CODEN STJSAO
ZX470/1426
ISSN 0562-1887
UDK 658.5.012.2:658.513:004.434

Process Selection, Sequence of Operations and Shape Complexity - Criteria for Process Improvement

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Original scientific paper

The problem of the workpiece shape recognition, and technological process selection and optimization always includes the possibility of shape complexity assessment, and selection of primary process and sequence of operations. The process plans for mechanical products include selection of manufacturing processes: a primary process, and subsequent processes. In the first part, the objective of our research was to investigate the relation between requirements of the design, production quantity and material on one hand and capability of particular process on the other hand in order to be able to consider only the processes that make sense. Also, production costs, quality, lead-times and ecological aspects had to be considered. Our intention was to research and to give some guidance in classifying these requirements, to find a way how to deal with overlapping capabilities of the processes and to explore methods of dealing with numerous data that would facilitate decisions regarding "best" process selection. In the second part, our research explains the procedure for calculating shape complexity. The possibility to express it as an exact value is useful because it enables distinction on the quantitative level. This is needed for research of shape influence on process planning. In the third part, the focus of our research is creation of learning materials for defining the main criteria for selection of primary processes and types of operations in production. The selection of a primary process is based on material nature, quantity, shape complexity, part size and some other factors. Type and sequence of operations are the result of the influence of different factors such as product shape, surface roughness and tolerance. The application enables users to fully understand the procedure of primary process and operation sequence selection through step by step tutorials. The base programming language of E-Lapp application is Visual Basic.Net, the tools used to create e-learning materials are Microsoft PowerPoint 2007 and iSpring Presenter (Adobe Flash).

Odabir procesa, redosljed operacija i složenost oblika - kriterij unapređenja procesa

Izvornoznanstveni članak

Problem prepoznavanja oblika izratka, odabir tehnološkog procesa te optimizacija uvijek uključuju mogućnost procjene složenosti oblika, odabir primarnog procesa te redoslijeda operacija. Plan procesa za proizvode u strojogradnji uključuje odabir strojarskih procesa: primarnog procesa i redoslijeda operacija. U prvom dijelu, cilj istraživanja bio je istraživanje relacije između zahtjeva designa, proizvodne količine i materijala s jedne strane te prikladnosti određenog procesa s druge strane kako bi bili u stanju razmatrati samo odgovarajuće procese. Također, bili su razmatrani i proizvodni troškovi, kvaliteta, vodeća vremena te ekološki aspekti.

Namjera je bila istražiti i dati naputak u klasifikaciji tih zahtjeva, pronaći način kako se baviti sa preklapanjem mogućnosti procesa te se baviti metodama prikladnim za obradu numeričkih podataka koji će olakšati donošenje odluka koje pomažu kod odabira "najboljeg" procesa.

U drugom dijelu istraživanje objašnjava proceduru za proračun složenosti oblika izratka. Mogućnost njegova izdvajanja kao egzaktne veličine korisno je jer omogućuje razlikovanje na kvanitativnoj razini. Potrebno je to u istraživanju utjecaja oblika u procesu planiranja. U trećem dijelu , fokus našeg istraživanja je kreiranje materijala za učenje kako bi se kreirao glavni kriterij u odabiru primarnih procesa i vrste operacija u proizvodnji. Odabir primarnog procesa temeljeno je na materijalu, količini, složenosti oblika, veličini dijela te neih drugih faktora. Tip i redoslijed operacija su rezultat utjecaja različitih faktora kao što su oblik izratka, površinska hrapavost i tolerancija. Aplikacija omogućuje korisnicima potpuno razumijevanje procedure odabira primarnog procesa i redoslijeda operacija korak po korak u priručniku. Osnovni programski jezik e-Lapp aplikacije je Visual Basic. Net, a alati korišteni za kreiranje e-learning materijala su Microsoft Power Point 2007 te iSpring Presenter (Adobe Flash).

