednica 1. *Uporaba in poznavanje enoobdobnih metod glede na strokovno smer izobrazbe*
Table 1. *Use and knowledge of single-period methods according to the field of education degree*

Strokovna smer izobrazbe Field of education degree	uporabljajo use of methods	poznajo knowledge of methods	ne poznajo unfamiliar with the methods
strojniška smer mechanical engineering	81,3 %	12,5 %	6,3 %
druge tehnične smeri other technical sciences	65,6 %	15,6 %	18,8 %
matematična in naravoslovna smer mathematical and natural science	50,0 %	10,0 %	40,0 %
preostale smeri other sciences	81,8 %	18,2 %	0,0 %

znaša nekoliko več ko tri četrtine.

Iz rezultatov je mogoče razbrati, da kombinacijo enoobdobnih metod najpogosteje uporabljajo strokovnjaki z matematično in naravoslovno izobrazbo ter vprašani z ekonomsko ali družboslovno izobrazbo, obakrat okrog tri četrtine. Analiza je tudi pokazala, da slabih 7 % anketirancev z ekonomsko, elektrotehniško in gradbeniško izobrazbo v svojih organizacijah presoja upravičenost in uspešnost investicij tudi z drugimi metodami (kot npr. študijo izvedljivosti ali z analizo dobička/izgub), medtem ko anketirani strojniki drugih metod ne uporabljajo.

Ključno raziskovalno vprašanje je zadevalo poznavanje pomanjkljivosti metod evalvacije projektov. Pri enoobdobnih metodah največ pomanjkljivosti vsebuje metoda časa vračila sredstev, za katere lahko ugotovimo, da so vendarle premalo poznane, da bi smeli sklepati o brezhibno izpeljanih presojah investicijskih projektov.

Z ugotavljanjem poznavanja pomanjkljivosti metode časa vračila vloženih sredstev v odvisnosti od smeri izobrazbe smo ugotovili, da anketiranci s strojniško izobrazbo nadpovprečno dobro poznajo vse pomanjkljivosti omenjene metode (62,5 % jih pozna popačenost rezultata zaradi

of use, which is a little over three-quarters.

These results lead to the conclusion that the combination of single-period methods is most commonly used by experts with a mathematical or natural science education and by those with an education in economics or social science; in both cases the percentage of use is around 75 %. The analysis also showed that less than 7 % of experts with an education in economics, electrotechnics or construction also evaluate the justification and success of investments in their organisations by other methods (such as a feasibility study or a profit/ loss analysis). On the other hand, experts with an education in other sciences use no other methods.

A key research question concerns the knowledge of flaws in these project evaluation methods' faults. Among single-period methods, the payback period method has the most faults with which experts are not sufficiently familiar to be absolutely confident in producing faultlessly executed investment project evaluations.

In establishing how much the experts know about the faults of the payback period method, depending on their field of education, we concluded that experts with an education in mechanical engineering have an above-average knowledge of all the flaws in this method. 62.5 % of them are familiar with result deformation due to a disregard for payment maturity; 37.5 % are familiar with result deformation due to a disregard of payments after

Preglednica 2. *Poznavanje pomanjkljivosti metode časa vračila vloženih sredstev v odvisnosti od strokovne smeri izobrazbe*

Table 2. *Knowledge of faults in the payback period method by field of education*

Popačenje ali omejitev Deformation or restriction	strojniška smer mechanical engineering	druge tehniške smeri other technical sciences	matematična in naravoslovna smer mathematical and natural sciences	preostale smeri other sciences
zaradi neupoštevanja časovnega prihajanja plačil due to disregard of payment expiration	62,5 %	46,7 %	20,0 %	62,5 %
zaradi neupoštevanja plačil po preteku časa vračila investicije due to disregard of payments after expiration of investment payback time	37,5 %	33,3 %	20,0 %	50,0 %
zaradi nezmožnosti prilagajanju tveganja due to incapacity for risk adjustment	50,0 %	46,7 %	40,0 %	56,3 %
zaradi upoštevanja stabiliziranih plačil v evalvacijskem obdobju due to consideration of fixed (stabilized) payment during evaluation period	12,5 %	20,0 %	0,0 %	18,8 %
drugo other	0,0 %	6,7 %	0,0 %	0,0 %

neupoštevanja časovnega prihajanja plačil, 37,5 % jih pozna popačenje zaradi neupoštevanja plačil po preteku časa vračila investicije in 50 % jih pozna omejitev zaradi nezmožnosti prilagajanju tveganja), z izjemo popačenja zaradi upoštevanja stalnih (stabiliziranih) plačil v obdobju evalvacije, ki jo pozna le 12,5 % strojnikov, kar je primerjalno z drugimi strokami prikazano v preglednici 2.

Izpostaviti velja, da 6,7 % anketiranih z drugo tehniško smerjo izobrazbe po lastnem mnenju pozna tudi druge pomanjkljivosti enoobdobnih metod presoje investicijskih projektov.

Uporaba metod razobrestovanja denarnih tokov in poznavanje njihovih pomanjkljivosti

Izmed metod razobrestovanja denarnih tokov se v slovenskih podjetjih največkrat uporablja metoda čiste sedanje vrednosti (v povprečju 70,5 %), najbolj skromna pa je uporaba prirejene notranje donosnosti (v povprečju manj ko 30 %). Izpostaviti pa velja, da strojniki najpogosteje uporabljajo metodo notranje donosnosti (kar 87,5 %), medtem ko jih metodo prirejene notranje donosnosti uporablja polovica. Primerjavo med pogostostjo uporabe posamezne metode med strokovnjaki različnih smeri prikazujemo v preglednici 3.

the expiration of the payback period, and 50 % know about result deformation due to the incapacity for risk adjustment. The only exception is knowledge about result deformation due to a consideration of fixed (stabilized) payments during the evaluation period: only 12.5 % of respondents with a mechanical engineering education are familiar with this. The results showing the knowledge of various deficiencies in the payback period method are shown in Table 2.

We need to stress the fact that according to their opinion, 6.7 % of experts with an education in other sciences are also familiar with additional faults of single-period investment project evaluation methods.

Use of discounting cash-flow methods and knowledge of their flaws

Among the discounting cash flow methods, the most commonly used method in Slovene companies is the net present value method (average use is 70.5 %), while the least popular is the use of the modified internal rate of return method (on average less than 30 %). We need to stress the fact that employees with an education in mechanical engineering most often use the internal rate of return method (87.5 %), while the modified internal rate of return method is used only by half of these. A comparison of the use of individual methods among experts from different sciences is shown in Table 3.

Preglednica 3. *Uporaba metod razobrestovanja denarnih tokov glede na strokovno smer izobrazbe*
Table 3. *Use of discounting cash-flow methods by field of education*

Metoda Method	strojniška smer mechanical engineering	druge tehniške smeri other technical sciences	matematična in naravoslovna smer mathematical and natural science	ostale smeri other sciences
metoda čiste sedanje vrednosti net present value method	62,5 %	66,7 %	40,0 %	87,5 %
metoda notranje donosnosti internal rate of return method	87,5 %	46,7 %	60,0 %	81,3 %
indeks čiste sedanje vrednosti net present value index method	50,0 %	26,7 %	20,0 %	56,3 %
metoda prirejene notranje donosnosti modified internal rate of return method	50,0 %	13,3 %	0,00 %	43,8 %

Pogostost uporabe metode notranje donosnosti med strokovnjaki s strojniško izobrazbo je mogoče pojasniti z njeno lahko razumljivostjo, saj je rezultat izražen v odstotkih (donosnosti) in hkrati s preprosto primerljivostjo med različnimi projekti ter tudi z različnimi oblikami drugih naložb. Izračunavanje sicer zahteva iteracijski postopek ali interpolacijo, vendar finančna računala in elektronske preglednice vsebujejo standardne podlage za izračun notranje donosnosti. Pogostost uporabe metode čiste sedanje vrednosti lahko razložimo s preprostostjo njenega izračunavanja ter s splošno razširjenostjo (običajno delovanje računal in elektronskih preglednic).

Metoda prirejene notranje donosnosti je najmanj uporabljana med preučevanimi navkljub dejstvu, da se z njo izognemo pomanjkljivostim, ki jih vsebuje metoda notranje donosnosti (na primer izločimo predpostavko, da so vsa plačila reinvestirana po isti donosnosti, kakor je notranja, kar je tudi ključna prednost metode prirejene notranje donosnosti). Delno lahko manjšo "priljubljenost" omenjene metode pojasnimo z nižjo ravnijo poznavanja (metoda sodi v razširjena znanja metod razobrestovanja denarnih tokov), bržkone pa gre del pripisati tudi dolgotrajnejšemu postopku izračunavanja.

Omeniti velja, da večina strokovnjakov uporablja več metod razobrestovanja denarnih tokov hkrati, kar zmanjša možnost napačnega sklepanja. Strojniki, ki presojajo investicije z metodami razobrestovanja denarnih tokov, največkrat uporabljajo kombinacijo dveh izmed njih (57,1 %), strokovnjaki preostalih smeri pa dve metodi uporabljajo v povprečju 35,7 odstotno.

Pri ugotavljanju poznavanja pomanjkljivosti smo se osredotočili na metodo notranje donosnosti, saj avtorji, ki jih navajamo v uvodu, tej pripisujejo največ pomanjkljivosti. Ugotovili smo, da le slaba polovica (43,2 %) anketirancev (vseh smeri) v slovenskih podjetjih pozna večkratno notranjo donosnost, le okrog 16 % pa problem navzkrižnega rezultata (indikacije) med metodo notranje donosnosti in metodo čiste sedanje vrednosti. Velike razlike pa se pojavljajo med strokovnjaki različnih profilov, kar je natančneje razvidno iz preglednice 4.

Iz raziskave je mogoče ugotoviti, da 12,5 % anketirancev z ekonomsko ali družboslovno smerjo

The use of the internal rate of return method among experts with an education in mechanical engineering is explicable in terms of the method's ease of understanding, since the result is expressed as a percentage (of rate of return). At the same time, the results can easily be compared between different projects and between different forms of other investments. Although the calculation demands on iteration procedure or interpolation, financial calculators and electronic spreadsheets contain standard procedures for an internal rate of return calculation. The frequency of use of the net present value method can be explained by the simplicity of its calculation and by the generally widespread use of this method (a standard function on calculators and electronic spreadsheets).

The modified internal rate of return method is the least used among the methods studied in our research, despite the fact that this method avoids the deficiencies that occur with the internal rate of return method (e.g., one avoids the presumption that all payments are reinvested at the same rate of return as the internal one – which is the key advantage of the modified internal rate of return method). The lower "popularity" of this method can be explained by its lower level of recognition (the method forms part of the extended knowledge of discounting cash flow) and partly by the lengthy calculation procedure involved.

It is also interesting that most experts simultaneously use a number of discounting cash-flow methods, a technique which diminishes the possibility of false conclusions. A total of 57.1 % of experts with an education in mechanical engineering who evaluate investments by means of discounting cash-flow methods most often use a combination of two methods, but only 35.7 % of experts in other sciences use a combination two methods.

In establishing the level of knowledge about faults, we focused on the internal rate of return method, because the authors quoted at the beginning of this article ascribe most faults to this method. We established that in Slovene companies less than half (43.2 %) of experts (in all sciences) are familiar with multiple internal rate of return, and only 16 % know the problem of results (conflicting indications) between the internal rate of return method and the net present value method. Major differences occur between experts of different profiles; Table 4 shows these differences in detail.

Research results show that, according to their opinion, 12.5 % of experts with a degree in

Preglednica 4. *Poznavanje pomanjkljivosti metode notranje donosnosti v odvisnosti od strokovne smeri izobrazbe*
Table 4. *Knowledge of flaws in the internal rate of return method by field of education degree*

Popačenje ali omejitev Deformation or restriction	strojniška smer mechanical engineering	druge tehniške smeri other technical sciences	matematična in naravoslovna smer mathematical and natural sciences	preostale smeri other
navzkrižna indikacija čiste sedanje vrednosti in notranje donosnosti cross indication of net present value and internal rate of return	37,5 %	33,3 %	0,0 %	43,8 %
večkratna notranja donosnost multiple internal rate of return	37,5 %	6,7 %	0,0 %	18,8 %
popačenje zaradi predpostavke, da se vsa plačila reinvestirajo po donosnosti, ki je enaka interni deformation due to a presumption that all payments are reinvested according to the rate of return identical to the internal one	37,5 %	40,0 %	20,0 %	56,3 %
drugo other	0,0 %	0,0 %	0,0 %	12,5 %

izobrazbe po lastnem mnenju pozna druge pomanjkljivosti metode notranje donosnosti.

Odvisnost poznavanja metod presoje investicijskih projektov ter poznavanja njihovih pomanjkljivosti od smeri in stopnje izobrazbe

Povezanost poznavanja metod presoje investicijskih projektov s smerjo in stopnjo izobrazbe smo ugotavljali z izračunavanjem koeficienta negotovosti. Pri ugotavljanju jakosti povezanosti enoobdobnih metod od strokovne smeri izobrazbe je popravek koeficienta negotovosti znašal 0,447, pri ugotavljanju jakosti povezanosti razobrestovalnih metod s smerjo izobrazbe pa 0,4, iz česar je mogoče sklepati, da ni močne povezanosti med poznavanjem metod evalvacije in strokovno smerjo izobrazbe.

