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# Razvoj programskega orodja za izbiro obrisnih postopkov rezanja

## The Development of a Software Tool for the Selection of Contour-Cutting Processes

**Davorin Kramar - Miha Junkar**

*Prispevek opisuje programsko opremo za izbiro izdelovalnega postopka pri načrtovanju posameznega strojnega dela. Predstavljen je sistematični postopek izbire za določeno izdelovalno opravilo – obrisno rezanje. Razviti računalniški program uporablja splošne podatke o zmožnostih postopkov in v postopek izbire vključuje postopkovne in stroškovne modele.*

*Obdelovalnost določenega materiala je utemeljena na razmerju med obnašanjem materiala obdelovanca med obdelavo in po njej in nastavljenimi postopokovnimi parameteri. Prepleteni vplivi so podani v obliki empiričnih pravil, izpeljanih s prilagajanjem funkcij na specifične materialno-postopkovne podatkovne krivulje. V naši študiji so bili tako pridobljeni empirični modeli uporabljeni za razločevanje postopkovnih zmožnosti in optimalno soizbiro materiala in postopka. Zaradi velikega obsega postopkovnih parametrov izbira optimalnega skupka parametrov ponuja možnost občutnega prihranka stroškov izdelave. Rezultati podajajo tehnologu in konstrukterju povratno informacijo o zmožnosti obdelave in stroških izdelave za določeno konstrukcijo kakor tudi napotke za poskusne postopkovne parametre.*

**(Ključne besede: postopki rezanja, izbor postopkov, rezanje obodno, orodja programska, razvoj orodij)**

*This paper describes software for the selection of a manufacturing process in the design of a single mechanical part. A systematic selection procedure for a specific manufacturing task – contour cutting – is presented. The developed software uses general data on process capabilities and incorporates process and cost modeling into the selection procedure.*

*The machinability of a certain material is established by the relationships between the behaviour of a workpiece material during and after processing and by the preset process parameters. Complex interactions are interpreted in the sense of empirical rules derived from experimental and specific, material-process, database curve fits. In our study such empirical models were used for discriminating between processing options, for optimum co-selection of materials and processes. Since many processing parameters are involved, selection of an optimum set of parameters offers the opportunity for a significant cost saving. The results provide the technologist and the designer with feedback on the likely influence of processing, on the viability and cost of design, as well as indicating trial processing parameters.*

**(Keywords: cutting processes, proces selection, contour cutting, software tools, software development)**

## 0 UVOD

Ključni izziv, ne samo za tehnologa, ampak tudi za konstrukterja, ostaja uporaba ustrezne tehnologije za določeno izdelovalno opravilo. Za izbiro najboljših kandidatov postopkov je bistvena določitev odločitvenega kriterija. Zahteva razumljivo in zanesljivo tehnološko informacijo, s katero lahko učinkovito izvajamo načrtovanje za izdelavo (NZI - DFM) [1]. Veliko dejavnikov npr.: material, geometrijska oblika, tolerance, celovitost površine in stroški, vpliva na izbiro postopka. Pri obravnavi drugačnih konstrukcijskih rešitev z vidika kakovosti in stroškov je treba raziskati še

## 0 INTRODUCTION

Applying the appropriate technology to a specific manufacturing task remains the basic challenge not only for the technologist but also for the designer. The definition of the decision criteria for the selection of the best process candidates is therefore crucial. It requires comprehensible and reliable technological information, according to which the design for manufacturing (DFM) can be efficiently implemented [1]. There are many factors affecting process selection, these include: material, geometry, tolerances, surface integrity, and costs. In considering alternative design solutions for quality and cost, it is necessary to explore druge možnosti materialov, geometrijskih oblik in toleranc itn. ter mogoče izdelovalne postopke. To zahteva izbiro ustreznega postopka prek vseh možnosti in oceno stroškov izdelave že v fazi razvoja izdelka.

Veliko podjetij običajno sledi zaporednemu razvoju izdelka. Tu izdelovalna vprašanja sledijo konstrukcijskim korakom brez povratne informacije, tako vpliv potencialno slabega načrtovanja na stroške izdelka ni prepoznaven.

Stroške izdelka sestavljajo stroški načrtovanja, stroški izdelave, stroški, povezani z jamstvom in stroški inženirske rekonstrukcije. Načelo NZI pomaga odpravljati rekonstrukcije in stroškovne pasti. Cilj je zmanjšati stroške, potrebne za izdelavo ter izpopolniti in olajšati način izdelave. Tipično načrtovanje prispeva približno 10% celotnih stroškov izdelka, vendar določa 80% izdelovalnih stroškov. Vzrok je v tem, da konstrukcijska raven določa glavne stroškovne postavke: material in izdelavo. Zato ni pomembno, kako ustvarjalni so tehnologi in vodje proizvodnje, saj ne morejo vplivati na stroške izdelave izdelka za več ko 20%. Del dejavnosti NZI je tudi izbira in določevanje ustreznosti materiala in postopka ([2] in [3]).

Konstrukter torej potrebuje sistematično pot za ocenjevanje primernosti različnih materialov in izdelovalnih možnosti. Večina akademskega dela s področja izbire za inženirsko konstruiranje je osredotočena na izbiro materialov [4], medtem ko je delo na izbiri izdelovalnih postopkov manj razvito – posebno na konstrukcijski ravni, oblikovanje [5]. Predpostavimo lahko, da je na tej stopnji konstruiranja večina zahtev primerno določena za izbiro med tehnično izvedljivimi in stroškovno učinkovitimi možnostmi iz ustreznega skupka postopkov in materialov [6]. Ta niz določa dano izdelovalno opravilo.

V prispevku najprej pojasnjujemo problem izbire postopka in opisujemo splošen postopek izbire, na ravni konstruiranja za izdelovalno opravilo, ko so material in postopkovna opravila do določene mere že določeni. Cilj je sistematično identificirati zahteve konstrukcije in zmožnosti postopkov. Najznačilnejše značilnosti postopkov so največkrat specifične za določen razred postopkov.

Izbirni postopek na podlagi izdelovalnega opravila je bil uporabljen na razred obrisnih postopkov rezanja. Na tem mestu je konstrukcija (oblika) v glavnem določena, predpostavimo, da je izbran tudi določen material, tako je problem izbire predvsem kateri postopek uporabiti. Omenjena skupina postopkov vsebuje nekonvencionalne postopke, namreč: rezanje z abrazivnim vodnim curkom (RAVC - AWJ), rezanje z laserjem $CO_2$, plazemsko rezanje (PzR - PAC), plamensko rezanje (PlR - OFC) in rezanje z žično erozijo (RŽE - WEDM). Njihove tehnološke in ekonomske

candidate materials, geometry, tolerances etc., against possible manufacturing routes. This requires some means of selecting the appropriate processes and estimating the costs of manufacture early on in the product-development stage, across the whole range of options.

Traditionally, many companies followed the sequential approach, to product development. In this approach manufacturing issues follow the design steps without information feedback, so the impact of potentially poor design on product cost is not recognized.

The product cost includes the design cost, the manufacturing cost, expenses associated with product warranties and engineering redesign costs. The DFM principle helps to avoid these redesign and cost pitfalls. Its goal is to reduce the costs required to manufacture a product and improve the ease whit which the product can be made. Typically, design accounts for approximately 10% of the whole product cost, but determinates 80% of the manufacturing costs. The reason is that the design stage is decisive in terms of the main cost constituents: material and manufacturing. Therefore, no matter how creative the manufacturing engineers and the production managers are, they cannot influence the manufacturing costs of the product by more than 20%. Part of DFM is also related to material and process selection and suitability ([2] and [3]).

A designer then needs a systematic way of assessing the various materials and manufacturing options available. Most of the academic work carried out in the field of selection for engineering design has focused on materials [4], the work on processes is less well developed, particularly at the embodiment stage of the design [5]. At this stage of the design, it may be assumed that most of the requirements have been sufficiently well defined for selection between the technically viable and the cost-effective options from an appropriate subset of processes and materials [6]. This set will define a given manufacturing task.

In our paper we first state the problem of process selection and describe a general process selection procedure at the task level in design, when the material and processing operations have, to some extent, already been defined. The goal is to identify systematically the requirements of the design and the capabilities of the processes. The most discriminating characteristics of processes are often specific to the particular class of processes.

The task-based selection procedure was applied to the class of contour-cutting processes. Here the design (shape) is essentially fixed, and we assume that the specific material has been selected, so the selection problem is primarily one of choosing which process to use. This group of processes contains nonconventional processes such as abrasive water-jet cutting (AWJ), $CO_2$ laser cutting, plasma-arc cutting (PAC), oxygen flame cutting (OFC) and wire electric-discharge machining (WEDM). Their technological and economic information characterise informacije karakterizirajo lastnosti izdelovalnih postopkov, ki jih uporabljamo za obdelavo različnih kovinskih in nekovinskih materialov.

V nadaljevanju sledi opis tehnoloških in ekonomskih podatkov. Določeni so kot odločilni cilji izdelovanega dela za izbrane izdelovalne alternative. Stroškovna analiza in optimizacija stroškov sta pogosto tolmačena različno, tako v različnih, kot tudi znotraj iste organizacije. Poslovne perspekive bi morale upoštevati alternativne investicije, davčne politike, priložnostne stroške in v svoji najboljši verziji tudi prilagodljivost. Prilagodljivost je težko količinsko ovrednotiti, pa vendar je včasih prav ta najpomembnejša pri investiciji v prilagodljivo avtomatsko opremo, kakor je sistem za RAVC ali laserski sistem.

Glavni namen te raziskave je prikazati podporo specifičnih postopkovnih in stroškovnih modelov pri izbirnih pravilih, ki upoštevajo izdelovalne omejitve ob različnih obnašajnih postopkov in njihovo ekonomično učinkovitost pri vodenju izbire. Odločitev o izbiri postopka postane zelo zapletena naloga, saj se pri izbiri srečujemo z različnimi cilji, na voljo pa imamo mnogo alternativ. Enostavnost empiričnih modelov z zadovoljivo natančnostjo rezultatov je tako pomembna pri soočenju s to nalogo.

## 1 IZBIRA POSTOPKA

Med izbiro materiala in izbiro izdelovalnega postopka obstaja razlika v lastnostih zahtev. Konstrukcijski vidiki prevladujejo pri prvotni izbiri materiala, po drugi strani pa je izbira postopka že v zgodnji fazi z veliko večjo širino gnana z izdelovalnimi in ekonomskimi vidiki [7]. Neodvisno od uporabljene metode za reševanje problema izbire postopka, bo postopek vedno odvisen od stopnje, dosežene v postopku načrtovanja. Tri glavne stopnje inženirskega konstruiranja, zasnova (preliminarna), oblikovanje (vmesna) in podrobnost (končna stopja), določajo raven podrobnosti, potrebnih za izbiro [6]. V nasprotju z ustaljenim načrtovanjem izdelave, je osnovni cilj sočasnega inženirstva obravnavanje

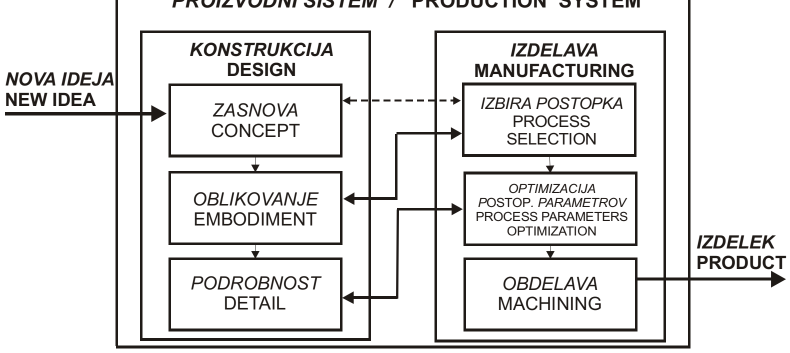
the performance of the machining processes used in the manufacturing of several different metal and nonmetal materials.