Keywords
E-learning
Selection of primary processes
Sequence of operations
Shape complexity

Ključne riječi
E-učenje
Odabir primarnih procesa
Redosljed operacija
Složenost oblika

Received (primljeno): 2009-05-11
Accepted (prihvaćeno): 2009-11-30

Symbols/Oznake

V_f	- volume of finished component, mm^3 - volumen gotove komponente
V_c	- waste coefficient - koeficijent otpada
C_{mt}	- cost of material per unit volume - trošak materijala po jedici volumena
C_{mp}	- relative cost associated with material-process suitability - relativni trošak povezan sa prikladnim materijalom i procesom
C_c	- relative cost associated with component geometrical complexity - relativni trošak povezan sa geometrijskom složenosti komponente
C_s	- relative cost associated with size and component cross section - relativni trošak povezan sa veličinom i poprečnim presjekom komponente
C_{ft}	- relative cost associated with tolerance or surface finish - relativni trošak povezan sa tolerancom ili završnom kvalitetom površine
H	- entropy - entropija
M_i	- eurocent - cent EUR-a
P_c	- basic processing cost - temeljni trošak obrade
p_i	- probability of a certain outcome (angle change along the contour) - vjerojatnost određenog rezultata (promjena kuta uzduž krivulje)
R_a	- surface roughness, µm - površinska hrapavost
T_m	- temperature of melting, °C - temperatura taljenja
ρ	- density, kg/mm^3 - gustoća

1. Introduction

Process planning can be defined by a sequence of activities. A decision implementation has to be based on intuition, on partially estimated data or accurate data. Different process planners have different experience. Thus, it is no wonder that for the same part, different process planners will design different processes. An experienced process planner usually makes decisions based on comprehensive data without breaking it down into individual parameters. As there is no time to analyse the problem, good interpretation of the part drawing includes mainly dimensions and tolerances, geometric tolerances, surface roughness, material type, blank size, number of parts in a batch, etc. A logical approach to the process planning, as a very complicated, multilevel and comprehensive approach of generating alternative process plans will be discussed in this article, considering several topics: a) selection of primary processes, b) sequencing the operations, influence of shape complexity, etc.

The selection of processes should be made with precision, taking into consideration economic and technological factors. The following factors will be the basis for decision support in the selection of manufacturing process as the primary process and for process sequence selection [1]: a) quantity, b) complexity of form, c) nature of material, d) size of part, e) thickness section, f) dimensional and geometric accuracy, g) surface roughness, h) cost of raw material, i) possibility of defects and crap rate, etc [2].

The objective of our work and research was to develop a web application for fast and simple selection of the primary process and sequence of operations. These criteria are most important for process improvement and costs reduction in production.

2. Methods for manufacturing process selection

Several authors have proposed the procedures through which the number of processes is reduced through several steps of "screening" procedure based on different process attributes and product demands [2-7]. Initially, when a product is in the concept stage a great number of processes and materials are considered. As the product starts to develop its shape and more details, the number of processes and materials reduces. The application of these criteria results in an optimal process selection and design that is adapted to the process and material, avoiding a review of the part design in the advanced process planning stage.

All methods included in the research have a few things in common. They all give some general capability range for each process (tolerances, surface roughness, shape). Each method has its own shape classification but one thing is common; shapes are generally divided into round shapes, prismatic shapes and shapes that belong to neither of these two. Within this classification, the shapes are further divided into subclasses depending on whether they contain features such as holes, or change of section thickness. More complex shapes include threads or gears. An economical batch is given by some of them [2,3], although some give this in a very wide range, which is not very useful for making quality decisions [7]. Material and process combinations are included in each of the methods, giving plain sight which combinations are out of the question, but selection of material does not always forego process selection [4]. In order to make a final decision on process selection some authors [2, 4] developed manufacturing cost estimation procedures.

Our intention is to test some methods through case study and to compare the results. The part for which process selection will be carried out is presented in Fig. 1. Valve material is stainless steel (X45CrNi18-9; yield strength – 400MPa). The likely annual requirement is 50.000 units. Valve weight is 0.07 kg. Other properties of the part can be found in the drawing (Figure 1.).

are excluded from the list. An example of process information data for shell molding is given in Figure 2. After the analysis, the process candidates eliminated from further consideration are: centrifugal casting (shape does not match - circular bore remains in the finished part), shell molding (problem with parting line), ceramic mold casting (problem with parting line), drawing (simple uniform cross-section shapes), swaging (used to close tubes, produce tapering, clamping and steps in sections), powder metallurgy (maximum length to diameter ratio 4:1), electro-chemical machining (high degree of shape complexity possible, limited only by ability to produce tool shape), electro-beam machining (multiple small diameter holes, engraving), laser beam machining (for holes, profiling, scribing, engraving and trimming), chemical machining (primary used for weight reduction by producing shallow cavities).

Remaining processes: investment casting, forging, automatic machining, should be able to produce the part (valve) in accordance with the requirements. It is obvious that further elimination is necessary in order to select the optimal process. Relative component processing cost analysis for each candidate process can be done according to equation (1).