Pri ugotavljanju povezanosti poznavanja enoobdobnih metod in metod razobrestovanja denarnih tokov s stopnjo izobrazbe, smo ugotovili, da ne glede na stopnjo izobrazbe, ki jo imajo ankentiranci (magisterij oz. doktorat dobrih 34 %, univerzitetno izobrazbo skoraj 39 %, visokošolsko več kot 20 % in srednješolsko izobrazbo slabih 3 %), med poznavanjem metod presoje investicij in stopnjo izobrazbe obstaja dokaj šibka povezanost, saj sta vrednosti izračunanih popravkov koeficienta negotovosti znašali le 0,377 in 0,355.

Izračunani popravek koeficienta negotovosti, s katerimi smo določili odvisnost

economics or social science do know about other faults of the internal rate of return method.

Dependence of knowledge about investment project evaluation methods and familiarity with their faults by field and level of education degree

The connection between the knowledge of investment project evaluation methods and the field and level of education degree was established by calculating the contingency coefficient. In establishing the level of connection between single-period methods and the field of education the correction of contingency was 0.447, and in establishing the level of connection between discounting cash-flow methods and the field of education, the contingency coefficient was 0.4. These results show that there is no strong connection between knowledge about evaluation methods and the field of education.

In establishing a connection between knowledge of single-period methods and discounting cash-flow methods and level of education, we found that, regardless of their level of education (over 34 % had a PhD or an MSc degree, almost 39 % a university degree, more than 20 % a college degree and less than 3 % had a secondary-school degree), there is a relatively weak interdependence between the knowledge of investment evaluation methods and the level of education. The values of the calculated correction of contingency were only 0.377 and 0.355.

The calculated correction of contingency through which we established the dependence between poznavanja pomanjkljivosti metode časa vračila vloženih sredstev od strokovne smeri izobrazbe, je znašal 0,634, torej med poznavanjem pomanjkljivosti časa vračila vloženih sredstev in izobrazbo zaposlenih v slovenskih podjetjih obstaja zmerna povezanost. Ugotovili pa smo močno povezanost med poznavanjem pomanjkljivosti metode notranje donosnosti in smerjo izobrazbe, saj je vrednost izračunanega popravka koeficienta 0,91.

Rezultati so tudi pokazali, da je poznavanje pomanjkljivosti metode časa vračila vloženih sredstev močno odvisno od tega, kako visoko izobrazbo so dosegli ankentiranci (popravek koeficienta negotovosti je znašal 0,866), med poznavanjem pomanjkljivosti notranje donosnosti in stopnjo izobrazbe pa obstaja šibka povezanost (popravek koeficienta negotovosti je 0,256).

3 RAZPRAVA IN SKLEP

Rezultati preteklih raziskav, ki smo jih navedli na začetku, so pokazali povečano uporabo metod presoje investicijskih projektov do osemdesetih let preteklega stoletja, kasneje pa večanja ni mogoče potrditi. S pričujočo raziskavo smo raziskali stanje na področju uporabe metod presoje investicijskih projektov v Sloveniji s posebnim poudarkom na področju strojništva. Raziskava je pokazala, da je uporaba metod presoje investicijskih projektov v Sloveniji povsem primerljiva s stanjem v drugih državah, zaradi pomanjkanja primerljivih raziskav pa nismo mogli izvesti primerjave poznavanja pomanjkljivosti obravnavanih metod.

Dobljeni rezultati raziskave uporabe in poznavanja pomanjkljivosti metod presoje investicijskih projektov nakazujejo, da večina strokovnjakov strojniške smeri, podobno pa tudi tistih z ekonomsko in družboslovno izobrazbo, za ugotavljanje upravičenosti in uspešnosti investicij uporablja tako enoobdobne metode kakor tudi metode razobrestovanja denarnih tokov. Ne glede na strokovno smer izobrazbe pa so enoobdobne metode še vedno bolj priljubljene od metod razobrestovanja denarnih tokov; izmed obeh preučevanih enoobdobnih metod je bolj priljubljena metoda časa vračila vloženih sredstev.

V raziskavi se je pokazalo, da strokovnjaki, ki se ukvarjajo s presojo investicijskih projektov in imajo strojniško izobrazbo, nadpovprečno veliko uporabljajo metode evalvacije investicijskih

the knowledge about the faults of the payback period method and the field of education was 0.634. This shows that there is a moderate level of connection between knowledge about deficiencies in the payback period method and the field of education of the people working in Slovene companies. But we established that there is a strong connection between knowledge about flaws in the internal rate of return method and the field of education, since the calculated correction of contingency coefficient is 0.91.

Results have shown that knowledge about the faults of the net present value method is highly dependent on the level of education of the respondents (the correction of contingency was 0.866), but according to our results there is only a weak connection between knowledge of the deficiencies in the internal rate of return and the level of education (the correction of contingency is 0.256).

3 DISCUSSION AND CONCLUSION

The results of past research, cited at the beginning of this article, have shown an increase in the use of investment project evaluation methods until the 1980s; after that, there was no proof of a continuing increase. Our research project investigated the situation in the field of use of investment project evaluation methods in Slovenia, with special stress on the field of mechanical engineering. Our results show that the use of investment project evaluation methods in Slovenia is fully comparable with the situation in other countries. However, due to a lack of comparable research we could not compare knowledge about the deficiencies of the subject methods.

The results obtained through research into the use and knowledge of faults in investment project evaluation methods show that most experts in the field of mechanical engineering as well as experts with a degree in economics or social sciences use single-period methods and discounting cash-flow methods to establish the justification and success of investments. Regardless of the field of education, single-period methods are still more popular than discounting cash-flow methods; the more popular of the two single-period methods studied in our research was the asset payback period method.

The research also shows that experts who have an education in mechanical engineering and are involved in investment project evaluation practice are more likely than average to use discounting cash-projektov, ki temeljijo na razobrestovanju denarnih tokov. Pri tem se uvrščajo ob bok strokovnjakom ekonomskih in sorodnih smeri (druge smeri), hkrati pa bistveno presegajo druge tehniške smeri. Prav tako tudi nadpovprečno dobro poznajo pomanjkljivosti metod evalvacije investicijskih projektov, kljub temu pa se postavlja vprašanje, ali je poznavanje pomanjkljivosti metod zadostno. Navkljub nadpovprečnemu poznavanju pomanjkljivosti namreč le slabi dve tretjini strojnikov pozna popačenost rezultata zaradi neupoštevanja časovnega prihajanja plačil, kar je ne le ključna pomanjkljivost, temveč tudi ključna razlikovalna značilnost med enoobdobnimi metodami in metodami razobrestovanja denarnih tokov.

Pri metodi notranje donosnosti izstopa poznavanje večkratne notranje donosnosti, ki je v teoriji najpogosteje opisovana pomanjkljivost omenjene metode, bržkone zaradi tega, ker so veliki projekti v strojništvu zaradi spremenljivih denarnih tokov tipični predstavniki projektov, katerih presoja je izpostavljena večkratni notranji donosnosti.

Ugotovimo lahko, da se z višanjem izobrazbene stopnje poznavanje izboljšuje le delno in velja le za statične metode. Iz tega je mogoče sklepati, da je veliko znanj pridobljenih ali vsaj temeljito poglobljenih na podlagi praktičnega dela v podjetjih. Glede na to ugotovitev lahko sklepamo, da potrebe v podjetjih v splošnem presegajo raven znanja, ki ga ponujajo šole na vseh ravneh. Hkrati je mogoče ugotoviti, da obravnavana tematika pridobiva pomen tudi v slovenskih izobraževalnih ustanovah v okviru aktualnih družbenih in gospodarskih sprememb. S tem se odpira potreba po primerjanju stanja v različnih časovnih obdobjih, kar pomeni smernico za nadaljnje raziskovalno delo.

flow methods. In this way they stand side by side with experts in economics and similar sciences (other sciences) and at the same time greatly exceed experts from other technical sciences. They also possess above-average knowledge about the deficiencies in investment project evaluation methods, but this raises a question at the same time: Is their knowledge of such flaws sufficient? Despite their above-average familiarity with the drawbacks, only two-thirds of respondents with an education in mechanical engineering are familiar with result deformation due to a disregard for payment maturity. This is not only the key fault but also a key distinguishing characteristic between single-period methods and discounting cash-flow methods.

When using the internal rate of return method, experts with a mechanical engineering education are most familiar with multiple internal rate of return, which is, in theory, the most commonly presented fault of this method. Familiarity with the multiple internal rate of return is above average, most probably because big projects in the field of mechanical engineering are, owing to variable cash flow, typically subject to a multiple internal rate of return.

We can establish that, with an increased level of education, knowledge about methods increases partially and only with single-period methods. This leads to the conclusion that much of this knowledge has been acquired or thoroughly revised through practical work in companies. With regard to this conclusion, we can establish that the needs of companies generally exceed the levels of knowledge that schools transfer to their students at all levels. At the same time experience leads us to the conclusion that, in the light of actual social and economic changes, these topics will gain in significance in Slovenian educational institutions. Consequently we can identify a need to compare the conditions at different time periods, which represents a guideline for further research work.

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Naslov avtorjev: doc. dr. Igor Pšunder
Nadja Ferlan
Univerza v Mariboru
Fakulteta za gradbeništvo
Smetanova 17
2000 Maribor
igor.psunder@uni-mb.si
nadja_ferlan@yahoo.com

Authors' address: Doc. Dr. Igor Pšunder
Nadja Ferlan
University of Maribor
Faculty of Civil Engineering
Smetanova 17
2000 Maribor, Slovenia
igor.psunder@uni-mb.si
nadja_ferlan@yahoo.com

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Uporaba metode premičnih najmanjših kvadratov za gladko aproksimacijo vzorčenih podatkov

The Use of Moving Least Squares for a Smooth Approximation of Sampled Data

Igor Grešovnik
(Center za računalništvo v mehaniki kontinuuma, Ljubljana)

Predstavljena je uporaba metode premičnih najmanjših kvadratov za glajenje podatkov in aproksimacijo odzivnih funkcij s šumom. Obravnavane so lastnosti aproksimacije glede na raven šuma, gostoto vzorčenja in dejanski doseg vpliva vzorcev. Uporabnost metode je prikazana pri glajenju merskih podatkov in reševanju optimizacijskega problema s šumom z metodo zaporednih aproksimacij. Metoda premičnih najmanjših kvadratov se izkaže za uporabno pri reševanju različnih problemov zaradi gladkosti, možnosti natančne aproksimacije na poljubno velikem območju, možnosti aproksimacije na podlagi neurejene množice vzorčnih točk in prilagodljivosti različnim lastnostim aproksimirane funkcije v različnih območjih.

(Ključne besede: vzorčni podatki, aproksimacije funkcij, metode premičnih najmanjših kvadratov, glajenje, optimiranje)

The use of the moving least-squares approximation for the smoothing of data and the approximation of noisy response functions is presented. The approximation properties are treated with respect to the level of noise, the sampling density and the effective range of the sample. The applicability of the method is demonstrated by smoothing experimental measurement data and solving an optimization problem with a noisy response by the successive response approximation technique. The results indicate that the moving least-squares approximation is applicable to a wide variety of problems due to its smoothness, its accurate approximation over arbitrarily large domains using low-order basis functions, its ability to deal with an irregular arrangement of sampling points and to adapt to different modes of the approximation function in different regions.

(Keywords: sample data, function approximation, moving least squares methods, smoothing, optimization)

0 UVOD

Pogosto želimo množico točk, ki predstavljajo neko funkcijsko zvezo, zamenjati s približno funkcijo z določenimi zveznostnimi lastnostmi. Ena od možnosti je aproksimacija s polinomi določenega reda ali s trigonometrijsko vrsto. To je učinkovito, kadar potrebujemo približek na omejenem območju. V nasprotnem primeru potrebujemo veliko število členov aproksimacije, posebej, ko imamo več neodvisnih spremenljivk. Aproksimacija s polinomi je nestabilna, ko je število točk veliko in se število členov približa številu točk. Ta problem lahko rešujemo z odsekovno polinomsko aproksimacijo [4]. Pri tem postopku se odpovemo zveznosti poljubne stopnje. V primeru več neodvisnih spremenljivk navadno

0 INTRODUCTION

It is often useful to replace a set of points that represent a functional relation with an approximate relation that has certain continuity properties. One of the possibilities is an approximation with a polynomial of a given order or a series of trigonometric functions. This approach is efficient when an approximation is needed over a limited domain. In other cases a large number of terms is necessary, especially in the multivariate case. The polynomial approximation also becomes unstable when the number of points is large and close to the number of terms. However, this problem can be tackled by a piecewise polynomial approximation [4]. With this approach, one gives up the continuity of an arbitrary order and in the potrebujemo strukturirano razdelitev območja aproksimacije.