Later on come the descriptions of the technological and economic data. They are defined as crucial objectives of the manufactured part for the selected machining alternatives. Cost analysis and cost optimisation are often interpreted differently by various organizations, and sometimes differently within the same organization. The business perspective should take into account alternative investment, tax policies, opportunity costs and its most refined versions for flexibility. While flexibility is the hardest to evaluate in hard numbers, it is also sometimes the most beneficial in terms of investment in flexible automation equipment like, AWJ or laser systems.

The main aim of this research is to present the benefit of specific process and cost modeling in selection rules, taking into account manufacturing restrictions due to the performances of different processes and their economic efficiency. Since there are many objectives we should meet and many alternatives available, the decision on process selection becomes a very complex task. Simplicity with sufficient accuracy of empirical models and their results is therefore important for confronting this task.

## 1 PROCESS SELECTION

There is a difference in the nature of the requirements for material selection and process selection. The initial selection of a material tends to be dominated by the design aspects, whereas the selection of the process, even at an early stage, is driven to a much larger extent by the manufacturing and economics aspects [7]. Independent of the method used to address this problem of process selection, the approach taken will have to depend on the stage reached in the design process. The three main stages in the engineering design process – conceptual (preliminary), embodiment (intermediate) and detail (final) – determinate the degree of detail required for selection [6]. In contrast to traditional production planning the primary goal of



Sl. 1. *Sočasno načrtovanje proizvodnje [3]*
Fig. 1. *Concurrent production planning [3]*

izdelave pri konstruiranju v čim bolj zgodnji fazi (sl. 1).

V začetni stopnji konstruiranja, ko je določeno le malo konstrukcijskih in materialnih podrobnosti, imajo vsi izdelovalni postopki enako možnost obravnave. To je v primeru preliminarne izbire postopka [5]. Stopnja detajlov z napredovanjem konstruiranja se zvečuje, število ustreznih postopkov pa se zmanjšuje na manjše skupine ali družine postopkov, ki določajo izdelovalni način oz. ‘opravilo’. Razumljivo je, da noben izbirni postopek nikoli ne bo zmožen upoštevati raznolikosti vseh izdelovalnih opravil. V naši raziskavi smo sledili splošnemu postopku na podlagi izdelovalnega opravila, ki jo predlagata Lowatt in Shercliff [8].

## 2 IZBIRNI POSTOPEK NA PODLAGI OPRAVILA

Obdelava podrobnosti za raven izbire na podlagi opravila je v primerjavi s preliminarno izbiro bolj industrijsko usmerjena. Večina akademskega dela s področja izbire postopka je osredotočena na tehnike preliminarne izbire za uporabo na ravni zasnove konstrukcije ([4] in [5]). Za izbiro na podlagi opravila so potrebni bolj osredotočeni postopki za izboljšanje izbire, potem ko so nekatere podrobnosti že določene. Taki postopki nameravajo dopolniti bolj splošne preliminarne metode izbire, s tem da so bolj osredotočeni na podrobnosti specifičnega opravila, brez omejitve po potrebi, da bi bile splošno uporabne. Na tej ravni podrobnosti postane vedno bolj pomembno upoštevati povezave in funkcionalne odvisnosti med lastnostmi materiala, postopkovnimi parameteri in obnašanjem. Potem ko je področje problema izbire določeno, postane vhodni podatek za izbiro niza zahtev. Določitev zahtev je zaporedni postopek, ki sloni na obsežnem znanju o družini postopkov, ki jih obsega določeno izdelovalno opravilo. Postopki in njihove zmožnosti so z namenom, da jih primerjamo z zahtevami konstrukcije opisani s procesnimi prilastki. V primeru preliminarne izbire so prilastki splošni za vse postopke in vrednosti oz. območja izvedljivih postopkovnih razmer [5]. Prilastki pri izbiri na podlagi opravil ne potrebujejo predefiniranih vrednosti in enoličnosti za vse postopke. Obstajajo trije tipi postopkovnih prilastkov, ki vsebujejo različno zapletenost pri hranjenju podatkov:

1. *posamezne vrednosti* npr. združljivost z materialom;
2. *območja*, ki določajo najmanjšo in največjo teoretično možno vrednost in so neodvisna od preostalih prilastkov, npr. debelina materiala, ki jo lahko režemo;
3. *funkcije*, ki prikazujejo odvisnost med različnimi prilastki postopka, npr. rezalna hitrost za dani material je odvisna od debeline, uporabljene moči in v določenih primerih tudi od kakovosti in

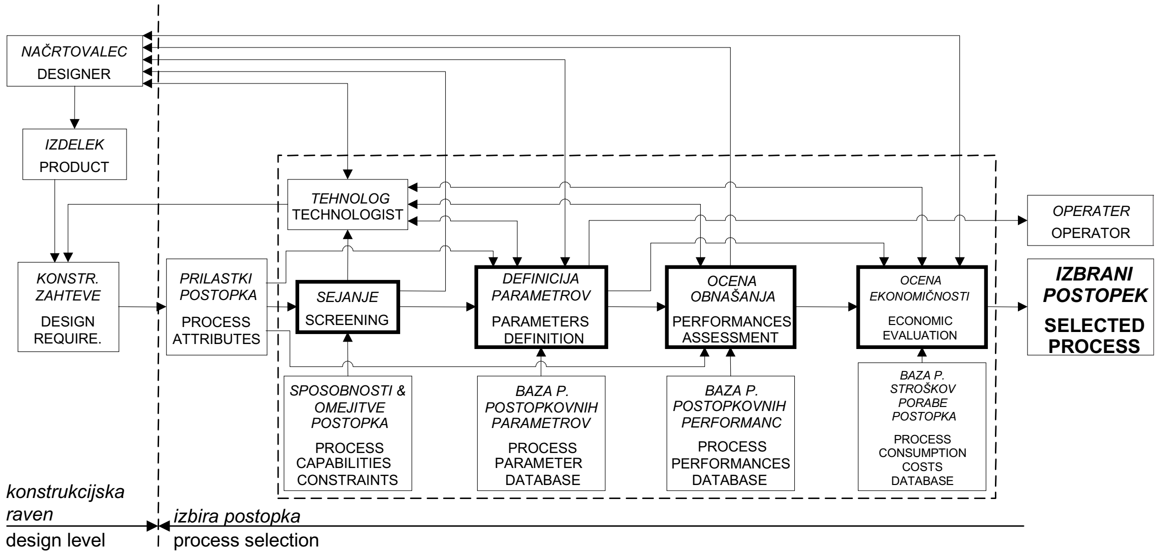
concurrent engineering is to consider manufacturing at as early stage of the design as possible (Fig. 1).

At the beginning of the design process, when little design and material detail has been fixed, all processes have an equal right to be considered. That is the case of preliminary process selection [5]. As the design proceeds, the level of detail increases but suitable processes decrease to smaller groups or families of processes, which define a manufacturing method or ‘task’. It is clear that no single selection procedure will ever be able to take all the diversity of the manufacturing tasks into account. In our investigation we have followed the general task-based selection procedure proposed by Lowatt and Shercliff [8].

## 2 A TASK-BASED SELECTION PROCEDURE

Work at a task-based level of detail tends to be more industrially oriented than that of preliminary selection. Much of the academic work on process selection has focused on preliminary selection techniques for use at the concept stages of design ([4] and [5]). For task-based selection, more focused approaches are required to improve selection once some details have been fixed. Such approaches and procedures are intended to supplement the more general preliminary selection methods, by being more focused on task-specific details, without the constraint of needing to be generally applicable. At this level of detail it becomes increasingly important to consider the correlations and functional dependences between material properties, process parameters and performances. Once the scope of the selection problem has been defined, the inputs to the selection will be a set of requirements. The determination of requirements will be an iterative procedure and it relies on the extensive knowledge of a group of processes that encompass a specific manufacturing task. A process and its capabilities are to be compared to the design requirements described by the process attributes. In the case of preliminary selection, the attributes are universal for all processes and consist of values or ranges for the viable processing conditions [5]. In task-based selection, attributes do not need to take a pre-determined value, and do not need to be the same for all processes. There are three types of process parameters, each implying a different level of complexity in data storage:

1. *single values*, e.g. material compatibility;
2. *ranges*, which define minimum and maximum theoretically possible values and are independent of other attributes, e.g. thickness of the material that can be cut;
3. *functions*, which show correlations between the various process attributes, e.g. cutting velocity for a given material depends on thickness, power used and in some cases also the quality and performance that is required by the design. These



Sl. 2. *Splošna shema izbirnega postopka na podlagi opravila*
Fig. 2. *General scheme of task-based selection procedure*

obnašanja, ki jo zahteva konstrukcija. Te funkcije so navadno predstavljene v obliki postopkovnih modelov. Tip prilastka, ki ga uporabimo, je odvisen od stopnje v izbirnem postopku.

Slika 2 prikazuje splošno shemo izbirnega postopka. Na načrtovalni ravni, načrtovalec skonstruira izdelek z vsemi konstrukcijskimi zahtevami. Te so vstopni podatek za izbiro postopka in se primerjajo s prilastki posameznega postopka. Prva stopnja postopka izbire postopka se imenuje *sejanje*. Cilj te stopnje je izločiti kombinacije material/zahteve konstrukcije/postopek, ki očitno niso mogoče. Na tej ravni je izbira na podlagi prilastkov navadno izvedena z uporabo prilastkov z določenim območjem. Sejanje se lahko izvede za vse konstrukcijske zahteve na nizki ravni podrobnosti. Enostavno sklaplanje med prilastki in zahtevami je lahko izvedeno s primerjavo parameterov posamezno ali v parih [9]. Baza podatkov je lahko organizirana običajno, kakor so preglednice podatkov in/ali različna tehnološka okna, ki so lahko preprosto spremenjena v pogojna pravila za dodatno računalniško podprto sejanje. Rezultat te stopnje izbire je niz postopkov, ki so zmožni izdelave izdelka iz določenega materiala po konstrukcijskih zahtevah. Ta informacija potuje na naslednjo stopnjo izbire, lahko pa je uporabna tudi za tehnologa in konstrukterja. Z zmanjšanjem zahtev in zamenjavo materiala lahko najdeta boljšo rešitev za konstrukcijo izdelka, kar lahko vključuje manj potratne izdelovalne postopke.

Ustrezne kombinacije postopek/material in zahteve konstrukcije so preračunane v naslednji stopnji izbirnega postopka, namreč *definiciji parameterov*. Ta potencialni niz še vedno lahko vsebuje postopke, ki ne morejo izoblikovati izdelka. Eden glavnih vzrokov za to je soodvisnost med

functions are usually presented in the form of process models. The type of attribute we should utilize depends on the stage in the selection procedure.