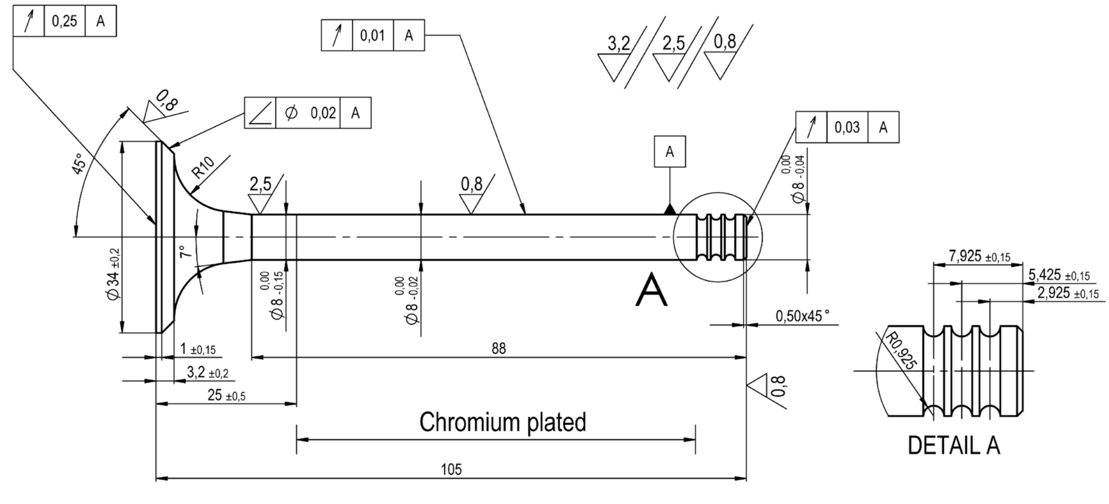


Figure 1. Considered air throttle valve for Diesel engine

Slika 1. Razmatrani usisni ventil kod Diesel motora

2.1. Selection strategies using primas (process information maps) [2]

The starting point is a table that provides information which processes are economically viable for a certain combination of material and quantity (Table 1). For stainless steel and batch quantity of 50.000 pieces a combination list of economically viable processes is created. Process candidates are compared with product requirements and ones that do not match them

$$M_{\mathrm{i}} = V_{\mathrm{f}} \cdot W_{\mathrm{C}} \cdot C_{\mathrm{mt}} + \sum \Big[\big(C_{\mathrm{mp}} \cdot C_{\mathrm{C}} \cdot C_{\mathrm{S}} \cdot C_{\mathrm{ft}} \big) \cdot P_{\mathrm{C}} \Big]. \tag{1}$$

Where V_f is volume of finished component, W_C is waste coefficient, C_{mt} is cost of material per unit volume, C_{mp} is relative cost associated with material-process suitability, C_C is relative cost associated with component geometrical complexity, C_S is relative cost associated with size and component cross section, C_{ft} is relative cost associated with tolerance or surface finish, P_C is basic processing cost.

Table 1. Suggested combinations of material and quantity

Tablica 1. Sugerirana kombinacija materijala i količine

Economic considerations / Ekonomska razmatranja	Typical applications / Tipične primjene	Design aspects / Aspekti projektiranja	Quality issues / Zahtjevi kvalitete
Leading time from several days to weeks depending on complexity and size. / Vodeće vrijeme od nekoliko dana do tjedana, zavisno o složenosti i veličini Material utilization high; little scrap generated. / Visoka iskorištenost materijala, stvaranje malo otpadnog materijala With use of gating systems several castings in a single mold possible. / Upotrebom sustava odušaka za nekoliko odljevaka moguće je u jednostrukom kalupu Resin binders cost more, but only 5 per cent as much sand used as compared to sand casting. / Vezivo smolom stoji više, ali samo 5 % više koliko i pijesak te se koristi kada se upotrebi lijevanje u pijesku	Small mechanical parts requiring high precision / Mali strojni dijelovi koji zahtjevaju visoku preciznost Connecting rods / Spojni štapovi	Sharper corners, thinner sections, smaller projections than possible with sand casting. / Oštriji kutevi, tanji presjeci, manje projekcije nego što je moguće sa lijevanjem u pijesku Cored holes greater than 13 mm. / Izrađeni provrti veći od 13 mm Draft angle ranging 0.25–1°, depending on section depth. / Kut između 0.25–1°, zavisno o dubini presjeka Maximum section = 50 mm. / Maksimalni presjek =50 mm Minimum section = 1.5 mm. / Minimalni presjek=50 mm Sizes ranging 10 g–100 kg in weight. Better for small parts less than 20 kg. / Veličina težine 10g do 100kg. Bolje je za male dijelove i manje težine od 20kg	Few castings scrapped due to blowholes or pockets. Gases are able to escape through thin shells or venting. / Nekoliko odljevaka slomljeno obzirom na prolazne rupe ili "džep". Plinove je moguće ispustiti kroz tanke ljuske ili propuhivanjem Moderate porosity and inclusions. Uniform grain structure. Surface roughness ranging from 0.8–12.5 mm Ra. / Ograničena poroznost i uključci. Jednolika zrnata struktura. Površinska hrapavost između 0,8 i 12,5 mm Ra Allowances of ±0.25–±0.5mm should be added for dimensions across the parting line. / Tolerancija od ±0.25–±0.5mm biti će dodana dimenzijama kroz diobenu liniju