Kot druga možnost je v tem prispevku predstavljena metoda premičnih najmanjših kvadratov. Metoda omogoča gladko in stabilno aproksimacijo na poljubno velikem območju. Ni potrebna kakršnakoli delitev območja aproksimacije in za gladke funkcije lahko dosežemo poljubno natančnost aproksimacije z uporabo omejenega števila osnovnih funkcij, če lahko ustrezno povečujemo gostoto vzorčenja. Oris metode je podan v poglavju 1. Lastnosti aproksimacije so v poglavju 2. prikazane na primeru z analitično funkcijo ene spremenljivke. Dva primera praktične uporabe sta prikazana v poglavju 3. V prvem primeru je metoda uporabljena za glajenje časovno odvisnega signala zaznavala pri laboratorijski meritvi, kar omogoči učinkovito uporabo minimizacijskega postopka pri določitvi modelskih parametrov z reševanjem obrnjenega problema. V drugem primeru je metoda uporabljena pri zaporednih prilagodljivih aproksimacijah namenske in omejitvenih funkcij. Aproksimacije uporabimo v iterativnem optimizacijskem postopku, primernem za reševanje problemov s šumom.

multivariate case a structured division of the domain of approximation is usually needed.

As an alternative, the moving least-squares approximation method is presented. The method enables a smooth and stable approximation over arbitrarily large domains. No particular partition of the domain of approximation is necessary and arbitrary accuracy can be achieved for smooth functions with a small number of basis functions, provided that the sampling density can be increased correspondingly. An outline of the method is given in Section 1. The properties of the approximation are studied in Section 2 on a synthetic example with a function of a single variable. In Section 3, two practical applications of the method are demonstrated. In the first example the method is used for the smoothing of a time-dependent sensor output in a laboratory experiment, which makes it possible to perform an efficient minimization procedure for an inverse estimation of the model parameters. In the second example the method is used for successive adaptive approximations of the noisy objective and constraint functions, which are used in an iterative optimization procedure suitable for optimization with a noisy response.

1 OPIS METODE

1.1 Linearna aproksimacija po metodi najmanjših kvadratov z utežmi

Pri linearni metodi najmanjših kvadratov aproksimiramo neznano funkcijo $f(\mathbf{x})$ z linearno kombinacijo n osnovnih funkcij $f_1(\mathbf{x})$, ..., $f_n(\mathbf{x})$ na podlagi znanih (vzorčenih) vrednosti funkcije v določenem številu točk:

1 METHOD DESCRIPTION

1.1 Linear Weighted Least-Squares Approximation

Using the least-squares method we approximate an unknown function $f(\mathbf{x})$ by a linear combination of n basis functions $f_1(\mathbf{x})$, ..., $f_n(\mathbf{x})$ on the basis of known (sampled) values of the function at a number of points:

$$y_k = f\left(\mathbf{x}_k\right) + r_k\ ,\ \ k = 1,...,m \qquad (1).$$

Člen r_i pomeni naključno napako (šum) pri merjenju ali računanju vrednosti funkcije. Aproksimacija:

The term *ri* accounts for a random error (noise) that is eventually accomplished when the function is measured or evaluated. We want the approximation:

$$y\left(\mathbf{x}\right) = \sum_{j=1}^{n} a_j f_j\left(\mathbf{x}\right) \qquad (2)$$

se mora čim bolje ujemati z vzorčenimi vrednostmi, torej:

to agree as much as possible with the sampled values, i.e.:

$$y\left(\mathbf{x}_k\right) \approx y_k \quad \forall k = 1,...,m \qquad (3).$$

V enačbi (2) so a_j neznani koeficienti aproksimacije, ki jih je treba določiti. To storimo

In Equation (2), a_j are the coefficients of the approximation that must be determined. This is tako, da poiščemo najboljše ujemanje v skladu najmanjših kvadratov, torej z minimizacijo naslednje funkcije koeficientov:

done by looking for the best agreement in the least-squares sense, i.e., by a minimization of the following function of coefficients:

$$\phi(\mathbf{a}) = \sum_{k=1}^{m} w_k^2 \left(y(\mathbf{x}_k) - y_k\right)^2 = \sum_{k=1}^{m} w_k^2 \left(\left(\sum_{j=1}^{n} a_j f_j(\mathbf{x}_k) \right) - y_k \right)^2 \quad (4).$$

V zgornji enačbi smo koeficiente a_i uredili v vektor **a**. Nenegativne uteži w_k merijo sorazmerno pomembnost vzorčnih točk. Večje so vrednosti uteži, bolj je aproksimacija prilagojena pripadajočim vzorčenim vrednostim na račun slabšega ujemanja z vrednostmi z manjšimi utežmi.

Metoda najmanjših kvadratov z utežmi ima statističen pomen [1]. Če so merske napake r_i porazdeljene normalno z znanimi standardnimi odstopanji σ_i in je (2) pravilen model za $f(\mathbf{x})$, dobimo z minimizacijo $\Phi(\mathbf{a})$ vrednosti koeficientov **a** z največjo verjetnostjo, da so izračunani koeficienti pravilni, če postavimo uteži na:

In the above equation the coefficients a_i were arranged in a vector **a**, and non-negative weighting coefficients w_k measure the relative significance of the samples. The higher these coefficients are, the more the approximation will attempt to accommodate the corresponding sampled values on account of the poorer agreement with the samples with smaller weights.

The weighted least-squares formulation has a statistical meaning [1]. When measurement errors r_i have a normal distribution with known standard deviations σ_i and (2) represents a correct model for $f(\mathbf{x})$, a minimization of $\Phi(\mathbf{a})$ yields the values of the coefficients **a** with the highest probability that they are correct, provided that the weights are set to:

$$w_k = \frac{1}{\sigma_k} \quad (5).$$

Največja verjetnost se tu nanaša na vrh verjetnostne gostote za porazdelitev koeficientov **a**, ki jih dobimo z minimizacijo $\Phi(\mathbf{a})$ pri različnih udejanjenjih izmerkov glede na njihovo verjetnostno porazdelitev. Čeprav porazdelitve merskih napak pogosto niso normalne in uporabljeni modeli niso natančni, je uporaba najmanjših kvadratov pri prilagajanju podatkov povsod navzoča in se izkaže za primerno v veliko primerih, ko nimamo na voljo fizikalno utemeljenih modelov.

Minimizacijo $\Phi(\mathbf{a})$ lahko izvedemo z iskanjem ustaljene točke, zato zahtevamo:

The highest probability refers to the maximum of the probability density function for the distribution of coefficients **a** obtained for different realizations of measurements according to their probability distribution. Although the distributions of measurement errors are often not normal and in particular the model used is not correct, the least-squares approach is ubiquitously used for fitting data and proves suitable in many situations when we do not have physically founded models for the measured data at our disposal.

The minimization of $\Phi(\mathbf{a})$ is performed by finding the stationary point, i.e., by setting

$$\frac{d\,\phi(\mathbf{a})}{d\,a_i} = 2\sum_{k=1}^{m} \left(w_k^2 \left(\sum_{j=1}^{n} a_j f_j(\mathbf{x}_k) - y_k \right) f_i(\mathbf{x}_k) \right) = 0 \quad \forall i = 1,\ldots,n \quad (6).$$

Dobimo sistem enačb za koeficiente **a**:

This yields the system of equations for coefficients **a**:

$$\mathbf{Ca} = \mathbf{d} \quad (7),$$

kjer so:

where:

$$C_{ij} = \sum_{k=1}^{m} w_k^{\,2} f_i(\mathbf{x}_k) f_j(\mathbf{x}_k) \quad (8)$$

in

and

$$d_i = \sum_{k=1}^{m} w_k^{\,2} f_i(\mathbf{x}_k)\, y_k \quad (9).$$

1.2 Premični najmanjši kvadrati

Izbira osnovnih funkcij je odločilna za to, kako natančno lahko aproksimacijo prilagodimo podatkom. Če nimamo primernega fizikalnega modela, pogosto vzamemo množico enočlenikov do določene stopnje, kar je utemeljeno s Taylorjevim izrekom [2]. Za dobro aproksimacijo funkcije na večjem območju je treba ustrezno povečati število členov. Posebej pri večjem številu neodvisnih spremenljivk je lahko težko določiti primerno število osnovnih funkcij. Nekateri členi aproksimacije so lahko odveč kljub velikemu presežku podanih vrednosti glede na število koeficientov, zato je lahko sistem (7) slabo pogojen.

Opisane težave lahko olajšamo s prostorsko omejitvijo aproksimacije, tako da je odvisna le od vzorčnih točk v omejeni okolici točke izračuna aproksimacije. Da ohranimo zveznost in zagotovimo zmožnost prilagoditve na celotnem območju, ki nas zanima, obdržimo obliko (2), vendar s spremenljivimi koeficienti, ki so zvezno odvisni od neodvisnih spremenljivk. Aproksimacijo lahko torej zapišemo kot:

1.2 Moving Least Squares (MLS)

The choice of the basis functions has a crucial impact on the degree to which the approximation can accommodate the data. With the lack of an appropriate physical model, a set of monomials up to a given degree is often taken, with the justification relying on Taylor's theorem [2]. When the function is to be approximated over a larger range of independent variables, an increased number of terms must be taken for a good approximation. In particular when the number of independent variables is large, it may be difficult to estimate a suitable number of basis functions. Some terms of the approximation may be redundant, and in spite of the large excess of data with respect to the number of coefficients, the system of Equations (7) can be badly conditioned.

The above-mentioned difficulties can be alleviated by localizing the approximation in the sense that it depends only on samples in a certain neighborhood of the evaluation point. In order to preserve the continuity of the approximation and ensure its accommodation ability over the whole range of interest, we keep the form of the approximation similar to (2) but let coefficients continuously depend on independent variables. Therefore, we can write the approximation as:

$$y(\mathbf{x})=\sum_{j=1}^{n} a_j(\mathbf{x})\, f_j(\mathbf{x}) \qquad (10).$$

Koeficiente $\mathbf{a}(\mathbf{x})$ moramo posebej izračunati v vsaki točki, kjer izračunamo vrednost aproksimacije. V metodi premičnih najmanjših kvadratov [3] to dosežemo z uvedbo utežnih funkcij, ki se zmanjšujejo z razdaljo od pripadajočih vzorčnih točk. Koeficiente $\mathbf{a}(\mathbf{x})$ izračunamo posebej v vsaki točki računanja aproksimacije $\mathbf{x}$ z reševanjem sistema enačb, ki ustreza sistemu (7) do (9), pri čemer so uteži $w_k(\mathbf{x})$ odvisne od točke izračuna:

The coefficients $\mathbf{a}(\mathbf{x})$ are thus calculated at each point where the approximation is evaluated. In the moving least-squares method [3] this is done by introducing weight functions that fall with increasing distance from the corresponding samples. The system of equations equivalent to that defined by Equations (7) to (9) is then solved to obtain the coefficients $\mathbf{a}(\mathbf{x})$ in each evaluation point $\mathbf{x}$, with weights $w_k(\mathbf{x})$ dependent on the point of evaluation:

$$\begin{aligned} &\mathbf{C}(\mathbf{x})\,\mathbf{a}(\mathbf{x})=\mathbf{d}(\mathbf{x}) \\ &C_{ij}(\mathbf{x})=\sum_{k=1}^{m} w_k(\mathbf{x})^2 f_i(\mathbf{x}_k)\, f_j(\mathbf{x}_k) \\ &d_i(\mathbf{x})=\sum_{k=1}^{m} w_k(\mathbf{x})^2 f_i(\mathbf{x}_k)\, y_k \end{aligned} \qquad (11).$$

Utežne funkcije $w_k(\mathbf{x})$ se morajo v vseh smereh enakomerno zmanjševati z razdaljo od pripadajočih vzorčnih točk $\mathbf{x}_k$ in morajo imeti določeno stopnjo zveznosti, s čimer zagotovimo zveznost aproksimacije. V tem prispevku uporabimo naslednjo obliko ta utežne funkcije:

Weighting functions $w_k(\mathbf{x})$ must, in any direction, monotonously decrease with the distance from the corresponding sampling points $\mathbf{x}_k$ and must be have a certain degree of continuity, which ensures continuity of the approximation. In the present work, we use the same form for all the weighting functions:

$$w_k(\mathbf{x},\mathbf{d}) = w\left(\sqrt{\sum_{i=1}^{N}\left(\frac{(\mathbf{x}-\mathbf{x}_k)_i}{d_i}\right)^2}\right) \quad (12).$$

Parametri d_i v enačbi (12) določajo dejanski doseg vpliva vzorcev v različnih koordinatnih smereh. Različne oblike $w(r)$ lahko pripravno prilagodimo namenu. Primera sta Gaussova in nasprotna polinomska oblika (sl. 1):

The parameters d_i in Equation (11) define the effective influence range of samples in the coordinate directions. A variety of forms of $w(r)$ can be conveniently adapted, depending on the purpose. Examples are the Gaussian and reciprocal polynomial forms (Figure 1):

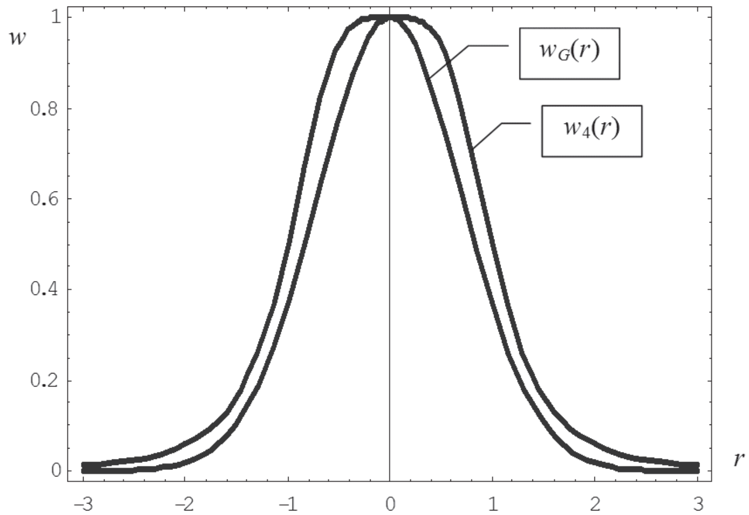
$$w_G(r) = e^{-r^2}$$
$$w_p(r) = \frac{1}{1+|r|^p},\ p = 2, 3, 4, ... \quad (13).$$

Mogoča je tudi uporaba funkcij s končno podporo, s čimer popolnoma izločimo vpliv oddaljenih točk na vrednost aproksimacije v dani točki. Temu se v glavnem izogibamo in za predstavljena področja uporabe uporabljamo funkcije, ki se dovolj hitro zmanjšujejo z razdaljo (na primer w_G in w_4), kar je po naših izkušnjah zadovoljivo. Takšne funkcije se dobro obnesejo pri neenakomerni porazdelitvi vzorčnih točk, ko na območjih z manjšo gostoto bolj oddaljene točke zagotovijo, da ostane sistem za določitev koeficientov (11) dobro definiran.