Figure 2 shows the general scheme of the selection procedure. In the design level the designer constructs the product with all the design requirements. They are the input data for the process selection procedure and are compared to each of the process attributes. The first stage of the selection process procedure is called *screening*. The aim of this stage is to eliminate the material/design requirements/process combinations that are clearly not viable. At this level, attribute-based selection using range-type attributes is usually performed. Screening can take place for all the design requirements at a low level of detail. Simple coupling between the attributes and the requirements can be captured by one-to-one matching or paired-parameter matching [9]. The database may be organised conventionally, such as in the form of data sheets and/or different technological windows, which can be easily transformed into *if-then* rules for additional computer-based screening. The result of this selection stage is a set of processes that are able to manufacture a product out of a certain material under its design requirements. This information passes to the subsequent stage of selection, but could also be useful for the technologist and the designer. They can find a better solution for the design of the product by requirements reduction and material swap, which may incorporate less expensive manufacturing processes.

The viable combinations of process/material and the design requirements are calculated in the next stage of selection procedure: *parameters definition*. This potential set may still contain processes that cannot physically form the product. One of the main reasons for this is the correlation zahtevami in prilastki – na primer, s $CO_2$ laserjem je mogoče rezati 5mm debelo aluminijasto pločevino z visoko sposobnostjo, toda potrebujemo vsaj 3 kW laser. Uporabimo lahko tudi nižje moči, vendar bo sposobnost povzročena z drugo nastavitvijo parameterov in uporabljenim rezalnim plinom (kisikom namesto dušika), neustrezna. Rezultat tega je, da moramo uporabiti zapleteno združevanje prilastkov [9]. Povezave in funkcijske odvisnosti med spremenljivkami postopka in lastnostmi materiala so podane v modelih postopka. Prednost postopka na podlagi opravila z uporabo modelov je v tem, da lahko izbira poda smernice tudi operaterju v obliki ustreznih razmer za možne postopke. Tehnolog prav tako lahko sodeluje s spremembo predefiniranih nastavitev parameterov na stvarne, tj. nastavitve na lastnih izdelovalnih sistemih ali na sistemih kooperantov.

Stopnja *ocene obnašanja* omogoča, da ocenimo, ali so zahteve obnašanja izdelka lahko dosežene z uporabo nastavitev parametrov iz prejšne stopnje. Preračunavanje interakcij med postopkovnimi spremenljivkami/materialom in inženirskim obnašanjem vsebuje uporabo modelov na enaki ravni podrobnosti kakor pri *definiciji parameterov*. Tako lahko to stopnjo, z uporabo istih modelov za obe stopnji, združimo s stopnjo *definicija parameterov*. Z uporabo ‘hypertext’ postopka lahko vključimo še dodatne informacije. Pri tem so mišljeni razni predlogi v tekstovni obliki za specifične postopkovne razmere.

Ti izdelovalni parameteri lahko pomagajo pri določevanju ekonomskih parameterov (rezalna hitrost, operativni potroški itn.) za naslednjo *oceno ekonomičnosti*. Kalkulacija stroškov izdelave mora na tej ravni podrobnosti vsebovati investicijske, operativne in stroške režije. Prispevek posamezne skupine stroškov k celotnim izdelovalnim stroškom je lahko vgrajen v stroškovne modele. Taki modeli lahko vsebujejo poskusne izdelovalne parametere, nastale med prejšno stopnjo.

Če hočemo doseči končni cilj, zmanjšanje stroškov, moramo tehnološko možne postopke oceniti tudi glede na ekonomsko ustreznost. Končno odločitev in izbiro med možnimi postopki je moč izvesti s primerjavo med izračunanimi izdelovalnimi stroški na kos ali na meter reza za vsako trojico material/zahteve/postopek.

## 3 PREDLAGAN POSTOPEK

Metodologija na podlagi opravila je bila uporabljena na postopkih obrisnega rezanja, ki so našteti zgoraj. Ključna vprašanja za take tehnologije so: “Kako hitro lahko režem, katere parametere naj uporabim in kakšni bodo stroški za dani material in debelino?” Odgovore na ta vprašanja lahko najdemo z uporabo prej omenjenega izbirnega postopka.

between the requirements and the attributes. For instance, with a $CO_2$ laser it is possible to cut 5–mm-thick aluminium plate in a high–performance process, but at least a 3-kW laser is needed. A lower power could be used, but the performance resulting from the different parameters and cutting gas (oxygen instead of nitrogen), would be insufficient. As a result, complex attribute coupling [9] should be applied. Correlations and functional dependencies between process variables and material properties are interpreted in process models. A benefit of a task-based approach using models is that selection may also give some guide to the operator by giving the relevant processing conditions for the viable processes. The technologist could also cooperate by changing the predefined parameter settings to the real ones that of the in-house, or that of the cooperator manufacturing systems.

At the stage of *performance assessment* it becomes feasible to assess whether the performance requirements for the product can be achieved using the parameters setting from the previous stage. Accounting interactions between process variables/material and engineering performance involve the use of models in a similar manner to that detailed for *parameter definition*. It is clear that this stage may be incorporated in a previous *parameter-definition* stage by using the same models for both stages. The inclusion of extra information can be done using a hypertext approach. This means suggestions in the text form for specific process conditions.

These production parameters may help to determine the economic parameters (cutting speed, operation consumables, etc.) for a subsequent *cost evaluation*. The calculation of costs for the processing operation should, at this level of detail, include investment, operational and overhead costs. The contribution of an individual group of costs to the total manufacturing costs can be built into cost models. Such models may include the trial production parameters generated during the previous stage.

To achieve the ultimate aim of minimising cost, technically viable processes must also be assessed for economic viability. The final decision and selection from among possible processes could be done by making a comparison between calculated manufacturing costs per part or per meter of cutting for each material/requirements/process trinity.

## 3 PROPOSED APPROACH

A task-based methodology was applied to the contour cutting processes listed above. Key questions for such technologies are: “for a given thickness and material, how fast can I cut, what it will cost and which parameters should I use?” The answers to these questions could be foud by utilizing the aforementioned selection procedure. The

Postopek je bil razvit v uporabniku prijazno programsko izbirno orodje – ‘Cutting Master’ (*CM*). Ko je enkrat področje problema izbire določeno, predstavlja niz zahtev vhodnih podatkov postopka izbire. Zahteve v primeru obrisnega rezanja so večinoma vezane na konstrukcijo in so lahko določene iz določil, ki jih lahko najdemo na inženirskih risbah, to so oblika, izdelovalne tolerance in kakovost obdelane površine.

### 3.1Prilastki postopka

Določiti moramo posebne prilastke postopka, ki karakterizerajo zmožnosti in obnašanja postopkov obrisnega rezanja. Prilastki postopka so različni in odvisni od stopnje v izbirnem postopku. Zahteve materiala in konstrukcije se na stopnji sejanja primerjajo s konstrukcijsko naravnanimi prilastki postopka. Ti prilastki navadno obsegajo geometrične prilastke, ki vodijo do glavnih dejavnikov, ki določajo, ali je izdelek ne glede na podrobnosti obnašanja moč izdelati. V nadaljevanju so na stopnjah definicija parameterov ocena obnašanja in ocena ekonomičnosti izdelave uporabljeni le-tem sorodni prilastki. Ti prilastki pomagajo odgovoriti na vprašanja o praktičnosti in obnašanju ter tudi ekonomičnosti postopka.

### 3.2 Sejanje

Prilastki postopka za sejalno stopnjo izbirnega postopka so določeni na podlagi osnovnega znanja o konturnih rezalnih tehnologijah.

Energijski žarek ali curek je značilen za vse obrisne rezalne postopke z izjemo RŽE; tako lahko pričakujemo koničen rez. V primerjavi s hladnim mehanskim postopkom namreč RAVC, ostali toplotni postopki (PlR, PzR, lasersko rezanje in RŽE) povzročajo toplotno prizadeto cono (toplotno vplivana cona TVC - HAZ). Glede na izdelovalne tolerance sta PlR in PzR za dekado manj natančna kot RAVC in lasersko rezanje, pri rezanju električno prevodnih kovin pa je RŽE desetkrat bolj natančno od prej omenjena postopka.

Območje materialov, ki jih lahko režemo z laserjem je zelo široko. V tem pogledu je boljši rezalni način RAVC, vendar je postopek navadno veliko počasnejši pri rezanju materialov na območju debelin, kjer postopka tekmujeta. RAVC je primerno za materiale, kjer je laser neučinkovit (odbojni ali debelejši materiali).

PlR se največkrat uporablja za razrez konstrukcijskih jekel, vendar s tem postopkom režemo tudi nekaj drugih eksotermično-oksidnih kovin. PlR ni primerno za uporabo, kjer se mora rezalni postopek hitro ustaviti in ponovno startati; plamen in curek kisika namreč ne moremo enostavno prižigati in ugašati in rez vsakič začeti v sredini pločevine z

procedure has been developed as a user-friendly software-selection tool called ‘Cutting Master’ (*CM*). Once the scope of the selection problem has been defined, the inputs to the selection procedure will be a set of requirements. The equirements in the case of contour cutting are mostly design-related and could be determined from the specifications that might be found on the engineering drawings, such as shape, manufacturing tolerances and surface finish.

### 3.1 Process attributes

Specific process attributes that characterize the abilities and performances of contour-cutting processes need to be defined. The process attributes are different and depend on the stage in the selection procedure. At the initial screening stage, the material and the design requirements are compared with design-related process attributes. In general, these attributes encompass geometric attributes governing the major factors that determine whether the product can be made, irrespective of performance details. Later on in stage of defining the process *parameters*, *performance assessment* and *economic evaluation,* and manufacturing related attributes are used. These attributes help to answer questions about both the practicalities and the performance, and also about the economics of the process.

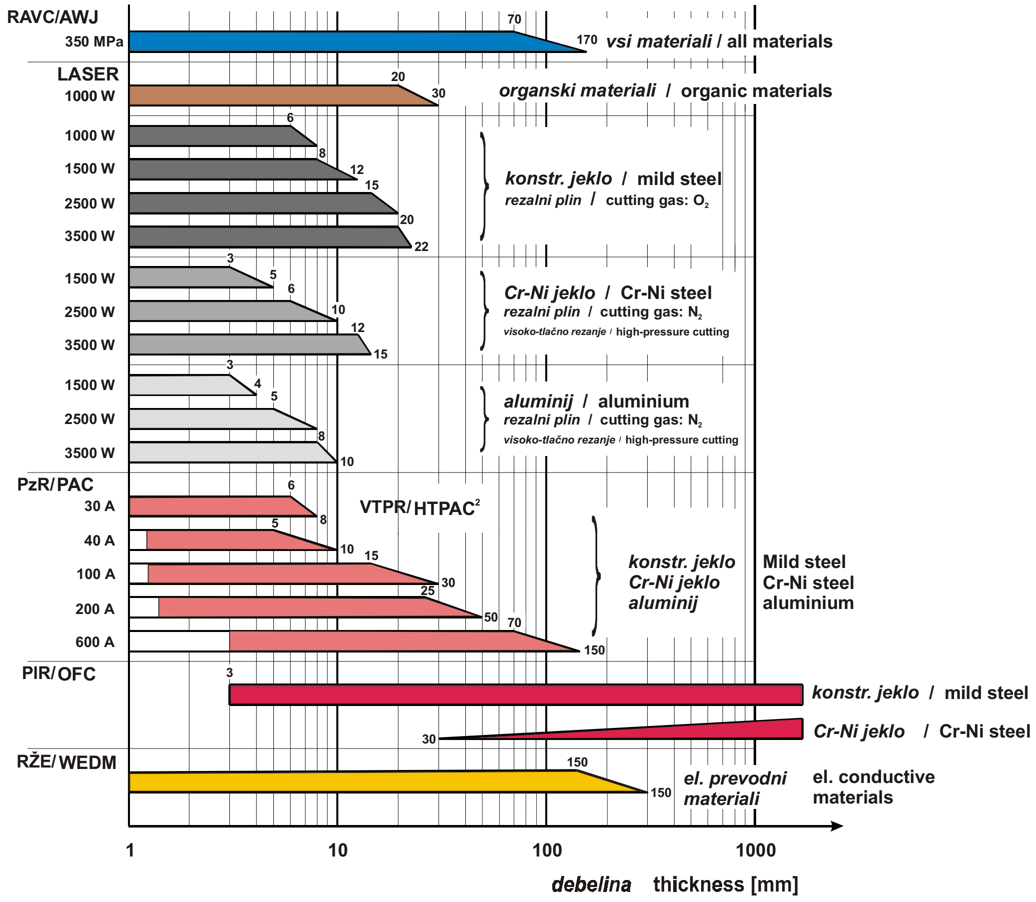
### 3.2 Screening

The process attributes for the screening stage of the selection procedure are determined from basic knowledge of the contour-cutting technologies.

An energetic beam or jet is characteristic for all the contour-cutting processes, except for WEDM; so a tapered form of kerf should be expected. As distinguished from cold mechanical process, namely AWJ cutting, the three other thermal processes (OFC, PAC, laser cutting) produce a heat-affected zone (Heat Affected Zone - HAZ). When considering manufacturing tolerances OFC and PAC are, by a factor of ten, less precise than AWJ and laser cutting, and WEDM is a factor of ten more precise than the latter for cutting electrically conducting metals.

The range of materials that can be cut by laser is very wide. In this respect the only superior cutting method is AWJ, but the process is generally much slower for cutting materials in the range of thicknesses where the two compete. AWJ cutting is appropriate for materials where a laser is inefficient (reflective or thicker materials).

OFC is most commonly used for mild steel, but some other exothermically oxidising metals can be cut as well. OFC does not lend itself to applications where the cutting process must be repeatedly stopped and restarted; the flame and oxygen jet cannot be rapidly turned on and off with ease and must be initiated at a cut in the middle of the sheet by blowing



Sl. 3. *Območja uporabe obrisnih rezalnih postopkov za različne materiale*
Fig. 3. *Applicable ranges of contour cutting processes for variety of materials*

izpihanjem luknje iz nje, kar povzroča eksplozijski izmet kovine in časovno zakasnitev prebijanja.

Plazemsko rezanje je visoko učinkovit grobi postopek za razrez električno prevodnih kovin. Na razpolago je veliko različnih kombinacij plazemskih in zaščitnih plinov, ki jih lahko uporabimo z namenom, da izboljšamo rezalno obnašanje na različnih kovinskih materialih in uporabah. Natančnost rezanja in kakovost površine reza ne tekmuje z laserskim rezanjem pri pločevinastem materialu in materialu v tankih ploščah. S tem namenom je razvito novo ti. visoko tolerančno plazemsko rezanje VTPR (HTPAC). Ta postopek daje ‘lasersko’ kakovost reza na tanjših materialih (do 10 mm) pri manjših rezalnih hitrostih.

Slika 3 prikazuje pregled uporabnih območij analiziranih rezalnih postopkov. Pri pregledovanju diagrama lahko opazimo, da so laserski parametri in obnašanje močno odvisni od materiala, ki ga režemo. Po drugi strani parametri rezanja z AVC ostanejo enaki za širok spekter materialov.

Upoštevanje vseh teh podrobnosti in splošnih značilnosti obrisnih rezalnih postopkov omogoča definicijo prilastkov postopkov za prvo stopnjo pri izbiri postopka, namreč *sejanje*. Ti prilastki so vezani na konstrukcijo in material, saj vsak mate-

a hole in it, which results in the explosive ejection of metal and also in a time delay for piercing.

Plasma cutting is highly-effective rough-cutting process for electrically conductive metals. There are many different plasma-and shield-gas combinations available, which can be used to enhance the cut performance for different metal materials and applications. The cutting accuracy and surface quality cannot compete with laser cutting for sheet and thin-plate materials. In efforts to compete the new High Tolerance Plasma Arc Cutting - HTPAC process has been developed. This process produces a “laser” cut quality on thinner materials (up to 10 mm) at lower cutting speeds.

Figure 3 represents an overview of the applicable ranges of the analyzed cutting processes. When examining the diagram, it is clear that the laser parameters and the performance strongly depend on the material being cut. On the other hand, AWJ cutting parameters remain the same for a wide range of materials.

Capturing all these details and the general characteristics of a contour-cutting process enables definition of process attributes for the first step of the process selection, i.e. screening. These attributes are design and material related, since each material

rial določa specifično obnašanje postopka [8]. Predlagali smo niz prilastkov, ki so značilni za obravnavano skupino postopkov:

- Material; določa združljivost postopka.
- Debelina; obdelovalna območja za določeno kombinacijo material/postopek.
- IT tolerančni razred; zmožnost postopka, ki združuje izdelovalno natančnost in hrapavost površine.
- TVC; vsi toplotni postopki dajejo TVC, vendar je količina (širina) odvisna od kombinacije materiala in uporabljenega postopka; RAVC je netoplotni postopek.
- Kot reza; koničnost je karakteristična za to skupino postopkov (z izjemo RŽE), ker 'rezalni curek-žarek' izgublja energijo med prodiranjem v obdelovanec.
- Najmanjši polmer na obrisu; je določen s širino 'rezalnega curka-žarka' oz. premer žice v primeru RŽE.
- Najmanjši premer izvrtine; odvisen je od načina prebijanja.
- Širina reza; določa zmožnost gnezdenja izrezov.
- Širina mostiča; skupaj s širino reza določa zmožnost rezanja mrežastih izdelkov.

Postopkovna podatkovna baza *CM* vsebuje zapise za 8 inženirskih materialov, ki se navadno obdelujejo s temi postopki, z dokumentiranjem njihovih obdelovalnosti v obliki prilastkov postopkov. Preglednica 1 prikazuje značilen zapis baze podatkov za primer rezanja konstrukcijskega jekla. Podatki vsebujejo vrednosti za zgoraj navedene

defines a specific process performance [8]. We have proposed a set of attributes, which are typical for the group of processes under consideration:

- Material; defines the process compatibility.
- Thickness; the ranges of processability for a certain material/process combination.
- IT tolerance class; the ability of a process that incorporates the production accuracy and the surface roughness.
- HAZ; all thermal processes produce a HAZ, but the quantity depends on a combination of the material and the process used; AWJ is non-thermal process.
- Kerf angle; the taper is characteristic for this group of processes (excluding WEDM), since the 'cutting beam' loses its energy when penetrating the workpiece.
- Minimum on-contour radius; is defined by the 'cutting beam' diameter or by the wire diameter in the case of WEDM.
- Minimum hole diameter; depends on the piercing method.
- Width of cut; defines the capability of the process for worpiece nesting.
- Section rate; together with the width of cut defines the ability of processing netlike products.

The *CM* process database contains records for eight engineering materials that are commonly processed with such processes, documenting their manufacturability in terms of process attributes. Table 1 shows a typical database record for the case of mild-steel cutting. The data consist of values for the above described stated process attributes on different thickness ranges. Much of these values, in other words,

Preglednica 1. *Tehnološke karakteristike obrisnih rezalnih postopkov za primer rezanja konstrukcijskega jekla*
Table 1. *Technological characteristics of contour-cutting processes for the case of mild-steel cutting*

| **Material: konstr. jeklo Mild Steel** | **RAVC/AWJ** | **LASER** | **PlR/OFC** | **PzR/PAC** | **RŽE/WEDM** |
|---|---|---|---|---|---|
| debelina / thickness $t$ mm | 150 | 20 | $5< t<150$ | 100 | 150 |
| IT tolerančni razred<br>IT tolerance class | 12 | 11 | 16 | 16 | 6 |
| TVC/HAZ<br>mm | 0 | 0,05$t$ | 0,1+0,05$t$; $t<20$<br>0,75+0,015$t$; $t>20$ | 0,3$t$; $t<20$<br>0,6$t$; $t\geq20$ | 0,02 |
| kot reza - koničnost<br>kerf angle - 'taper'<br>mm | 0,05; $t\leq10$<br>0,1; $10< t<20$<br>0,05+0,0025$t$; $t>20$ | 0,05+0,0025$t$ | 0,1+0,015$t$; $t<10$<br>0,6+0,05$t$; $t>10$ | 0,25+0,025$t$; $t<5$<br>0,6+0,05$t$; $t\geq5$ | 0,001 |
| najm. polmer na obrisni $r$<br>min. on-contour radius $r$<br>mm | 0,5; $t\leq15$<br>1; $t>15$ | 0,5; $t\leq12$<br>1; $t>12$ | 1; $t<20$<br>2; $t\geq20$ | 1,5; $t<20$<br>2,5; $t\geq20$ | 0,15 |
| najm. premer izvrtine $\phi$<br>min. hole diameter $\phi$<br>mm | 1,2; $t<10$<br>2; $10\leq t\leq30$<br>3; $t>30$ | 0,5$t$ | 15; $t<20$<br>20; $t\geq20$ | 10; $t<20$<br>20; $t\geq20$ | 0,2 |
| širina reza $w$<br>width of cut $w$<br>mm | 1,2; $t<20$<br>1,5; $20\leq t<40$<br>2; $t40$ | 0,2; $t<5$<br>0,35; $5\leq t<10$<br>0,55; $t>10$ | 1,06+0,035$t$ | 2; $t<20$<br>4,5; $20\leq t<40$<br>5,5; $t>40$ | 0,25; $t<60$<br>0,3; $t\geq60$ |
| širina mostička $m$<br>section rate $m$ mm | 1; $t<20$<br>2; $t>20$ | 1 | 6; $t<20$<br>10; $t>20$ | 6; $t<20$<br>10; $t>20$ | 1 |

prilastke postopka za različen razpon debelin. Večina teh vrednosti je z drugimi besedami odvisna od debeline obdelovanca *t*. Baza podatkov je plod obsežne raziskave in praktičnega dela s področja obrisnih rezalnih postopkov v Laboratoriju za alternativne tehnologije na Univerzi v Ljubljani. Preostali materiali, ki jih vsebuje baza *CM*, so orodna in nerjavna jekla, aluminij, baker kot kovine in akrilno steklo, najlon in vezana plošča kot nekovine. Za vse je bila izdelana enaka preglednica, ki lahko rabi kot popolni vir informacij za prvi korak izbire postopka.