Ker prostorska odvisnost uteži zagotavlja krajevno prilagajanje aproksimacije vzorčenim podatkom, ni potrebna velika množica osnovnih funkcij. Pri veliki gostoti vzorčnih točk in majhnih napakah lahko zadoščajo že monomi do prvega reda. Uporaba kvadratične polinomske osnove je

Functions with a finite support can be utilized as well, which completely eliminates the distant points from affecting the approximation at the point of evaluation. We mainly avoid this and find functions with a sufficiently strong decay (e.g., w_G and w_4) adequate for the presented applications. These functions are handy for situations with a non-uniform distribution of samples, where in the region with small concentrations more distant samples ensure that the system for a determination of the coefficients (10) remains well posed.

Since a spatial variation of weights ensures a local accommodation of the approximation to the sampled data, a large set of basis functions is not necessary. When the sample density is large and the errors are small, a linear basis consisting of monomials up to the first order may be sufficient. Experience shows that the quadratic polynomial basis, which we



Sl. 1. *Obliki utežnih funkcij $w_G(r)$ in $w_4(r)$*
Fig. 1. *Weighting function forms $w_G(r)$ and $w_4(r)$*

glede na izkušnje primerna za veliko število različnih problemov. Dejanski doseg vpliva je odločilen parameter aproksimacije, katerega izbira je tesno povezana z izbiro osnove in lastnostmi aproksimirane funkcije. Enostavno vodilo pri tem je, da doseg vpliva ne sme biti večji od velikosti območja, na katerem lahko linearna kombinacija osnovnih funkcij z nespremenljivimi koeficienti dobro aproksimira funkcijo. Po drugi strani mora biti dejanski doseg v prisotnosti šuma čim večji, da se pri aproksimaciji izravna vpliv naključnih napak.

Sl. 2 shematično prikazuje metodo premičnih najmanjših kvadratov, pri katerih apsoksimiramo osem vrednosti s polinomskimi baznimi funkcijami drugega reda $\{1, x$ in $x^2\}$. Utežne funkcije pripadajoče vzorčnim točkam so narisane v spodnjem delu slike. Za izbrano točko izračuna aproksimacije so označene vrednosti uteži za vplivne vzorčne točke.

used in the presented examples, is suitable for a large range of problems. The effective influence range is a crucial parameter for the approximation, and it is inseparably related to the chosen basis and properties of the approximated function. In simple terms, the range of influence should not be larger than the range on which a linear combination of basis functions with constant coefficients can adequately approximate the function. In the presence of noise, on the other hand, the effective range must be as large as possible in order to level out the effect of random errors.

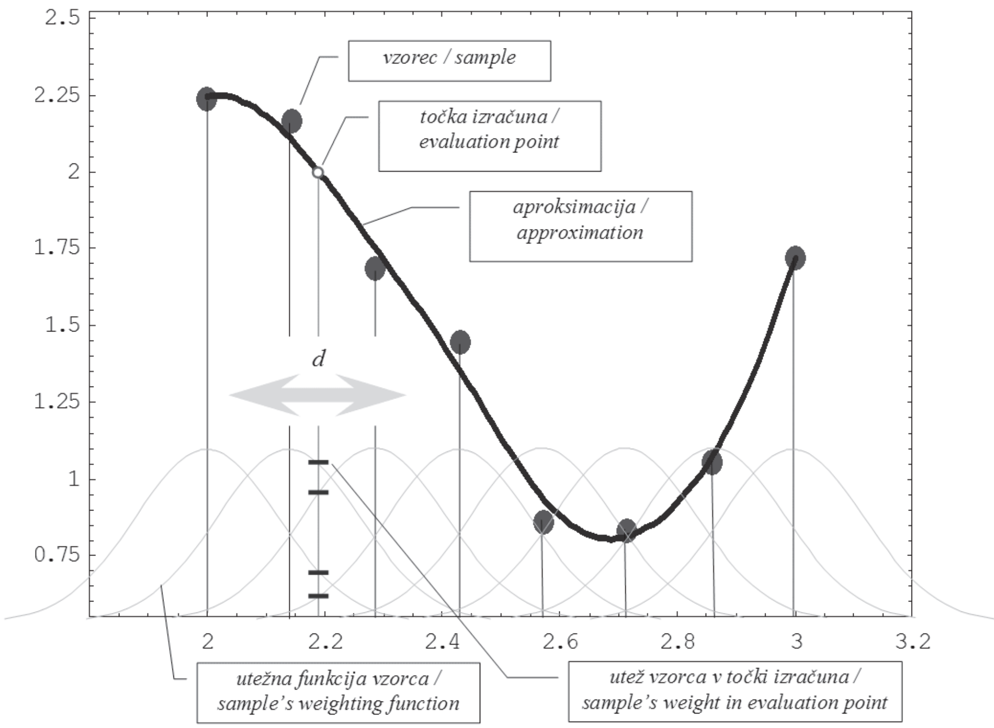
Figure 2 schematically presents the moving least-squares method where a set of eight sampled points are approximated with quadratic polynomial basis functions $\{1, x$ and $x^2\}$. The weighting functions corresponding to the sampling points are plotted in the lower part of the figure. For a chosen evaluation point, the values of the weights corresponding to the influencing samples are indicated.

2 ŠTUDIJA: APROKSIMACIJA ANALITIČNE FUNKCIJE

V tem poglavju je obravnavana uporaba aproksimacije po postopku premičnih najmanjših

2 STUDY: APPROXIMATION OF AN ANALYTICAL FUNCTION

In this section the application of the moving least-squares approximation is demonstrated on



Sl. 2. *Shematičen prikaz aproksimacije premičnih najmanjših kvadratov*
Fig. 2. *Scheme of the moving least-squares approximation*

kvadratov na podlagi podatkov, ki so dobljeni z vzorčenjem analitične funkcije z dodanim naključno napako:

data sampled from an analytical function with an added random error:

$$f\left(x\right)=\sin\left(4\,\mathrm{x}\right)+0,5\,e^{0,5x}+2\,R\left(\,rnd\,()-0,5\,\right) \quad (14),$$

kjer sta *rnd*() enakomerno porazdeljena naključna napaka na območju [0,1] in *R* stalnica, ki določa raven šuma. Funkcijo vzorčimo na območju $[x_1, x_r]$=[0, 5] v različnih številih *m* enakomerno oddaljenih točk. Proučujemo lastnosti aproksimacije glede na raven šuma *R*, število vzorčnih točk *m* in dejanski vplivni doseg *d*. Uporabimo kvadratično polinomsko osnovo:

where *rnd*() is a uniformly distributed random number on [0,1] and *R* is a constant that defines the level of noise. The function is sampled over the interval $[x_l, x_r]$=[0, 5] using different numbers of equidistant points *m*. The properties of the moving least-squares approximation are studied with respect to the level of noise *R*, the number of sampling points *m* and the effective influence range *d*. An approximation with a quadratic polynomial basis is studied, i.e.:

$$f_1\left(x\right)=1,\; f_2\left(x\right)=x\,,\; f_3\left(x\right)=x^2 \quad (15).$$

Za primerjavo rezultatov uvedemo mero za normalizirano gostoto vzorčenja, ki določa število vzorčnih točk na dejanski doseg *d*:

For a comparison of the results, a measure of the normalized sampling density is used that specifies the number of sampling points per effective influence range *d*:

$$\rho = m\frac{d}{x_r - x_l} \quad (16).$$

Kot mero za aproksimacijo napake uporabimo koren iz povprečne vrednosti vsote kvadratov odstopanj aproksimacije od *f* v N_e=600 točkah:

As a measure of the approximation error, the root mean square of the deviation between *f* and its approximation, calculated over a set of N_e=600 equidistant evaluation points, is used:

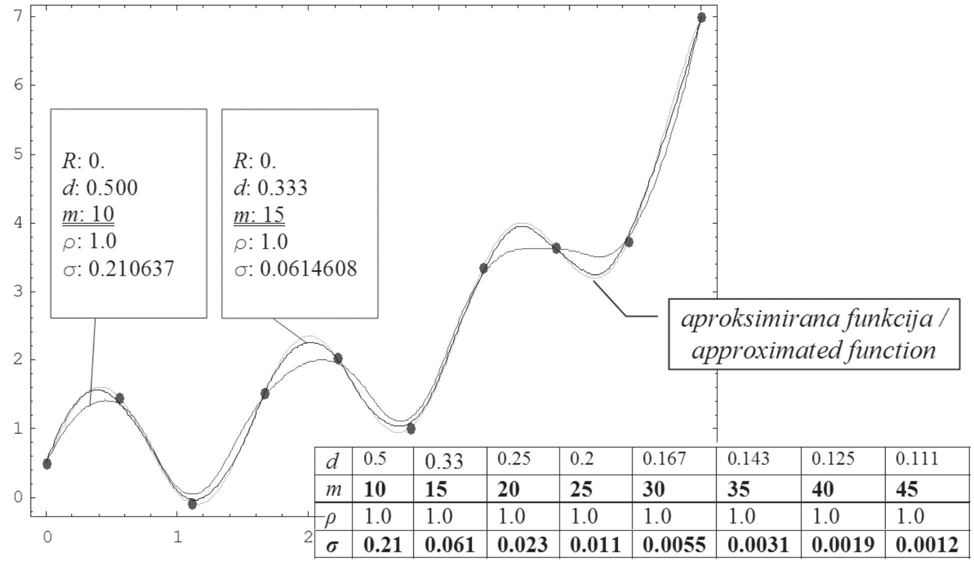
$$\sigma = \sqrt{\frac{1}{N_e}\sum_{i=1}^{N_e}\left(\,y\left(x_i\right)-f\left(x_i\right)\right)^2}\;;\; x_i = x_l + \left(i-1\right)\frac{x_r - x_l}{N_e - 1} \quad (17).$$

Najprej študiramo aproksimacijo brez prisotnosti šuma. Aproksimacijo izračunamo za različna števila vzorčnih točk, pri katerih izberemo dejanski doseg tako, da je normirana gostota vzorčenja stalna, in sicer ρ = 1. Sl. 3 prikazuje aproksimacijo z 10 in 15 točkami, ki ju primerjamo z aproksimirano funkcijo. Aproksimacijske napake so za različna števila točk prikazana v preglednici, ki je priložena k Sl. 3, ter na Sl. 4. Ko presežemo določeno število točk, se napaka enakomerno zmanjšuje z *m*. Tako je zaradi tega, ker se dejanski doseg zmanjšuje z naraščajočim *m* (saj se ρ ne spreminja) in ker lahko s končno polinomsko osnovo bolje aproksimiramo funkcijo na manjšem območju.

V nadaljevanju obravnavamo aproksimacijo na podlagi podatkov s šumom. Sl. 5 prikazuje aproksimacijo na podlagi 20 vrednosti z ravnijo šuma *R*=0,4 pri treh različnih vrednostih dejanskega dosega *d*. Jasno je viden vpliv dejanskega dosega

An approximation without the presence of noise is studied first. This approximation is calculated for different numbers of samples where the effective influence range is chosen in such a way that the normalized sampling density is kept constant at ρ = 1. Figure 3 shows approximations with 10 and 15 points compared to the approximated function. Approximation errors using different numbers of sampling points are shown in the table that is attached to Figure 3 and in Figure 4. After some number of sampling pints *m*, the error monotonously falls with *m*. This is because the effective influence range falls with increasing *m* (since ρ is kept constant) and the finite polynomial approximation basis can be a better approximated function over a smaller interval.