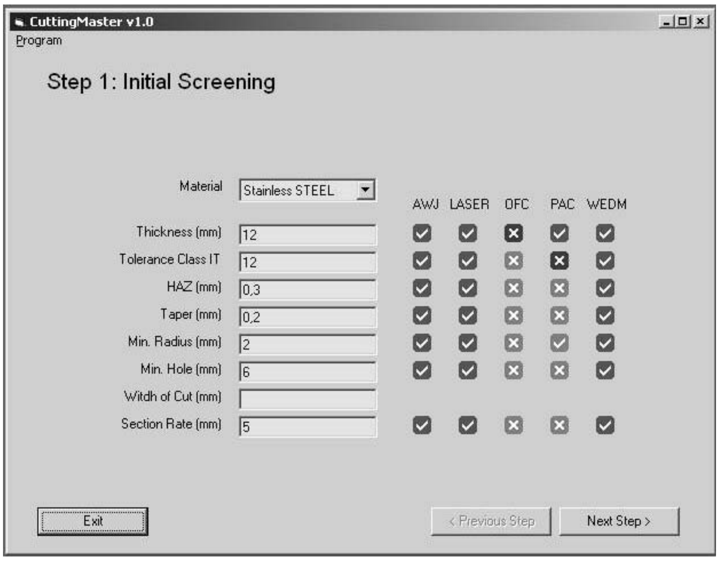
Podatki iz teh preglednic so uporabljeni v obliki pogojnih pravil v računalniško podprto *sejanje*. Slika 4 prikazuje uporabniški vmesnik za to stopnjo izbirnega postopka. Uporabnik izbere material izmed 8 predefiniranih, vnese zahteve konstrukcije in po vsakem vnosu dobi informacije o združljivosti postopka. Računalniški program omogoča iteracijo z zniževanjem zahtev, tako vidimo, kje so meje določenega postopka. Prav tako lahko enostavno primerjamo obdelovalnost različnih materialov pod enakimi konstrukcijskimi zahtevami.

Slika 4 prikazuje primer rezanja 12 mm debelega nerjavnega jekla. Rezanje z AVC, laserjem in RŽE so ustrezni postopki za izdelavo pod zahtevami, določenimi na tak način (*IT razred* 12, *TVC*=0,3mm itn.). PlR je izločeno zaradi nezdružljivosti z materialom, PzR pa je izločeno zaradi previsoko zahtevanega tolerančnega razreda. Naslednji korak v izbirnem postopku sledi za preostale kandidate.

depend upon the workpiece thickness *t*. The database is the result of extensive research and practical work in the Laboratory for Alternative Technologies at the University of Ljubljana in the field of contour-cutting techniques. Other materials included in the *CM* database are tool stel, stainless steel, aluminium, coeper as well as nonmetals such as acrylic glass, nylon and plywood. For each of these materials the same datasheet was formed, which could serve as a complete source of information for the first step of process selection.

The data from such tables are implemented in the form of '*if-then*' rules into the computer-aided screening. Fig. 4 shows a userinterface for this stage of the selection procedure. The user chooses a material from the eight predefined materials, enters the design requirements, and after each requirement is entered, obtains information about the processes compatibilities. The software enables iteration by decreasing the requirements to see where the limits of a certain process are. The machinability of different materials under the same design requirements can also be easily compared.

Figure 4 shows that in the case of 12-mm-thick stainless-steel cutting, AWJ, laser and WEDM are appropriate processes for manufacturing under the requirements defined in such a manner (*IT class* 12 *HAZ*=0.3mm etc.). The OFC is excluded because of material non-compatibility and PAC is excluded because the requested tolerance class is too high. The next step in the selection procedure is applied to the other remaining process candidates.



Step 1: Initial Screening

Material: Stainless STEEL

| | | AWJ | LASER | OFC | PAC | WEDM |
|---|---|---|---|---|---|---|
| Thickness (mm) | 12 | ☑ | ☑ | ☒ | ☑ | ☑ |
| Tolerance Class IT | 12 | ☑ | ☑ | ✗ | ☒ | ☑ |
| HAZ (mm) | 0,3 | ☑ | ☑ | ✗ | ✗ | ☑ |
| Taper (mm) | 0,2 | ☑ | ☑ | ✗ | ✗ | ☑ |
| Min. Radius (mm) | 2 | ☑ | ☑ | ✗ | ✓ | ☑ |
| Min. Hole (mm) | 6 | ☑ | ☑ | ✗ | ✗ | ☑ |
| Witdh of Cut (mm) | | | | | | |
| Section Rate (mm) | 5 | ☑ | ☑ | ✗ | ✗ | ☑ |

Simboli, uporabljeni v komunikacijskem oknu:

- ☑ postopek je primeren za izdelavo pod takimi konstrukcijskimi zahtevami;
- ☒ postopek ne bo izpolnil konstrukcijskh zahtev;
- ✓ postopek je načeloma ustrezen, vendar je izločen zaradi nesposobnosti pri prejšnji zahtevi;
- ✗ zahteva je previsoka, obenem pa je proces neustrezen že pri predhodnih zahtevah.

Symbols used in dialog screen:

- ☑ process is relevant for manufacturing under such a design requirement;
- ☒ process will not meet the design requirement;
- ✓ process is otherwise appropriate, but is eliminated because it does not meet the preceding requirement;
- ✗ requirement is too high, but the process is insufficient based on preceding requirements.

Sl. 4. *Primer CM komunikacijskega okna za stopnjo izbirnega postopka - sejanje*
Fig. 4. *Example of the CM dialog screen for the selection procedure stage - initial screening*

### 3.3 Definicija parametrov in ocena obnašanja

Predlagamo združitev obeh naslednjih stopenj izbirnega postopka: *'definicija parametrov'* in *'ocena obnašanja'*, saj baza podatkov za obe stopnji vsebuje iste prilastke postopka. Na tej stopnji so prilastki vezani na izdelavo, saj določajo obnašanje postopka v določenih razmerah. To omogoča veliko večje razlikovanje, poleg tega pa podaja pomembne informacije za oceno ekonomičnosti (npr. rezalna hitrost) in navaja ustrezne razmere za poskuse. Vrednosti prilastkov so določene z odvisnostmi med številnimi veličinami v obliki modelov postopkov.

#### *3.3.1 Modeli postopkov*

Modeliranje naj bi zmanjšalo število neodvisnih spremenljivk ali vsaj pokazalo, kako se združujejo in variirajo. To je pomemben korak, ki omogoča zmožnost napovedovanja in naj bi bil osnovni cilj vsake dejavnosti modeliranja. Enostavnost je odločilna pri izbiri postopka. Izogibati se moramo izkoriščanju surove računalniške moči. Modeliranje se ponuja kot močno orodje za razlikovanje med postopkovnimi možnostmi na ravni natančnosti, ki je potrebna za izpolnitev zahtev konstrukcije [9].

Takoj postane jasno, da za vse obravnavane postopke z enim modelom ne moremo odgovoriti tej zahtevi. Potrebna je uporaba različnih postopkovnih parametrov in modelov, ker vsak postopek deluje po povsem drugačnih fizikalnih načelih. V primeru rezanja z AVC smo uporabili postopkovni model, ki je znan iz študij in prakse na področju visokotlačne rezalne tehnike. Drugačen način gradnje izkustvenih modelov smo uprabili za toplotne postopke. Modeli so bili izpeljani z metodo prilagajanja funkcije krivulji rezanja. Metoda se opira na obsežno tehnološko bazo podatkov. Podatki vsebujejo vrednosti za rezalne hitrosti pri ravnem rezu za različne nastavitve postopkovnih parametrov (moč, rezalni plin, premer žice itn.), pri rezanju 8 predefiniranih materialov. Bazo podatkov za vse toplotne postopke rezanja smo zgradili na podlagi različnih virov, kot so baze podatkov lastnih praktičnih študij, veliko baz podatkov za operaterje, medmrežje itn. Obe metodi gradnje postopkovnih modelov sta predstavljeni na primeru RAVC in laserskega rezanja.

**Modeliranje rezanja z AVC**

Različni raziskovalci so predstavili modele za napovedovanje globine reza in hitrosti rezanja. Izhajali smo iz modela Zenga in Kima [10]. Utemeljen je na približku testnih podatkov za določitev vplivnih stalnic v enačbi modeliranja rezalnega postopka z namenom oblikovati razsežnostna

### 3.3 Definition of the parameters and performance assessment

Since the database for the definition of the parameters and the performance assessment stage consists of the same process attributes, we propose to incorporate both stages of selection procedure. At this stage the attributes are manufacturing-related, since they determine the process performance under defined conditions. This enables much greater discrimination, along with providing important information for estimating the process economics (i.e. cutting speed) and indicating suitable conditions for trials. The attribute values are determined by a relationship between many quantities in the form of process models.

#### *3.3.1 Process modeling*

Modeling should reduce the number of independent variables, or at least identify how they couple and vary. This is an essential step in providing the predictive capability, which should be the ultimate purpose of any modeling activity. Simplicity is crucial for the process selection, and the trap of unnecessarily trying to exploit raw computing power should be avoided. Modeling provides a powerful tool for discriminating between processing options at the level of precision needed to answer the design requirements [9].

It quickly becomes apparent that one model cannot be used to address this requirement for all the processes under consideration. As the processes each use different physical mechanisms, different process parameters and models need to be applied. In the case of AWJ cutting we have utilized process model, that is known from studies and practice in the field of this high-pressure cutting technique. We have used a different approach for building the empirical models for thermal processes. The models were derived using the curve-fitting method. This method relies on an extensive technological database. The data contains the values for cutting velocities for straight cutting for different process parameters (power, cutting gas, wire diameter etc) settings, cutting eight predefined materials. We have constructed a database for all the thermal cutting processes from different sources, such as the database of our own practical studies, many operators' databases, the internet, etc. Both methods of process model building are presented for the case of AWJ and laser cutting.

**AWJ Process Modeling**

Several researchers have presented models for the depth-of-cut or cutting-speed prediction for the AWJ cutting process. We have followed the model of Zeng and Kim [10]. It is based on the modeling of a cutting process to formulate a dimensional relationship and the use of test-data regression to determine the razmerja. Ko poznamo debelino in material obdelovanca in so izbrane vrednosti vodnega tlaka, velikost mešalne šobe, pretok abraziva, lahko napovemo hitrost rezanja z uporabo naslednje enačbe [10]:

power constants in the relationship. When the workpiece material and thickness are known and the preset values of water pressure, orifice/nozzle size, abrasive flow rate are defined, the cutting speed can than be predicted using the following equation [10]:

$$v = \left( \frac{N p^{1.25} m_w^{0.687} m_a^{0.343}}{C t q d_j^{0.618}} \right)^{1.15} \quad \text{mm/s} \qquad (1)$$

kjer so:

$v$ – rezalna hitrost v mm/s,
$p$ – tlak vode v MPa,
$t$ – debelina materiala v mm,
$N$ – obdelovalno število materiala obdelovanca,
$m_w$ – pretok vode v l/min,
$m_a$ – pretok abraziva v g/s,
$d_j$ – premer mešalne šobe v mm,
$C$ – 8800 konstanta za metrski sistem,

in kjer je $q$ kvalitativni parameter nivoja kakovosti.

Za lažjo predstavo so v nadaljevanju podane razlage za naslednjih pet ravni kakovosti [10]:

Razlaga ravni kakovosti

q = 1 Kriterij za ločilni rez. Navadno se uporablja q > 1,2.
q = 2 Groba površina reza z brazdami v spodnji polovici reza.
q = 3 Gladko/grobi prehodni kriterij. Pojavijo se lahko rahle brazde.
q = 4 Brez brazdavosti za večino materialov.
q = 5 Najboljša površina reza.

Upoštevati je treba, da izbira višjih kakovostnih ravni rezultira v manjših rezalnih hitrostih, torej zviša stroške.

Vrednosti obdelovalnega števila $N$ za obravnavane inženirske materiale so naslednje [10]:

| | |
|---|---|
| orodno jeklo | 80,4 |
| nerjavno jeklo | 82 |
| konstrukcijsko jeklo | 87 |
| baker | 110 |
| aluminij | 213 |
| najlon | 538 |
| akrilno steklo | 690 |
| vezana plošča | 1500 |

Enačba (1) je veljavna na širokem nizu parameterov, vendar le dokler ti parametri zavzemajo vrednosti znotraj normalno sprejemljivega delovanja. Npr., rezalna hitrost se vedno zveča s povečanjem dotoka abraziva, vendar v praksi le do določene meje. Vodni curek namreč lahko sprejme le določeno količino abraziva, nad katero postane prenasičen, kar rezultira v manjši hitrosti rezanja. Nihče si ne želi delovati v takem območju. Priporočena območja veljavnosti enačbe (1) so naslednja: tlak vode: $p$=240 do 375 MPa; premer vodne šobe $d_n$=0,18 do 0,56mm; razmerje med mešalno in vodno šobo $d_j/d_n$=2 do 4; razmerje pretokov abraziv/voda $m_a/m_w$=0,12 do 0,2 in pretok vode $m_w=1{,}479 \cdot d_n^{\,2} \cdot p^{1/2}$ [11]. Z namenom, da poenostavimo Zeng in Kimov model, smo izpeljali naslednjo preprosto izkustveno enačbo. Uporabili

where:

$v$ – cutting speed [mm/s],
$p$ – water pressure [MPa],
$t$ – material thickness [mm],
$N$ – machinability number of workpiece material,
$m_w$ – water flow rate [l/min],
$m_a$ – abrasive flow rate [g/s],
$d_j$ – mixing tube diameter [mm],
$C$ – 8800 constant for metric system,

and where $q$ is a qualitative quality-level parameter.

For convenience, descriptions are given for the following five quality levels /11/:

Quality Level Description

q = 1 Criteria for separation cuts. Usually, q > 1.2 should be used.
q = 2 Rough surface finish with striation marks on the lower-half surface.
q = 3 Smooth/rough transition criteria. Slight striations marks may appear.
q = 4 Striation free for most engineering materials.
q = 5 Best surface finish.

It should be noted that the selection of a high quality level results in slow cutting speeds, thereby increasing cost.

The values of the machinability number $N$ for some common engineering materials are as follows [10]:

| | |
|---|---|
| tool steel | 80.4 |
| stainless steel | 82 |
| mild steel | 87 |
| copper | 110 |
| aluminum | 213 |
| nylon | 538 |
| plexiglass | 690 |
| plywood | 1500 |

Equation 1 is valid for a wide range of parameters, as long as the values of these parameters stay within the realm of normally acceptable operation. For example, cutting speed always increases with abrasive flow rate; however, in practise, beyond a certain flow rate, the abrasive-jet mixture begins to get over-saturated, resulting in a reduced cutting speed. And in any case, it would not useful to operate the system in this range. The recommended range of validity for this equation is as follows: water pressure: $p$=240 to 375 MPa; orifice diameter $d_n$ = 0.18 to 0.56mm; nozzle ratio $d_j/d_n$ =2 to 4; abrasive/water flow-rate ratio $m_a/m_w$ =0.12 to 0.2 and water flow rate is $m_w=1.479 \cdot d_n^{\,2} \cdot p^{1/2}$ [11]. In order to simplify the Zeng and Kim model we derived the following simple empirical equation. The average values of the smo srednje vrednosti predhodno omenjenih priporočenih območji ter določena druga pravila in povezave, povezane z optimalnim delovanjem sistema:

aforementioned recommended ranges, some other empirical rules and relations related to the optimal system's operation were used:

$$v = \left( \frac{Np^{1.765} d_n^{1.442}}{233 \cdot tq} \right)^{1.15} \quad \text{mm/min} \qquad (2)$$

kjer so:
$v$ – rezalna hitrost v mm/min,
$p$ – tlak vode v MPa,
$t$ – debelina materiala v mm,
$d_n$ – premer vodne šobe v mm.

Enačba (2) ne upošteva vpliva odmika mešalne šobe od obdelovanca ter vrste in zrnatosti abraziva. Običajno se globina reza zmanjšuje z večanjem odmika mešalne šobe, vendar majhne spremembe odmika, v območju med 1 in 3 mm, bistveno ne vplivajo na spremembe v globini in kakovosti rezanja. Podobno imajo variacije v zrnatosti abraziva v običajnih mejah (zrna 50 do 150) majhen vpliv na največjo dosegljivo hitrost rezanja. Finejši abraziv se običajno uporablja za doseganje gladkejše površine reza. Vrsta abraziva je prav tako pomemben parameter. Uporaba različnih vrst abraziva lahko povzroči znatne spremembe rezalne sposobnosti. Enačbo (2) lahko neznatno spremenimo, če N pomnožimo s konstanto abraziva in tako pri napovedi hitrosti rezanja upoštevamo tudi vrsto abraziva.

**Modeliranje toplotnih postopkov**

Enak cilj smo imeli za preostale toplotne postopke rezanja. Poskušali smo odkriti povezavo med rezalno hitrostjo pri različnih debelinah materiala in glavnimi parameteri postopka. Zaradi različnosti v konstrukciji sistemov, v vodenju delovnega žarka in materiala ter izvedbah rezalnih glav, je natančno razmerje mogoče podati le z izvedbo preskusov. Rezalne hitrosti so neposredno vezane na gostoto energije v rezalni coni.

Pri laserskem rezanju je ta odvisna od moči laserja in velikosti žarka v gorišču ter lege gorišča. Leče s krajšimi goriščnimi razdaljami dajo manjšo površino žarka v gorišču, kar poveča gostoto energije in posledično vpliva na največjo hitrost rezanja. Način oz. mod laserskega žarka prav tako vpliva na zmožnost fokusiranja leč v majhno pego. Vsako odstopanje od osnovne Gaussove porazdelitve rezultira v povečanem prerezu žarka v gorišču in tako zmanjšuje rezalne hitrosti. Na splošno lahko v praksi vzamemo, da imajo močnejši laserji večji premer žarka v gorišču; lastnost, ki zmanjšuje pričakovane rezalne hitrosti in daje večjo širino reza.

Upoštevati moramo, da za vsako moč laserkega žarka obstaja neka največja debelina materiala, ki jo še kakovostno režemo, značilnost, ki ne bo predstavljena s to tehniko napovedovanja. Metoda gradnje izkustvenih modelov, rezalna hitrost v odvisnosti od debeline materiala in moči laserja, s prilagajanjem delovanja krivulji rezanja se opira na dveh faktorjih, ki ju lahko vzamemo kot pravilna [12]:

where
$v$ – cutting speed [mm/min],
$p$ – water pressure [MPa],
$t$ – material thickness [mm],
$d_n$ – orifice diameter [mm].

Equation 2 does not include the effects of stand-off distance, abrasive type and size. As a general trend, the depth of cut is reduced as the stand-off increases. However, variations of the stand-off over a small distance, in the range between of 1 and 3 mm, does not cause any significant changes in the depth of cut or in the quality of cutting. Similarly, variations in the abrasive size, within the ordinary range (mesh 50 to 150) have little effect on the attainable maximum cutting speed. Finer abrasive is usually used to achieve a smoother surface finish. The abrasive type is an important parameter as well. The use of different types of abrasives may result in a substantial difference in cutting performance. Equation 2 can be slightly modified by multiplying *N* by an abrasive constant to account for different kinds of abrasives.

**Modeling for thermal processes**

Our aim was the same for the remaining thermal cutting processes. We tried to find information relating to the cutting speeds at various material thickness and the main process parameters. Owing to the diversity of system design, working beam and material manipulation system and cutting-head configurations, accurate information is only made available by making trials. Cutting speeds are directly related to the energy density in the cut zone.

For laser cutting, this is affected by the laser power and the size and position of the focused spot. If a shorter focal length of lens is used, the spot size decreases giving an increase in the energy density and this consequently influences the maximum cutting speed. The mode of the laser beam also affects the ability of the lens to produce a small focal spot. Any variation away from the so-called primary Gaussian cross-section tends to enlarge the focused spot diameter and thus reduce the cutting speeds.

It should be borne in mind that each laser power will have a maximum thickness of material for good quality cutting, a feature that will not be shown up by this forecasting technique. The method of building empirical models of cutting speed versus material thickness and power by curve fitting relies on two factors, which can be assumed to be true [12]:

- Največja hitrost rezanja je sorazmerna moči laserskega žarka (s predpostavko, da je velikost žarka v gorišču nespremenljiva), kar pomeni dvojna moč da dvakratno hitrost.
- Oblika krivulje rezanja je približno enaka za vse materiale, čeprav se dejanske vrednosti, podane na oseh grafa spreminjajo. Tako lahko napovemo približno hitrost rezanja z uporabo testnih rezultatov rezanja in različnih baz podatkov ([13] in [14]) v kombinaciji z naslednjo preprosto formulo:

- The maximum cutting speed is proportional to the laser power (assuming a constant focused spot size), i.e. twice the power gives twice the cutting speed.
- The shape of the cutting curve is approximately the same for all materials, although the actual values given on the axes of the graphs change. So approximate cutting-speed forecasting can be carried out by using the results of cutting trials and different databases ([13] and [14]) in combination with the following simple formula:

$$v = Q \cdot P \cdot t^{-B} \tag{3}$$

kjer so:
$v$ – rezalna hitrost v mm/min
$P$ – laserska moč v W
$t$ – debelina material v mm
$Q$ – eksperimentalno izpeljane stalnice materialov pri uporabi določene laserske fokusirne optike.
$B$ – podaja obliko krivulje rezalne hitrosti.

where
$v$ – cutting speed [mm/min]
$P$ – laser power [W]
$t$ – material thickness [mm]
$Q$ – an experimentally derived constant for the material using a particular laser-focusing optics combination.
$B$ – gives the shape of the cutting curve.

Preglednica 2. *Vrednosti stalnic materiala Q in B, maksimalna debelina in način laserskega rezanja za obravnavane materiale*

Table 2. *Values of the material constants Q and B, thickness limitation and the type of laser cutting for analysed materials*

| **Material** | ***Q*** | ***B*** | **najv. debelina max. thickness mm** | **način rezanja / rezalni plin<br>type of cutting / cutting gas** |
|---|---|---|---|---|
| orodno jeklo<br>tool steel | 5,28 | 1,053 | 15 | III / $O_2$ |
| nerjavno j.<br>stainless s. | 4,65 | 1,265 | 12 | II / $N_2$ |
| konstrukcijsko j.<br>mild steel | 7,04 | 1,053 | 20 | III / $O_2$ |
| aluminij<br>aluminium | 4,79 | 1,495 | 8 | II / $N_2$ |
| najlon<br>nylon | 40 | 1,350 | 30 | II / *zrak* air |
| akrilno steklo<br>plexiglass | 70 | 1,350 | 35 | I / *zrak* air |

Vsako vpeljano vrednost stalnice $Q$ lahko uporabimo za podajanje približne hitrosti rezanja, saj so rezalni laserji postopoma vedno bolj podobni pri kakovosti izstopnega žarka. Ko je enkrat vrednost stalnice $Q$ ugotovljena s prilagajanjem krivulji reza, je mogoče napovedati hitrost rezanja določenega materiala za široko območje debelin in moči laserja [12].