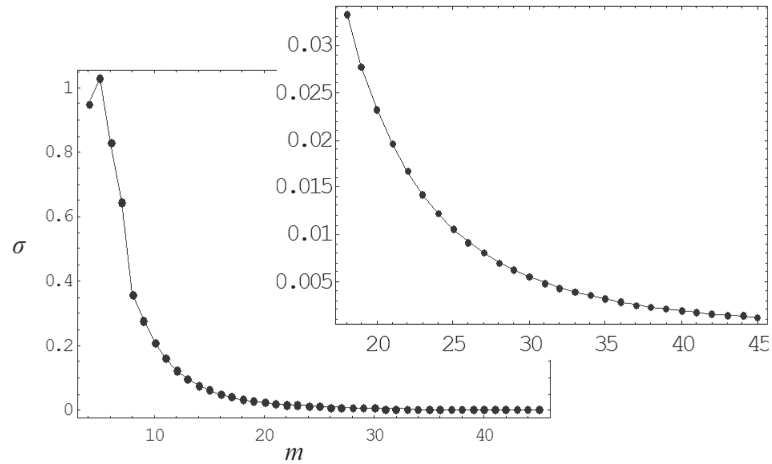
In what follows an approximation based of noisy sampled data is studied. Figure 5 shows approximations based on 20 sampled values with a noise level of *R*=0.4, for three different effective influence ranges *d*. The impact of *d* on the



d	0.5	0.33	0.25	0.2	0.167	0.143	0.125	0.111
m	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**
ρ	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
σ	**0.21**	**0.061**	**0.023**	**0.011**	**0.0055**	**0.0031**	**0.0019**	**0.0012**

Sl. 3. *Aproksimacija na podlagi vzorčenih vrednosti brez šuma. Izmerki so narisani le za primer z 10 točkami, aproksimacija pa za 10 in 15 točk.*

Fig. 3. *Approximation of sampled values without noise. Measurements are plotted only for the case with 10 sampled values, while the approximation is plotted for 10 and 15 sampled values.*

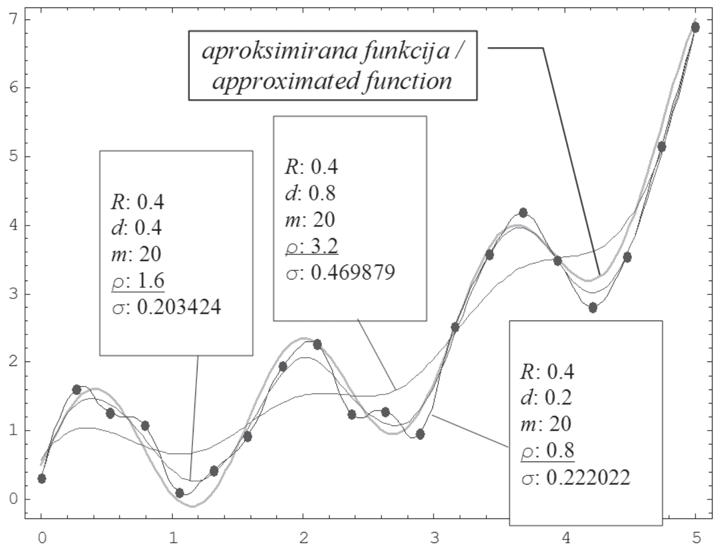


Sl. 4. *Odvisnost napake aproksimacije σ od števila vzorčnih točk za vzorčenje brez šuma in pri stalnem ρ =1,0. Dodan je bolj podroben prikaz pri večjih m.*

Fig. 4. *Dependence of the approximation error σ on the number of sampling points for sampling without noise, at constant ρ =1.0, with a detailed plot for larger m.*

na kakovost aproksimacije. Ko je d prevelik, postanejo izbrane osnovne funkcije nezadostne za aproksimacijo funkcije na območjih velikostnega reda 2d okrog točke izračuna, na katerih vzorčne točke pomembno prispevajo k aproksimaciji (enačbe (11), (12), (13)) Na Sl. 5 se to kaže v preveč zravnani aproksimaciji pri največjem d=0,4, ki ne zmore slediti nihanju aproksimirane funkcije. Ko je d premajhen, se aproksimacija nagiba k

approximation quality is clearly visible. When d is too large, the approximation basis becomes insufficient for adequately approximating the function over intervals of order of magnitude of 2d, on which the sample contributions are significant (consider Equations (10), (11), (12)). In Figure 5 this is reflected in a somehow flattened approximation with the largest d=0.4, which cannot follow the oscillations of the approximated



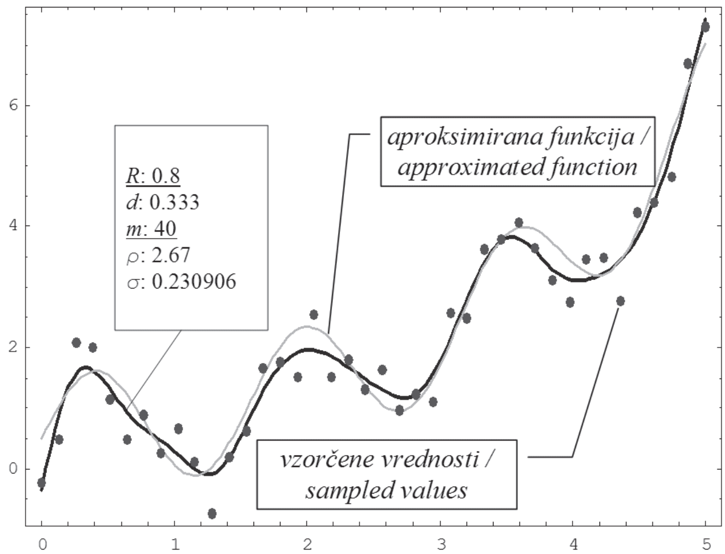
Sl. 5. *Učinek dejanskega dosega vpliva vzorčnih točk na aproksimacijo na osnovi 20 vzorčnih točk s šumom*
Fig. 5. *Impact of the effective influence range of samples on an approximation based on 20 sampled values with noise*

interpolaciji vzorčenih vrednosti in zato sledi tudi naključnim spremembam, ki so posledice šuma.

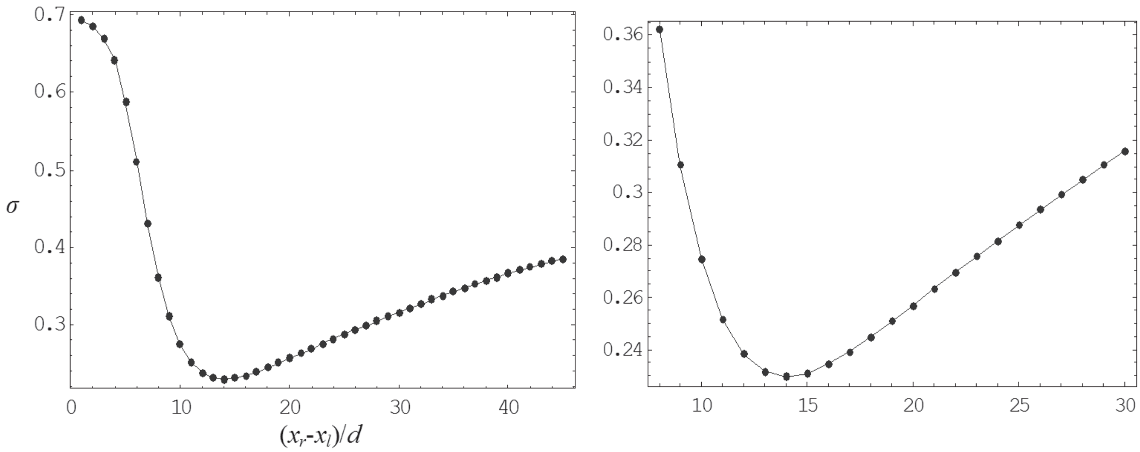
Videti je, da pri dani funkciji, ki jo aproksimiramo, izbranih vzorčnih točkah in določeni ravni šuma obstaja optimalen dejanski doseg, pri katerem je kakovost aproksimacije največja. To je vidno tudi na sliki 7, kjer je prikazana odvisnost mere za napako aproksimacije σ od

function. In contrast, when d is too small, the approximation tends to interpolate the sampled data and therefore follows the spurious fluctuations caused by the random noise.

It seems obvious that for a given approximated function, sampling points and level of noise, there exists an optimal effective range for which the approximation quality is the best. This is



Sl. 6. *Aproksimacija na osnovi 40 vzorčnih točk z višjo ravnijo šuma (R=0,8)*
Fig. 6. A*pproximation based on 40 samples with a larger noise level (R=0.8)*



Sl. 7. *Odvisnost mere za napako aproksimacije σ od obratnega dejanskega dosega za podatke s slike 6 s povečanim detajlom na desni strani slike*

Fig. 7. *Dependence of the error measure σ on the reciprocal effective influence range for data from Figure 6, with enlarged detail on the right-hand side*

količine, ki je obratno sorazmerna z *d*. Graf se nanaša na višjo raven šuma (*R*=0,8) in število vzorčnih točk (*m*=40). Za vsako točko grafa so uporabljene iste vzorčene vrednosti. Praviloma bi morali vrednosti na grafu povprečiti po več naključnih izidih vzorčenih vrednostih. Graf bi v tem primeru vseboval naključne spremembe, vendar bi bila usmeritev podobna. Sl. 6 prikazuje vzorčene vrednosti uporabljene pri sliki 7 in aproksimacijo na podlagi teh podatkov z dejanskim dosegom *d*, ki je blizu optimalnega.

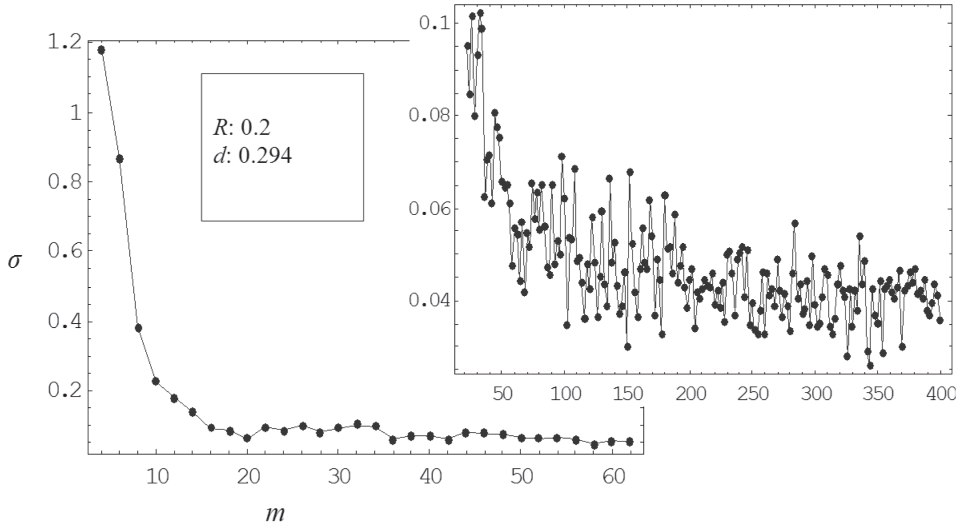
Podobno kakor v primeru brez šuma pričakujemo, da lahko kakovost aproksimacije izboljšujemo z večanjem števila vzorčnih točk *m*. Vendar šum preprečuje neomejeno hitro večanje natančnosti z večanjem *m*. To se zgodi v območju, kjer amplituda šuma doseže podoben velikostni red kot povprečna aproksimacijska napaka v primeru, ko ni šuma. Od tu naprej lahko aproksimacijsko napako še vedno manjšamo z večanjem gostote vzorčenja, vendar je to posledica dejstva, da naključne napake zaradi šuma povprečimo po večjem številu vzorčnih točk, ki jih zajamemo znotraj območja vpliva okrog vsake točke, v kateri izračunamo aproksimacijo.

Opisan učinek je jasno viden na sliki 8, kjer je narisana napaka aproksimacije pri različnih številih vzorčnih točk. Do približno *m*=15 se napaka hitro zmanjšuje z rastočim *m* zarasi zmanjševanja razdalje med točkami. Učinek šuma v tem delu ni izrazit, ker je premajhna količina podatkov poglaviten vir nenatančnosti. Pri večjih *m* je

seen from Figure 7, where the dependence of the error measure σ on reciprocal *d* is plotted. The graph refers to a larger level of noise (*R*=0.8) and number of sampling points (*m*=40). The same sampled data is used for each point in the graph. Otherwise, the values on the graph should be averaged over a number of sampling realizations and the graph would contain random fluctuations, but the trend would be similar. Figure 6 shows the sampled data used in Figure 7 and an approximation of this data with *d* that is close to the optimal value.

Similar to the data without noise, it is expected that the quality of the approximation can be improved by increasing the number of sampling points *m*. However, the noise prevents an unlimited rapid improvement of the approximation accuracy with increasing *m*. This happens at the point where the amplitude of the noise reaches a similar magnitude to the approximation error for the case without noise. From this point on the approximation error can still be reduced by increasing the sampling density, but this is attributed to the fact that the random sampling errors are averaged over a larger number of sampled values, captured within the area of influence around each calculation point.