*Preglednica 2* prikazuje vrednosti $Q$ in $B$ stalnic za inženirske materiale, analizirane v naši raziskavi, ki so v splošni rabi laserske rezalne prakse. Podane so tudi največje debeline določenih materialov, pri katerih še dosežemo kakovostne rezultate, kakor tudi načini laserskega rezanja. Obstajajo namreč trije mehanizmi laserskega rezanja, ki jih uporabljamo pri rezanju različnih materialov:

Any established value of $Q$ can be used to give an approximation of the cutting speed, because cutting lasers are becoming progressively more alike in their output beam quality. Once a value of the constant $Q$ has been found by curve fitting it is possible to forecast the cutting speeds for a material over a wide range of thicknesses and laser powers [12].

Table 2 shows the established values of the $Q$ and $B$ constants for the engineering materials analyzed in our investigation, which are commonly used in practical laser cutting. The maximum thickness for quality cutting results achieved on chosen materials and the type of laser-cutting mechanism are presented as well. Namely, there are three mechanisms of laser cutting that can be used for processing different materials:

1. **Lasersko izhlapevno rezanje (I)**: Večina materiala je izparjena z veliko močjo laserskega žarka in izpihnjeno s pretokom inertnega plina.
2. **Lasersko talilno rezanje (II)**: Material je segret in staljen z laserskim žarkom in izpihnjen s pretokom inertnega plina pod visokim pritiskom.
3. **Lasersko plamensko rezanje (III)**: Uporabljen je reaktivni-delovni plin za eksotermično reakcijo, ki vžge z laserjem segret material.

Način laserskega rezanja pomembno vpliva na delovanje in posebej na ekonomičnost rezanja.

Omejitve teh modelov so poleg največjih vrednosti za debeline tudi območja laserskih moči, ki jih lahko uporabimo in še zagotovimo zadovoljivo natančnost. *Enačba (3)* je zanesljiva na območju od 1,5 do 4kW za kovine in 100 do 1500W za nekovine. Pri nekovinah je bila uporabljena 5” leča. Za rezanje kovin so na voljo različne vrste fokusirnih leč.

Opisano modeliranje ne vsebuje parametrov kakovosti reza. Območje kakovostnega rezanja je namreč veliko ožje, kakor v primeru rezanja z AVC. Lasersko rezanje z neustreznimi parametri, npr. prevelika rezalna hitrost, rezultirajo v nižji ceni reza, vendar je kakovost reza na ravni plazemskega ali plamenskega rezanja. Kakovost reza je vezana na standard DIN 2310.

Postopkovni modeli za druge toplotne postopke so bili izpeljani na enak način.

Ti postopkovni modeli so bili vključeni v program za računalniško podprto *definicijo parametrov* in *oceno obnašanja.* Slika 5 prikazuje primer uporabniškega komunikacijskega okna za to stopnjo izbirnega postopka. V tem primeru program izračuna vrednost kakovostnega nivoja, določenega s kunstrukcijskimi zahtevami in vrednost hitrosti rezanja AVC pri predefiniranem

1. **Laser Sublimation Cutting (I)**: Most of the material is vaporised by a high-intensity laser beam and blown out by an inert gas flow.
2. **Laser Fusion Cutting (II)**: Material is heated and melted by the laser beam and blown out by a high-pressure an inert gas flow.
3. **Laser Flame Cutting (III)**: A reactive working gas is used for an exothermic reaction that burns the laser heated material.

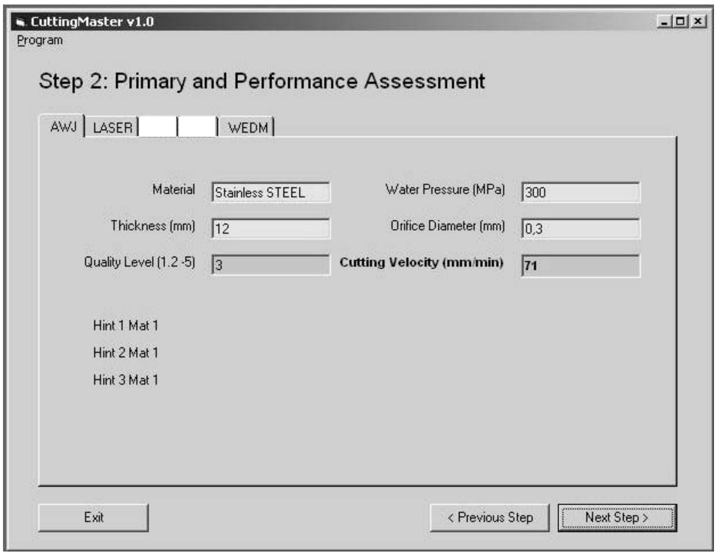
The type of laser cutting mostly influences the cutting performance and especially the cost efficiency.

The limitations of these models are the maximum values of the thickness and the ranges of the laser power that can be used while still ensuring sufficient accuracy. The reliability of Equation 3 is in the range of 1,5 to 4kW for metals and 100 to 1500W for non-metals. For non-metals the 5” lens was used. Various types of focusing lenses are available for metal cutting.

In the present laser-process modeling, no surface quality aspects are included, since the range of performance is much narrower than in the AWJ case. Laser cutting performed with non-appropriate parameter settings, i.e. higher cutting rates, results in lower costs but the quality of th surface is rather in the ‘plasma or flame’ class than in the AWJ class. The quality in these models is related to the DIN 2310 standard.

The process models for other thermal processes were derived in the same manner.

These process models were incorporated into the software for the computer-aided step of *parameters’ definition* and *performance assessment.* Figure 5 shows an example of a user-interface dialog screen for this step in selection procedure. In this case the software calculates the value for the quality level determined by the design requirements and the value for the cutting velocity for AWJ cutting under a predefined quantity



Step 2: Primary and Performance Assessment

Material: Stainless STEEL
Thickness (mm): 12
Quality Level (1.2 -5): 3
Water Pressure (MPa): 300
Orifice Diameter (mm): 0,3
**Cutting Velocity (mm/min): 71**

Hint 1 Mat 1
Hint 2 Mat 1
Hint 3 Mat 1

Sl. 5. *Primer komunikacijskega okna programa CM za stopnji definicija parametrov in ocena obnašanja*
Fig. 5. *Example of a CM dialog screen for the stage of parameters’ definition and performance assessment*

tlaku vode in premeru vodne šobe. Vrednosti za ta glavna parametera in za kakovostno raven lahko spremenimo in izračunamo novo vrednost za rezalno hitrost. To omogoča bolj realistično določanje nastavitev postopkovnih parametrov za izdelavo v določenih kakovostnih razmerah. Postopek je enak za oba preostala postopka, tj. lasersko in RŽE. Plr in PzR sta eliminirana že v predhodni fazi izbire. Ti proizvodni parameteri so v pomoč pri določanju ekonomskih parameterov za naslednjo *oceno stroškov*.

### 3.4 Ocena ekonomičnosti

Trije dejavniki naredijo analizo ekonomičnosti postopkov nekoliko zahtevno: 1) rezultati rezanja so lahko dobljeni z različnimi kombinacijami rezalnih parametrov; 2) prilagodljivost postopkov, zmožnost rezanja različnih oblik domala brez sprememb v strojni opremi je v večini primerov težko ovrednotiti; 3) različni dobavitelji imajo različne postavke ter lahko številne prilastke vrednotijo različno. Pravilna oz. dobra stroškovna analiza naj bi upoštevala te tri dejavnike.

Osnova za izračun strojne ure so stalni in spremenljivi stroški. Stroškovna analiza in izračun temelji na naslednjih postavkah:

*Osnova za izračun* ***stalnih*** *stroškov:*
- začetni stroški – investicija $I$ v €;
- amortizacijska doba $D$ v letih, letno delovanje oz. raba stroja $L_a$ v h/leto.

*Izračun* ***stalnih*** *stroškov:*
- izračun amortizacije:

of water pressure and orifice diameter. The values for these two main parameters and also for the quality level could be changed and a new value for the cutting velocity will be calculated. This allows a more realistic determination of the process-parameter settings for manufacturing under certain quality conditions. The procedure is the same for the other remaining processes, in this case laser and WEDM cutting. The OFC and PAC were excluded at the previous stage of the selection. These production parameters help to determine the economic parameters for a subsequent *economic evaluation*.

### 3.4 Economic evaluation

Three factors make process-cost analysis somewhat difficult: 1) some cutting results can be achieved by many different combinations of cutting parameters; 2) the flexibility of the processes, ability to cut different profiles almost without hardware changes, is hard to value in most cases; 3) different customers have different objectives and they may value various attributes differently. Thus, a good economic analysis model should account for these three factors.

Fixed and variable costs are part of machine costs on an hourly basis. The economic analysis and calculation basis are made up as follows:

*Calculation basis for the* ***fixed*** *costs:*
- initial cost $I$ [€];
- depreciation period $D$ [years], machine utilization $L_a$ [h/year].

*Calculation of fixed costs:*
- calculated depreciation:

$$C_d = \frac{I}{D \cdot L_a} \quad \text{€/h} \qquad (4)$$

V tem izračunu stalnih stroškov niso vštete obrestne mere in stroški prostora. Obe postavki dodata približno 20% stalnim stroškom, vendar zaradi podobnih lastnosti in zahtev vseh tehnologij nista pomembni pri primerjanju ekonomičnosti med njimi.

*Osnova za izračun* ***spremenljivih*** *stroškov:*

Izračun spremenljivih stroškov je specifičen za vsak postopek. Vsi postopki so gnani električno, vendar vsak uporablja različno vrsto rezalnega vira in parametre, tako je tudi poraba povezana s temi procesnimi parameteri in njihovimi nastavitvami. Ocena spremenljivih stroškov je predstavljena na primeru rezanja z AVC:
- poraba električne moči (celoten sistem) $E$ v kW, cena električne energije $c_e$ v €/kWh;
- stroški vzdrževanja letno $M$ v €/leto.

**Poraba RAVC:**
- poraba rezalne in hladilne vode $m_w + W$ v l/min, cena vode $c_w$ v €/l;
- poraba abraziva $m_a$ v kg/min, cena abraziva $c_a$ v €/kg;

In this calculation of fixed costs no interest rate and no cost for floor space are included. Both items usually add about 20 % to fixed costs, but are for all technologies much the same and as such not so meaningful when a comparison based on economic efficiency has to be made.

*Calculation basis for the* ***variable*** *costs:*

The calculation for variable costs is specific to the process. All processes are electrically driven, but each process uses a different kind of cutting source and parameters, so consumption is connected with these process parameters and their settings. The assessment of variable costs is presented for the case of AWJ cutting.
- electrical power consumption (entire system) $E$ [kW], electricity costs $c_e$ [€/kWh];
- maintenance costs per year $M$ [€/year].

**AWJ consumption special:**
- cutting-and cooling-water consumption $m_w + W$ [l/min], water price $c_w$ [€/l];
- abrasive material consumption $m_a$ [kg/min], abrasive price $c_a$ [€/kg];

- potrošni in obrabni deli; cena vodne šobe $c_n$ v €/kos, doba trajanja vodne šobe $L_n$ v h/kos, cena mešalne šobe $c_m$ v €/kos, doba trajanja mešalne šobe $L_m$ v h/kos.

***Spremenljivi*** stroški:

- stroški električne energije:

- replacement and wearing parts; orifice price $c_n$ [€/part], orifice lifetime $L_n$ [h/part], mixing-tube price $c_m$ [€/part], mixing-tube lifetime $L_m$ [h/part].

*Calculation of **variable** costs:*

- electric energy costs:

$$C_e = c_e \cdot E \quad \text{€/h} \tag{5}$$

- stroški vzdrževanja:

- maintenance costs:

$$C_m = \frac{M}{L_a} \quad \text{€/h} \qquad (6).$$

Izračun ***spremenljivih*** stroškov za **AVC**:

- stroški rezalne in hladilne vode:

*Calculation of special **AWJ variable costs**:*

- cutting-and cooling-water cost:

$$C_w = 60 \cdot c_w (m_w + W) \quad \text{€/h} \qquad (7),$$

kjer je:

where:

$$W = K_w \cdot E \qquad (8),$$

- stroški abraziva:

- cost of abrasive:

$$C_a = 60 \cdot c_a m_a \quad \text{€/h} \tag{9}$$

- stroški potrošnih delov (šob):

- costs of replacement and wearing parts (nozzles)

$$C_r = C_n + C_m = \frac{c_n}{L_n} + \frac{c_m}{L_m} \quad \text{€/h} \qquad (10).$$

V tem izračunu niso upoštevani stroški delavca. Vse analizirane tehnologije zahtevajo izkušenega delavca za vodenje in vzdrževanje sistema. Sistemi delujejo neprekinjeno, kar zahteva polno zasedene delavce.

In these calculations no direct labor costs are included. All technologies reqiure skilled operators to operate and maintain the system. Since systems are continously operating, full-time operators are required.

**Stroškovno modeliranje rezanja z AVC**

Celotni obratovalni stroški na uro oz. strojna ura $C_{AVC,\ h}$ so računani s seštetjem stalnih in spremenljivih stroškov in vsebujejo investicijske stroške in stroške vzdrževanja, kakor prikazuje naslednja enačba:

**AWJ cutting cost modeling**

Total operating costs per hour $C_{awj,\ h}$ are calculated by adding the fixed costs to the variable, including also capital investment costs and the cost of maintenance, as shown in the following equation:

$$C_{awj,h} = C_d + C_e + C_w + C_a + C_r + C_m \quad \text{€/h} \qquad (11).$$

Ključni parameter, ki vpliva na pretok vode ali posredno na hitrost rezanja je premer vodne šobe. Druga dva parametera, ki močno vplivata na hitrost, sta tlak sistema in pretok abraziva. Vseeno optimalne vrednosti teh parametrov niso povsem neodvisne. Optimalni pretok abraziva je odvisen od pretoka rezalne vode, kakor je to že prikazano. Parametra, premer vodne šobe in tlak vode tudi vplivata na obratovalne stroške. To prikazuje naslednja enačba v povezavi s porabo električne energije oz. moči [11]:

The key parameter that controls cutting speed is the orifice diameter or, indirectly, the cutting-water flow rate. The other two parameters that greatly influence the speed are the system pressure and the abrasive flow rate. However, the optimum values of these parameters are not totally independent. The optimum abrasive flow rate can be related to the cutting-water flow rate, as indicated earlier. These two parameters, i.e. orifice diameter and system pressure also mostly influence the operating costs, as shown among other relations, and also the following equation relating to the electric power consumption [11]:

$$E = 0.0455 \cdot d_n^{\,2} \sqrt{p^3} \quad \text{kW} \qquad (12).$$

Celotni stroški na podlagi obratovalne ure oz. strojna ura so lahko za namen izbire postopka vezani na prej omenjena pomembna sistemska parametera, tj. tlak $p$ in premer vodne šobe $d_n$ in so podani z:

The total costs, based on per hour of operation, can be, for process selection purposes, related to the aforementioned significant system parameters, i.e. the pressure $p$ and the orifice diameter $d_n$, and are given by:

$$C_{awj,h} = \frac{I}{D \cdot L_a} + \left[0.0455 \cdot (c_e + 15c_w)p + 1.479 \cdot (10.2c_a + 60c_w)\right] \cdot d_n^{\,2} \sqrt{p} + \frac{1}{100} c_m + \frac{1}{60} c_n + \frac{M}{L_a} \qquad (13).$$

Za končno primerjavo z drugimi postopki vpeljemo stroške na meter reza in jih izračunamo kot:

The costs, based on per meter of cutting, in order to make the final comparison with other processes' cutting costs, are established as:

$$C_{awj,m} = \frac{16,67 \cdot C_{awj,h}}{v} \quad \text{€/m} \qquad (14).$$

Stroškovni modeli za druge postopke so razviti na enak način. Vsak vsebuje parametre, specifične za postopek, upoštevajoč vrednosti za specifične nastavitve material/konstrukcija. Stroškovne modele vseh postopkov smo vgradili v program '*CM*' za zadnji korak v izbirnem postopku. Slika 6 prikazuje primer *CM* komunikacijskega okna za zadnjo stopnjo o*ceno ekonomičnosti*. Preračun je ponovno izveden samo za izdelavo ustreznega postopka. V program so vključene predefinirane vrednosti deležev stalnih in spremenljivih stroškov, vendar lahko uporabnik te vrednosti spremeni in računa s specifičnimi za krajevne razmere. Program izračuna celotne proizvodne stroške na uro in celotne proizvodne stroške na meter ravnega reza.

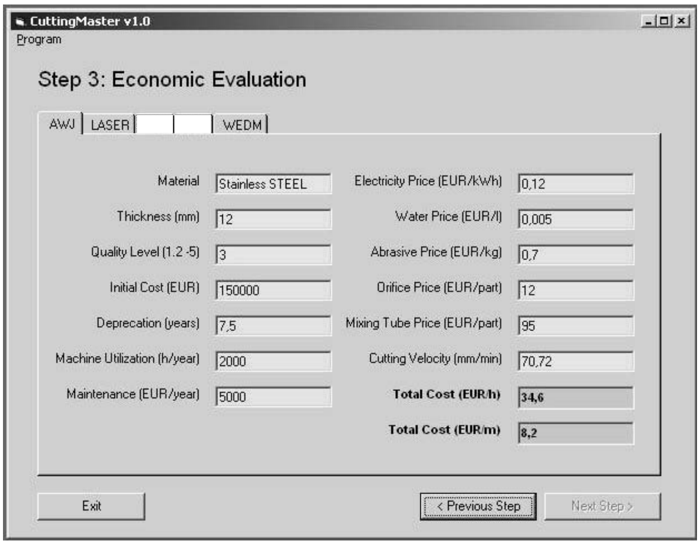
The cost models for other processes were developed in the same manner. Each includes the process-specific parameters considering their values for the specific material/design settings. All processes' cost models were implemented in '*CM*' software for the final step of selection procedure. Figure 6 shows an example of the *CM* dialog screen for the stage of *economic evaluation*. The calculation is again made only for the viable processes. The program incorporates predefined values for the components of fixed and variable costs, but the user could change these values and then calculate with those specific to the local situation. The program calculates the total production costs on an hourly basis and the total production costs for a meter of straight cutting.

## 4 SKLEPI

## 4 CONCLUSIONS

Večina člankov objavljenih na področju izbire postopka, je osredotočenih na preliminarno izbiro, kjer so upoštevani vsi postopki ([4] in [5]). Ta prispevek podaja podrobnejšo informacijo o izbiri postopka, kakor je bila podana v naših prejšnjih

Most of the papers published in the field of process selection are focused on preliminary selection, where all the processes are considered ([4] and [5]). This paper provides more detailed process-selection procedure than was made in our previous investigations [15] and



Step 3: Economic Evaluation

Material: Stainless STEEL
Thickness (mm): 12
Quality Level (1.2 -5): 3
Initial Cost (EUR): 150000
Deprecation (years): 7,5
Machine Utilization (h/year): 2000
Maintenance (EUR/year): 5000
Electricity Price (EUR/kWh): 0,12
Water Price (EUR/l): 0,005
Abrasive Price (EUR/kg): 0,7
Orifice Price (EUR/part): 12
Mixing Tube Price (EUR/part): 95
Cutting Velocity (mm/min): 70,72
**Total Cost (EUR/h)**: **34,6**
**Total Cost (EUR/m)**: **8,2**

Sl. 6. *Primer komunikacijskega okna programa CM za stopnjo ocena ekonomičnosti*
Fig. 6. *Example of a CM dialog screen for the stage of economic evaluation*

objavah [15] in [16]. Metodologija obsega načelo strukturirane izbire za specifično izdelovalno opravilo – obrisno rezanje. Posebej obravnava vpliv tehnoloških in ekonomskih dejavnikov. Postopkovni podatki so zbrani na ustrezen specifično materialno raven, ki omogoča potrebno ločevanje za preučevano izdelovalno opravilo. Izbira uporablja kombinacijo empirično utemeljenih postopkovnih modelov, ki olajšajo določitev ustreznih postopkovnih informacij. Cilj je izvleči ustrezeno raven natančnosti, ki še omogoča uporabno razločevanje. Kakovost izbire je močno odvisna od kakovosti podatkov in izluščenega znanja, kakor tudi od ocene rezultatov postopka. Posebna zapletenost fizike vseh postopkov prav tako narekuje določeno stopnjo pragmatizma. Tako so uporabljeni zgolj empirični modeli, ki zagotavljajo široko območje preučevanih možnosti. Na prvi pogled se zdita izračuna stroškov in optimizacijski problem brezupno zapletena, saj je število parametrov, ki vplivajo na strukturo stroškov, ekstremno veliko. Vseeno lahko problem močno poenostavimo z uporabo lokalne podoptimizacije. Prikazano je, da je optimizacija lahko izvedena s samo dvema parametroma za primer rezanja z AVC, tj. tlak in premer vodne šobe, in z enim za lasersko rezanje, tj. laserska moč.

Ostaja torej izziv, kako določiti najboljši postopek čim hitreje, torej tako da določimo karakteristične veličine izdelka, tj. zahteve konstrukcije, ki jih uskladimo z zmožnostmi. Izbira je vodena sekvenčno z uporabo preddefiniranih vrednosti. Na ta način lahko vodi prek ustreznih odločitev tudi manj izkušene konstrukterje. V načrtu je verifikacija programskega orodja s testiranjem na izbranih učnih primerih iz industrijske prakse.

[16]. The methodology embodies the principle of structured selection for a specific manufacturing task – contour cutting. It accounts separately for the influences of technical and economic factors. The process data are assembled at an appropriate material-specific level to provide the discrimination needed for the manufacturing task being considered. Selection uses a combination of empirically based process models to help determine the relevant processing information. The challenge is to extract an appropriate level of detail and approximation to provide a useful discrimination. The quality of the selection, however, depends greatly on the quality of the data and the extracted knowledge as well as on the estimation of the process objectives. The inherent complexity of process physics also calls for a degree of pragmatism, so that purely empirical models are used if required in order that as wide a range of options as possible is considered. At first sight, the cost calculation and optimisation problem seems hopelessly complex, since the number of parameters affecting the cost structure is extremely large. However, by using local sub optimisation, the problem can be greatly simplified. It is shown that the optimisation can be conducted with only two parameters for AWJ cutting, i.e. pressure and orifice diameter. The economic evaluation incorporates these parameters as factors in the process cost modeling.

In order to determine the best process as early as possible, the selection procedure is implemented in a computer-aided process-selection algorithm, which enables simultaneous process definition by the designer and the technologist. The selection is conducted sequentially using predefined parameter values, so that less-experienced designers are guided through the appropriate decisions. The verification of the software tool is planned by testing it on selected case studies from industrial practice.

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