The effects described above are clearly visible in Figure 8, where the approximation error is plotted for different numbers of sampling points. Up to about *m*=15 the error is rapidly decreasing with growing *m* because of the decreased spacing between the sampling points. The effect of noise is not clearly visible in this regime because insufficient



Sl. 8. *Aproksimacijska napaka v odvisnosti od števila vzorčnih točk pri R=0,2 in z nespremenljivim dejanskim dosegom vpliva d=5/17. Vsaka točka na grafu se nanaša na en sam izid zbiranja vrednosti.*
Fig. 8. *Approximation error dependent on the number of measurements for data for R=0.2 and with a constant effective influence range d=5/17. Each point on the graphs refers to a single realization of the sampled data.*

nadaljnje izboljševanje natančnosti omejeno z naključnimi napakami v podatkih. Aproksimacijske napake se počasi zmanjšujejo s povečevanjem gostote vzorčenja in naključno nihajo zaradi stohastične narave vzorčenja. Na Sl. 8 vsaka točka na grafu predstavlja en sam izid zajemanja podatkov, ki vsebujejo naključne napake. Usmeritev počasnega povprečenja napak pri povečani gostoti vzorčenja je vseeno razvidna, ker je prikazano večje število točk.

data is the main cause of the inaccuracy. At larger *m*, a further increase of accuracy is restricted by the random errors in the sampled data. Approximation errors tend to slowly decrease with the increasing sampling density and fluctuate randomly because of the stochastic nature of the sampling. In Figure 8 each point on the graph corresponds to a single realization of sampled data containing random noise, and the average trend for the error can be observed because of the large number of presented points.

3 PRIMERA UPORABE

3 EXAMPLE APPLICATIONS

3.1 Glajenje meritev pri poskusu

Na sliki 9 je prikazana uporaba aproksimacije po metodi premičnih najmanjših kvadratov pri glajenju signala zaznavala za merjenje temperature. Podatki so iz [5] in so bili uporabljeni za obrnjeno določitev parametrov prestopa toplote in trenja med kovinami z mazanjem iz meritev pri laboratorijskem testu zoževanja traku.

Test je bil simuliran z metodo končnih elementov, iskani modelski parametri pa so bili določeni z minimizacijo mere za odstopanje meritev od simuliranih podatkov, definirane kot:

3.1 Smoothing of the Experimental Measurements

Figure 9 shows the application of the moving least-squares approximation for smoothing the output from a temperature sensor. The data is from [5] and was used for an inverse reconstruction of the heat-transfer and friction parameters between lubricated metals from the measurements performed with the strip-reduction laboratory test.

The laboratory test was simulated using the finite element method and the unknown parameters were obtained by minimizing a measure of the discrepancy between measured and simulated data, defined as:

$$f(\mathbf{p}) = \sum_{i=1}^{n} \int_{t_{\min}}^{t_{\max}} W_i \left(M_i^{(m)}(t) - M_i^{(c)}(\mathbf{p},t) \right)^2 \, dt \qquad (18).$$

V zgornji enačbi i teče po uporabljenih časovno odvisnih merjenih količinah, $M_i^{(m)}(t)$ je ustrezna izmerjena količina (sila na trak ali temperatura v dani točki), $M_i^{(c)}$ je ustrezna količina, izračunana s simulacijo preizkusa pri preizkusnih vrednostih iskanih parametrov, in W_i uteži, izbrane za posamezne vrste meritev.

Ker je bila pri numerični simulaciji uporabljena integracija s prilagodljivim korakom in zaradi merskega šuma (sl. 9) vsebuje funkcija $f(\mathbf{p})$ naključna nihanja, kar preprečuje učinkovito uporabo numeričnih minimizacijskih metod. Ta problem je bil odpravljen z zamenjavo interpoliranih meritev z gladkimi aproksimacijami po metodi premičnih najmanjših kvadratov (nepretrgana črta na Sl. 9). Pri aproksimaciji je bila uporabljena kvadratična onova (15) z utežnimi funkcijami oblike $w_G(r)$ iz (13). Dejanski doseg vpliva je bil postavljen na d = 0,1 s. Na ta način nismo zameglili prehodnih pojavov pri časovnem poteku meritev, hkrati pa je bil vpliv šuma dovolj izravnan (povečan detajl na sliki 9), da smo dobili gladko odzivno funkcijo f, pri kateri smo lahko učinkovito določili minimum.

3.2 Aproksimacija odzivnih funkcij pri optimizaciji

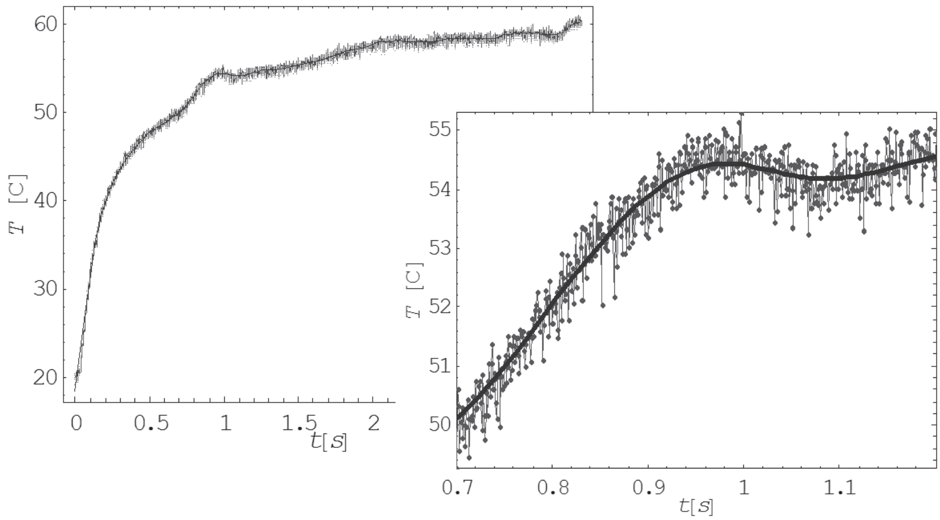
V naslednjem primeru obravnavamo optimizacijo, pri kateri imamo opravka z odzivnimi funkcijami s šumom. Podatki (Sl. 10) so iz [6], kjer smo optimirali širino in višino kanala, ki je izdelan

In the above equation, i runs over the measured quantities, $M_i^{(m)}(t)$ is the corresponding measured quantity (force on the strip or the temperature at a certain point), $M_i^{(c)}$ is the corresponding quantity obtained by the finite-element simulation with the trial values of the searched parameters $\mathbf{p}$ and W_i weights assigned to different kinds of measured data.

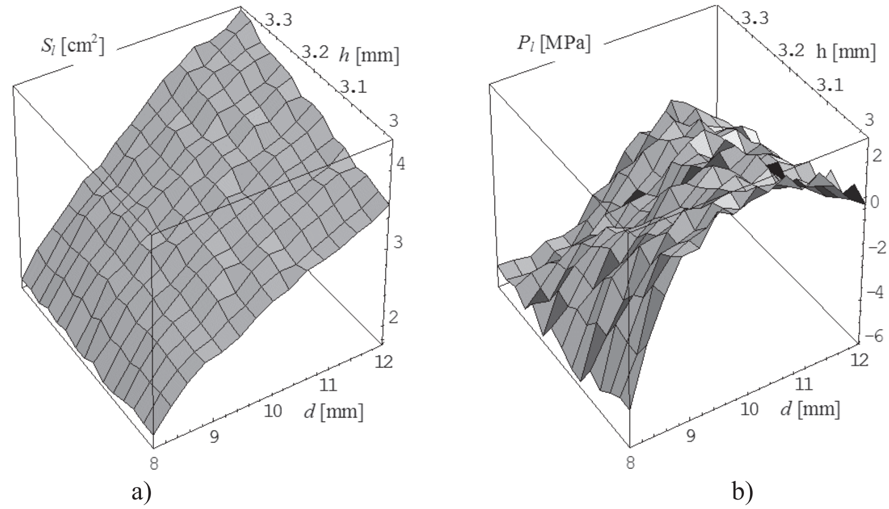
Because an adaptive time-integration scheme was applied in the numerical simulation and due to the measurement noise (Figure 9), the minimized function $f(\mathbf{p})$ contained random oscillations that prevented an efficient numerical minimization. This problem was alleviated by replacing the interpolated measurement data with a smooth moving least-squares approximation (the solid line in Figure 9). A quadratic basis (14) was used with the weighting function $w_G(r)$ from (12). The effective influence range was set to d = 0,1. In this way the transient features of the sensor response were not smeared, while the effect of the noise was sufficiently leveled (the enlarged detail in Figure 9) to obtain a smoothed response function f that could be efficiently minimized.

3.2 Approximation of the Response Functions During Optimization

The next example treats optimization with noisy response functions. The data (Figure 10) is taken from [6], where the width d and the height h of a channel produced by blow forming was



Sl. 9. *Zglajen signal (nepretrgana črta) temperaturnega zaznavala s povečanim detajlom na desni strani*
Fig. 9. *Smoothed data (solid line) from the temperature sensor with enlarged detail on the right-hand side*



Sl. 10. *Namenska (a) in omejitvena funkcija (b) optimizacijskega problema, izračunani z metodo končnih elementov na pravilni mreži 20×20 točk*

Fig. 10. *Objective (a) and constraint function (b) of the optimization problem calculated using a FEM simulation on a regular 20×20grid*

z napihovanjem, z namenom zmanjšati tveganje za nastanek razpok, ki se pojavijo zaradi lokalizacije deformacije. Naloga je bila postavljena kot maksimizacija površine prereza kanala $S_i(d,h)$ (Sl. 10 a)) pri omejitvi, da je tlak $P_i(d,h)$, pri katerem se začne lokalizacija, pod predpisano mejo. Zaradi tehničnih zahtev sta parametra omejena z 8 mm ≤ d ≤ 12 mm in 3 mm ≤ h ≤ 3,4 mm.

Šum v odzivnih funkcijah izvira iz numerične simulacije postopka napihovanja, ki je uporabljena za izračun odzivnih funkcij [6]. Uporabiti je bilo treba prilagodljivo izboljševanje mreže končnih elementov z veliko gostoto elementov v območju lokalizacije, zaradi česar bi bilo težko zmanjšati raven šuma. Da smo lahko poiskali optimalno rešitev, smo najprej izračunali odzivni funkciji v pravilni mreži točk. Dobljene podatke smo zgladili z aproksimacijo po metodi premičnih najmanjših kvadratov z obliko utežnih funkcij $w_G(r)$, dejanskima dosegoma d_1 = 1 mm in d_2 = 0,1 mm v smereh d in h ter kvadratnimi polinomskimi osnovnimi funkcijami:

optimized in order to reduce the risk of localization-induced defects. The task was formulated as a maximization of the channel cross-section $S_i(d,h)$ (Figure 10 a)) using a constraint that the forming pressure $P_i(d,h)$ at which localization occurs (Figure 10 b)) is below some prescribed limit. Due to technical requirements the parameters were limited to 8 mm ≤ d ≤ 12 mm and 3 mm ≤ h ≤ 3,4 mm.

The noise originating from the finite-element numerical simulation of the blow-forming process was applied for the calculation of the response functions [6]. Adaptive mesh refinement with a high mesh density at the localized zone had to be applied, because of which it would be difficult to reduce the level of noise. In order to find the optimal solution, the response functions were first sampled on a regular grid of points. The sampled data was smoothed by the moving least-squares approximation with the weighting function $w_G(r)$, effective ranges d_1 = 1 mm and d_2 = 0,1 mm (corresponding to d and h) and the basis functions:

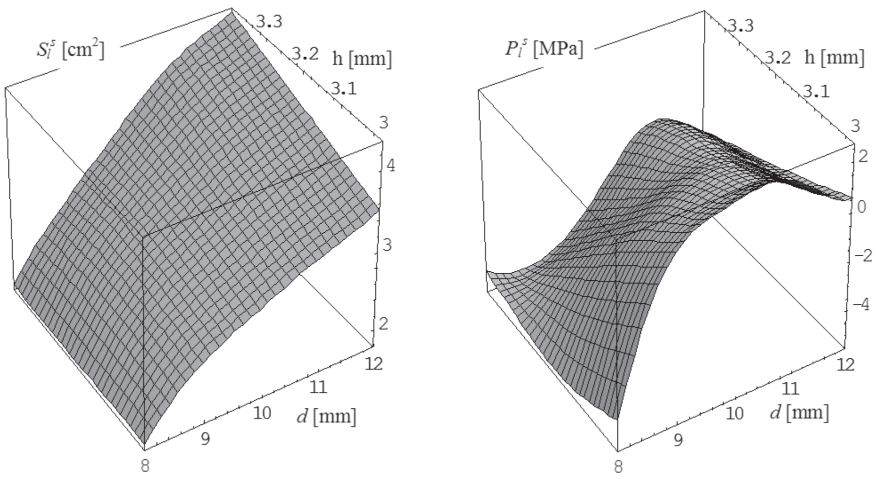
$$f_1(\mathbf{x})=1;\; f_2(\mathbf{x})=x_1;\; f_3(\mathbf{x})=x_2;\; f_4(\mathbf{x})=x_1^{\,2};\; f_5(\mathbf{x})=x_2^{\,2};\; f_6(\mathbf{x})=x_1x_2 \qquad (19),$$

kjer sta $x_1=d$ in $x_2=h$. Aproksimiran odziv je prikazan na sliki11.

V [6] je bil optimizacijski problem rešen z aproksimiranim odzivom z metodo zaporednega kvadratičnega programiranja. Tak postopek je

where $x_1=d$ and $x_2=h$. The approximated response is shown in Figure 11.

In [6] the optimization problem with smooth approximated response functions was solved by a sequential programming algorithm. Such an



c) d)

Sl. 11. *Zglajene odzivne funkcije s slike 10*
Fig. 11. *Smoothed response functions from Figure 10*

neučinkovit, ker zahteva dovolj gosto vzorčenje odziva po celotnem dovoljenem območju v prostoru parametrov. Pri večjem številu parametrov to postane zdaleč prezahtevno.

Zato smo uresničili drugačen iterativen postopek, pri katerem funkcije aproksimiramo krajevno na omejenem območju. V vsaki iteraciji določimo omejeno območje zanimanja. Na podlagi vzorčenih vrednosti odzivnih funkcij, ki smo jih izračunali v trenutni in predhodnih iteracijah, aproksimiramo odzivne funkcije po metodi premičnih najmanjših kvadratov. Ustrezno kakovost aproksimacije želimo doseči le na trenutnem območju zanimanja, kar dosežemo z ustrezno nastavitvijo dejanskega dosega. Nato rešimo optimizacijski problem, pri katerem nadomestimo prvotno namensko in omejitvene funkcije z ustreznimi aproksimacijami in dodamo omejitev koraka, s čimer omejimo možne rešitve na trenutno območje zanimanja. Rešitev tega notranjega optimizacijskega problema postane nov približek za rešitev prvotnega problema in središče področja zanimanja v naslednji iteraciji. Velikost območja povečamo, če leži rešitev na robu območja in zmanjšamo, če leži dovolj vstran od meje. Postopek ponavljamo, dokler ne dosežemo predpisane natančnosti, ali dokler ni več mogoče nadaljnje izboljšanje natančnosti glede na raven šuma.

Konvergenca opisanega algoritma je prikazana na sliki 12. Območja zanimanja in vzorčene vrednosti so prikazane po iteracijah. V

approach is inefficient because it requires a sufficiently dense sampling of the response over the whole allowed range of parameters. If the number of parameters is large, this becomes prohibitively expensive.

A different iterative solution approach was, therefore, designed, where the response approximation is maintained locally in a limited region of interest. For each iteration a restricted region of interest is defined. The response functions are calculated (sampled) at a number of points within the region of interest. Based on the sampled values from the current and previous iterations, the moving least-squares approximations of the response functions are constructed. A good approximation quality is considered only within the current region of interest, which is achieved by appropriately setting the effective range of influence. The optimization problem is then solved, with the original objective and constraint functions being replaced by the approximated ones. The step restriction is also added, which restricts the possible solutions to the current region of interest. The solution of this internal problem becomes the new current guess and the center of the region of interest in the next generation. The size of this region is increased if the solution lies on the edge of the region of interest, and decreased if it lies far enough from the edge. The procedure is repeated until the prescribed accuracy is reached or no further improvement is possible, with respect to the level of numerical noise.

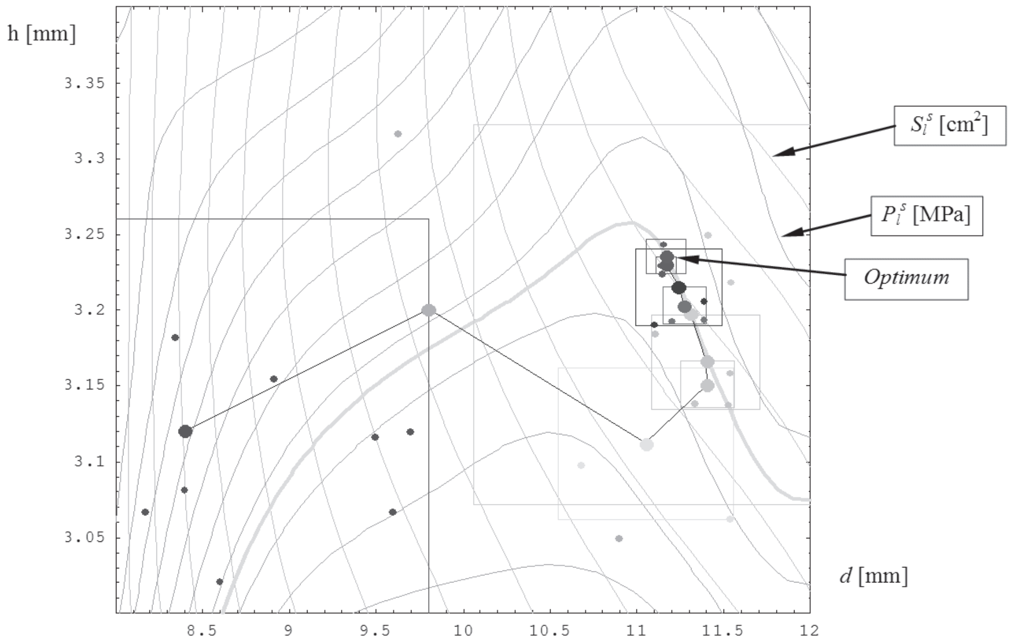
The convergence of the described algorithm is shown in Figure 12. Regions of interest and the sampled values through the iterations are indicated.

prvi iteraciji določi območje zanimanja uporabnik, število vzorčnih točk pa je izbrano tako, da je nekoliko večje od števila baznih funkcij. V naslednjih iteracijah je število novih točk na iteracijo za eno večje od števila parametrov, v našem primeru 3.

Vzorčne točke so naključno izbrane znotraj območja zanimanja. To je mogoče, ker pri metodi premičnih najmanjših kvadratov ni potrebna kakšna posebna razporeditev točk. Treba je omeniti, da so možne numerične težave povezane s slabo pogojenim sistemom enačb (11) za izračun koeficientov aproksimacije. Sistem lahko postane slabo pogojen, če je število vzorčnih točk z znatnimi utežmi premajhno, ali če so točke razporejene na poseben način, tako da so osnovne funkcije na množici točk skoraj linearno odvisne. Prvo možnost lahko učinkovito preprečimo z uporabo utežnih funkcij, ki se ne zmanjšujejo prehitro z naraščajočo razdaljo od vzorčnih točk. Tako ima vedno dovolj točk iz prejšnjih iteracij povsod tam, kjer računamo aproksimacijo, dovolj

For the first iteration the region of interest is defined by the user and the number of samples is chosen in such a way that it is slightly larger than the number of basis functions. In the subsequent iterations, the number of new sampling points per iteration is set to be one more than the number of parameters, i.e., 3.

The sampling points are chosen randomly within the region of interest. This is possible because no particular arrangement of the sampling points is required for the moving least-squares approximation. It must be mentioned that numerical difficulties related to a badly conditioned system of equations for the calculation of approximation coefficients (10) could potentially occur. The system can become badly conditioned if either the number of sampling points with significant weights is insufficient or the points are arranged in a special way such that the basis functions are close to being linearly dependent on the set of points. The first situation is efficiently prevented by using weighting functions that do not decay too rapidly with the distance from the sampling points. In this way enough sampling points from previous iterations will always have large enough



Sl. 12. *Konvergenca optimizacijskega algoritma, ki temelji na zaporednih aproksimacijah odzivnih funkcij. Pravokotniki označujejo območja vzorčenja v zaporednih iteracijah, krožci prikazujejo točke, v katerih so bile izračunane odzivne funkcije, večji krožci pa rešitve aproksimiranih problemov. Za ponazoritev so prikazane tudi obrisi zglajenih odzivnih funkcij (Sl. 10).*

Fig. 12. *Convergence of the optimization algorithm based on successive response approximations. Rectangles denote sampling regions within successive iterations, dots represent points where the response was sampled and larger dots represent the minima of successive approximated problems. The contours of smoothed response (Figure 10) are plotted for orientation.*

velike vrednosti utežnih funkcij, da se izognemo nezadostnosti podatkov. Glede na izkušnje je $w_4(r)$ iz (13) primerna oblika utežnih funkcij. Druga možnost je zelo malo verjetna, kadar uporabljamo naključno vzorčenje, posebej, če je število vzorčnih točk z znatnimi utežmi precej večje od števila osnovnih funkcij.

V predstavljenem primeru smo dobili rešitev v 10 iteracijah, v katerih sta bili odzivni funkciji izračunani v 36 točkah. To je precej bolj učinkovito kakor izvedba optimizacije na aproksimiranem odzivu po celotnem dovoljenem območju. Pri večjem številu parametrov postane razlika v učinkovitosti izrazita in aproksimacija po celotnem območju neizvedljiva.

4 SKLEP

V prispevku je nakazano, da je metoda premičnih najmanjših kvadratov vsestranska in prilagodljiva aproksimacijska metoda, ki je zaradi posebnih značilnosti uporabna pri reševanju številnih praktičnih problemov.

Za aproksimacijo ni potrebna kakšna posebna ureditev vzorčnih točk ali delitev območja aproksimacije. Razmeroma majhno število osnovnih funkcij zadošča za dovolj natančno aproksimacijo gladkih funkcij na poljubno velikem območju. Velikost sistema enačb za določitev koeficientov aproksimacije se ne poveča, če povečamo gostoto vzorčenja, zato pa moramo sistem enačb rešiti posebej v vsaki točki, v kateri izračunamo aproksimacijo. Povečevanje natančnosti z gostejšim vzorčenjem ne prizadene stabilnosti aproksimacije. Metoda je zato sorazmerno bolj učinkovita, kadar je potrebna večja natančnost, aproksimacijo pa je treba izračunati v manjšem številu točk.

Zveznost aproksimacije je odvisna od zveznosti osnovnih in utežnih funkcij. Kadar so oboje gladke, so tudi višji odvodi zvezni. Z uporabo utežnih funkcij, ki se počasneje zmanjšujejo z razdaljo, lahko dosežemo stabilnost metode tudi v primerih, pri katerih ne moremo zagotoviti enakomerne gostote vzorčenja po celotnem območju aproksimacije.

Pri določeni izbiri baznih funkcij se filtrirajo višjefrekvenčne oscilacije glede na dejanski doseg vpliva vzorcev, kar lahko uporabimo za izravnavo vpliva šuma v vzorčenih podatkih. Večji dejanski doseg pomeni boljše glajenje, vendar tudi slabšo zmožnost prilagajanja prehodnim lastnostim

weights at all points of the evaluation in order to prevent data deficiency. Based on experience, $w_4(r)$ from (12) is a suitable form for the weighting function. The second situation is very unlikely when random sampling is used, especially when the number of sampling points with significant influence is considerably larger than the number of basis functions.

In the presented case the algorithm converged in 10 iterations in which 36 evaluations of the response were performed. This is significantly more efficient than performing an optimization of the approximated response over the whole permitted domain. With a large number of parameters, the difference in the efficiency becomes drastic and the approximation over larger domains becomes unfeasible.

4 CONCLUSION

We have shown that the moving least-squares method is a versatile approximation technique suitable for many practical applications because of its distinctive set of features.

No regular grid of points or partition of the domain is necessary. A relatively small number of basis functions can be used for an accurate approximation of smooth functions over arbitrarily large domains. The size of the system of equations for the approximation coefficients is not increased when increasing the sampling density, at the cost that the system must be solved for every evaluation point. The stability of the approximation is not affected when improving the accuracy by increasing the sampling density. The method is therefore relatively more efficient when higher accuracy is required, but the approximation is evaluated fewer times.

The continuity of the approximation depends on the continuity of the basis and weighting functions. When both are smooth, the approximation does not have discontinuous higher derivatives. By using weighting functions with a slower decay, good stability of the method is achieved in cases when a uniform sampling density cannot be ensured over the approximation domain.

For a given set of basis functions, higher-frequency oscillations are filtered, depending on the effective influence range of the samples, which can be used to compensate for the effects of noise in the data. A larger effective range means better smoothing, but also a poorer ability to follow the transient features of the approximated function. By aproksimirane funkcije. S postavitvijo dejanskega dosega na red velikosti razdalje med vzorci ali manj lahko dosežemo približno interpolacijo podatkov. V praksi moramo doseči primeren kompromis med opisanimi učinki z ustrezno nastavitvijo dejanskega dosega glede na raven šuma, gostoto vzorčenja in lastnosti aproksimirane funkcije.

Aproksimacijo po metodi premičnih najmanjših kvadratov lahko preprosto izboljšujemo z dodajanjem vzorčnih točk. Zaradi tega je metoda posebej primerna za uporabo v optimizacijskih postopkih, ki temeljijo na zaporedni aproksimaciji odzivnih funkcij

setting the effective influence range at the order of the spacing between the samples and below, the approximation tends to interpolate the data. In practice, a suitable compromise between these effects must be achieved by appropriately adjusting the effective influence range with respect to the level of noise, sampling density and properties of the approximated function.

The moving least-squares approximation can be easily refined by the addition of new sampling points. This makes it particularly suitable for use in optimization methods with a successive adaptive approximation of the response functions.

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Avtorjev naslov: dr. Igor Grešovnik
Center za računalništvo v
mehaniki kontinuuma - C3M
p.p. 431
1102 Ljubljana
igor@c3m.si

Author's Address: Dr. Igor Grešovnik
Centre for Computational
Continuum Mechanics - C3M
P.O. Box 431
1102 Ljubljana, Slovenia
igor@c3m.si

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Poročila - Reports

Podpis pogodbe o sodelovanju med Mednarodni inštitutom za hlajenje in Strojniškim vestnikom

Spomladi sta na Fakulteti za strojništvo v Ljubljani, na pobudo Mednarodnega inštituta za hlajenje (International Institute of Refrigeration – IIR), direktor inštituta g. Didier Coulomb ter predsednik Izdajateljskega sveta SV in dekan prof. dr. Karl Kuzman podpisala pogodbo o sodelovanju Strojniškega vestnika in IIR.

Delovanje IIR je usmerjeno na področje promoviranja znanj hladilne tehnike na vseh dandanes najpomembnejših področjih, to so shranjevanje živilskih izdelkov, varovanje okolja (zmanjševanje globalnega segrevanja, preprečevanje tanjšanja ozonske plasti itn.) ter razvoj manj razvitih držav. IIR deluje za boljšanje življenjskih razmer in uveljavljanje sonaravnega razvoja.

S pogodbo o sodelovanju bo IIR vključil Strojniški vestnik v svojo bazo preko 300 virov s področja tehnike hlajenja. Baza Fridoc je dostopna vsem članom IIR iz 61 držav članic.

G. Coulomb se je udeležil tudi II. mednarodne konference o magnetnem hlajenju, ki ga je v sodelovanju z IIR organizirala Fakulteta za strojništvo.

Suzana Domjan

Osebne vesti - Personal Events

Doktorata, magisteriji in diplome - Doctor's, Master's and Diploma Degrees

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dne *21. junija 2007*: **Peter Krajnik**, z naslovom: "Načrtovanje sistemskih parametrov procesa brušenja brez konic" (mentorja: prof. dr. Janez Kopač in prof. dr. Alojz Sluga);

dne *28. junija 2007*: **Henri Orbanić**, z naslovom: "Modeliranje makromehanizma rezanja z abrazivnim vodnim curkom" (mentorja: prof. dr. Mihael Junkar in prof. dr. Ivan Bajsić).

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dne *10. julija 2007*: **Jože Torkar**, z naslovom: "Ekonomično vodenje kompleksnih sistemov daljinskega ogrevanja" (mentorja: prof. dr. Alojz Poredoš in prof. dr. Igor Grabec);

dne *31. junija 2007*: **Žiga Judež**, z naslovom: "Načrtovanje procesov v mrežah proizvodnih struktur" (mentorja: prof. dr. Alojz Sluga in prof. dr. Janez Peklenik).

S tem so navedeni kandidati dosegli akademsko stopnjo magistra znanosti.

DIPLOMIRALI SO

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dne *29. junija 2007*: Gašper ANTIČEVIĆ, Denis BIRSA, Igor BRŽAN, Iztok PALČIČ, Sebastjan ŽAGAR;

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*

Na Fakulteti za strojništvo Univerze v Ljubljani so pridobili naziv diplomirani inženir strojništva:

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Na Fakulteti za strojništvo Univerze v Mariboru so pridobili naziv diplomirani inženir strojništva:

dne *30. avgusta 2007*: Janez FERENC, Matej KANCLER, Jernej KERT, Klemen PETRIČ.

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Članki morajo vsebovati:
- naslov, povzetek, besedilo članka in podnaslove slik v slovenskem in angleškem jeziku,
- dvojezične preglednice in slike (diagrami, risbe ali fotografije),
- seznam literature in
- podatke o avtorjih.

Strojniški vestnik izhaja od leta 1992 v dveh jezikih, tj. v slovenščini in angleščini, zato je obvezen prevod v angleščino. Obe besedili morata biti strokovno in jezikovno med seboj usklajeni. Članki naj bodo kratki in naj obsegajo približno 8 strani. Izjemoma so strokovni članki, na željo avtorja, lahko tudi samo v slovenščini, vsebovati pa morajo angleški povzetek.

Za članke iz tujine (v primeru, da so vsi avtorji tujci) morajo prevod v slovenščino priskrbeti avtorji. Prevajanje lahko proti plačilu organizira uredništvo. Če je članek ocenjen kot znanstveni, je lahko objavljen tudi samo v angleščini s slovenskim povzetkom, ki ga pripravi uredništvo.

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Članek naj bo napisan v naslednji obliki:
- Naslov, ki primerno opisuje vsebino članka.
- Povzetek, ki naj bo skrajšana oblika članka in naj ne presega 250 besed. Povzetek mora vsebovati osnove, jedro in cilje raziskave, uporabljeno metodologijo dela,povzetek rezulatov in osnovne sklepe.
- Uvod, v katerem naj bo pregled novejšega stanja in zadostne informacije za razumevanje ter pregled rezultatov dela, predstavljenih v članku.
- Teorija.
- Eksperimentalni del, ki naj vsebuje podatke o postavitvi preskusa in metode, uporabljene pri pridobitvi rezultatov.
- Rezultati, ki naj bodo jasno prikazani, po potrebi v obliki slik in preglednic.
- Razprava, v kateri naj bodo prikazane povezave in posplošitve, uporabljene za pridobitev rezultatov. Prikazana naj bo tudi pomembnost rezultatov in primerjava s poprej objavljenimi deli. (Zaradi narave posameznih raziskav so lahko rezultati in razprava, za jasnost in preprostejše bralčevo razumevanje, združeni v eno poglavje.)
- Sklepi, v katerih naj bo prikazan en ali več sklepov, ki izhajajo iz rezultatov in razprave.
- Literatura, ki mora biti v besedilu oštevilčena zaporedno in označena z oglatimi oklepaji [1] ter na koncu članka zbrana v seznamu literature. Vse opombe naj bodo označene z uporabo dvignjene številke[1].

OBLIKA ČLANKA

Besedilo članka naj bo pripravljeno v urejevalnilku Microsoft Word. Članek nam dostavite v elektronski obliki.

Ne uporabljajte urejevalnika LaTeX, saj program, s katerim pripravljamo Strojniški vestnik, ne uporablja njegovega formata.

Enačbe naj bodo v besedilu postavljene v ločene vrstice in na desnem robu označene s tekočo številko v okroglih oklepajih

Papers submitted for publication should comprise:
- Title, Abstract, Main Body of Text and Figure Captions in Slovene and English,
- Bilingual Tables and Figures (graphs, drawings or photographs),
- List of references and
- Information about the authors.

Since 1992, the Journal of Mechanical Engineering has been published bilingually, in Slovenian and English. The two texts must be compatible both in terms of technical content and language. Papers should be as short as possible and should on average comprise 8 pages. In exceptional cases, at the request of the authors, speciality papers may be written only in Slovene, but must include an English abstract.

For papers from abroad (in case that none of authors is Slovene) authors should provide Slovenian translation. Translation could be organised by editorial, but the authors have to pay for it. If the paper is reviewed as scientific, it can be published only in English language with Slovenian abstract, that is prepared by the editorial board.

THE FORMAT OF THE PAPER

The paper should be written in the following format:
- A Title, which adequately describes the content of the paper.
- An Abstract, which should be viewed as a mini version of the paper and should not exceed 250 words. The Abstract should state the principal objectives and the scope of the investigation, the methodology employed, summarize the results and state the principal conclusions.
- An Introduction, which should provide a review of recent literature and sufficient background information to allow the results of the paper to be understood and evaluated.
- A Theory
- An Experimental section, which should provide details of the experimental set-up and the methods used for obtaining the results.
- A Results section, which should clearly and concisely present the data using figures and tables where appropriate.
- A Discussion section, which should describe the relationships and generalisations shown by the results and discuss the significance of the results making comparisons with previously published work. (Because of the nature of some studies it may be appropriate to combine the Results and Discussion sections into a single section to improve the clarity and make it easier for the reader.)
- Conclusions, which should present one or more conclusions that have been drawn from the results and subsequent discussion.
- References, which must be numbered consecutively in the text using square brackets [1] and collected together in a reference list at the end of the paper. Any footnotes should be indicated by the use of a superscript[1].

THE LAYOUT OF THE TEXT

Texts should be written in Microsoft Word format. Paper must be submitted in electronic version.

Do not use a LaTeX text editor, since this is not compatible with the publishing procedure of the Journal of Mechanical Engineering.

Equations should be on a separate line in the main body of the text and marked on the right-hand side of the page with numbers in round brackets.

Enote in okrajšave

V besedilu, preglednicah in slikah uporabljajte le standardne označbe in okrajšave SI. Simbole fizikalnih veličin v besedilu pišite poševno (kurzivno), (npr. *v, T, n* itn.). Simbole enot, ki sestojijo iz črk, pa pokončno (npr. ms^{-1}, K, min, mm itn.).

Vse okrajšave naj bodo, ko se prvič pojavijo, napisane v celoti v slovenskem jeziku, npr. časovno spremenljiva geometrija (ČSG).

Slike

Slike morajo biti zaporedno oštevilčene in označene, v besedilu in podnaslovu, kot sl. 1, sl. 2 itn. Posnete naj bodo v ločljivosti, primerni za tisk, v kateremkoli od razširjenih formatov, npr. BMP, JPG, GIF. Diagrami in risbe morajo biti pripravljeni v vektorskem formatu, npr. CDR, AI.

Pri označevanju osi v diagramih, kadar je le mogoče, uporabite označbe veličin (npr. *t, v, m* itn.), da ni potrebno dvojezično označevanje. V diagramih z več krivuljami, mora biti vsaka krivulja označena. Pomen oznake mora biti pojasnjen v podnapisu slike.

Vse označbe na slikah morajo biti dvojezične.

Preglednice

Preglednice morajo biti zaporedno oštevilčene in označene, v besedilu in podnaslovu, kot preglednica 1, preglednica 2 itn. V preglednicah ne uporabljajte izpisanih imen veličin, ampak samo ustrezne simbole, da se izognemo dvojezični podvojitvi imen. K fizikalnim veličinam, npr. *t* (pisano poševno), pripišite enote (pisano pokončno) v novo vrsto brez oklepajev.

Vsi podnaslovi preglednic morajo biti dvojezični.

Seznam literature

Vsa literatura mora biti navedena v seznamu na koncu članka v prikazani obliki po vrsti za revije, zbornike in knjige:

[1] A. Wagner, I. Bajsić, M. Fajdiga (2004) Measurement of the surface-temperature field in a fog lamp using resistance-based temperature detectors, *Stroj. vestn.* 2(2004), pp. 72-79.
[2] Vesenjak, M., Ren Z. (2003) Dinamična simulacija deformiranja cestne varnostne ograje pri naletu vozila. *Kuhljevi dnevi '03*, Zreče, 25.-26. september 2003.
[3] Muhs, D. et al. (2003) Roloff/Matek Maschinenelemente – Tabellen, 16. Auflage. *Vieweg Verlag*, Wiesbaden.

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Uredništvo Strojniškega vestnika si pridržuje pravico do odločanja o sprejemu članka za objavo, strokovno oceno recenzentov in morebitnem predlogu za krajšanje ali izpopolnitev ter terminološke in jezikovne korekture.

Avtor mora predložiti pisno izjavo, da je besedilo njegovo izvirno delo in ni bilo v dani obliki še nikjer objavljeno. Z objavo preidejo avtorske pravice na Strojniški vestnik. Pri morebitnih kasnejših objavah mora biti SV naveden kot vir.

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Avtorji vseh prispevkov morajo za objavo plačati prispevek v višini 20,00 EUR na stiskano stran prispevka. Prispevek se zaračuna po sprejemu članka za objavo na seji Uredniškega odbora.

Units and abbreviations

Only standard SI symbols and abbreviations should be used in the text, tables and figures. Symbols for physical quantities in the text should be written in italics (e.g. *v, T, n,* etc.). Symbols for units that consist of letters should be in plain text (e.g. ms^{-1}, K, min, mm, etc.).

All abbreviations should be spelt out in full on first appearance, e.g., variable time geometry (VTG).

Figures

Figures must be cited in consecutive numerical order in the text and referred to in both the text and the caption as Fig. 1, Fig. 2, etc. Pictures may be saved in resolution good enough for printing in any common format, e.g. BMP, GIF, JPG. However, graphs and line drawings sholud be prepared as vector images, e.g. CDR, AI.

When labelling axes, physical quantities, e.g. *t, v, m,* etc. should be used whenever possible to minimise the need to label the axes in two languages. Multi-curve graphs should have individual curves marked with a symbol, the meaning of the symbol should be explained in the figure caption.

All figure captions must be bilingual.

Tables

Tables must be cited in consecutive numerical order in the text and referred to in both the text and the caption as Table 1, Table 2, etc. The use of names for quantities in tables should be avoided if possible: corresponding symbols are preferred to minimise the need to use both Slovenian and English names. In addition to the physical quantity, e.g. *t* (in italics), units (normal text), should be added in new line without brackets.

All table captions must be bilingual.

The list of references

References should be collected at the end of the paper in the following styles for journals, proceedings and books, respectively:

[1] A. Wagner, I. Bajsić, M. Fajdiga (2004) Measurement of the surface-temperature field in a fog lamp using resistance-based temperature detectors, *Stroj. vestn.* 2(2004), pp. 72-79.
[2] Vesenjak, M., Ren Z. (2003) Dinamična simulacija deformiranja cestne varnostne ograje pri naletu vozila. *Kuhljevi dnevi '03*, Zreče, 25.-26. september 2003.
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