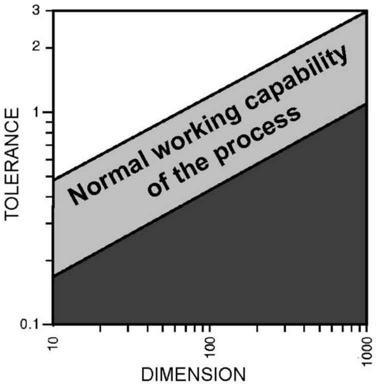


Figure 2. Shell molding process information [2]

Slika 2. Podaci o školjkastom lijevu [2]

The processing cost estimates for the part presented in Figure 1. are given in Table 2. They can help the process planner to select the optimal process and to minimize project and product costs. It is important to mention that relative cost associated with tolerance or surface finish coefficient (C_{ft}) takes into account the need of additional machining since most primary processes are not capable of achieving final tolerances and surface finishes. In this case, forging turns out to be the most suitable primary process due to material, design, batch quantity and other process limitations.

This cost estimation could be inaccurate since at this level it is not possible to determine sequence of operations, positioning and work-holding [8], queuing due to failures or facility occupation, number of machines. It has been shown that variants of process planning can have significant influence on production time and thus on the cost of production as well [9].

2.2 Screening Process Selection (Using Hard Copy Diagrams) [5]

This method produces a list of processes that are able to meet design requirements. The list of requirements usually includes size, minimum section, surface area, shape, complexity, tolerances, surface roughness and material (melting point or hardness). A pair of requirements is plotted onto charts to obtain the search area. Processes that overlap these areas are the ones that could meet design requirements.

For the valve (Figure 1.) the requirements are defined as follows: material is stainless steel (T_m = 1400 °C, ρ = 7900 kg/m3, yield strength 400 N/mm^3), minimal section is 6.15 mm, surface area is $4.65 \cdot 10^{-3}$ mm^2, volume is $8.76 \cdot 10^{-6}$ mm^3, weight is 0.07 kg, mean precision is ±0.2 mm, roughness is 0.8 μm. The complexity of the part in this method is estimated and is given as a number

Table 2. Estimated cost of processing the part in question

Tablica 2. Procijenjeni trošak izrade razmatranog dijela

Primary process / Primarni proces	Shape complexity / Složenost oblika	Volume / Volumen mm^3	C_{mt}	W_c	M_c	P_c	C_c	C_{mp}	Section / Presjek mm	C_s	Tolerance / Toleranca mm	C_t	Surface finish / Hrapavost obrađene površine Ra, µm	C_f	C_{ft}	$P_c \times R_c$	Mi (euro-cent) / cent EUR-a
Invest-ment casting / Precizni lijev	A1	8760	0.00377	1.0	33.03	29.2	1	1	6.1	1	0.01	4.3	0.8	1.3	4.3	125.35	158.37
Forging / Kovanje	A1	8760	0.00377	1.1	36.33	1.9	1	2	6.1	1.3	0.01	4.2	0.8	2.4	4.2	20.75	57.08
Automa-tic machin-ing / Automatska obrada	A1	8760	0.00377	1.6	52.84	2.9	1	4	6.1	1.0	0.01	3.5	0.8	1.3	3.5	40.60	93.44

within the range from 1 (simple) to 5 (very complex). This may be a bit subjective rating. In our work [10] we developed an algorithm for shape complexity measure. The algorithm is still under development because it did not include data such as tolerances and surface roughness, which certainly have an impact on the complexity of the part regarding production.

For a given pair of parameters, the charts suggest processes that should be able to meet these requirements. Combining the results from different charts according to various parameters, as shown in Table 3., processes that do not meet all requirements are eliminated process candidates.

Table 3. Process selection results from different charts

Tablica 3. Odabir rezultata procesa temeljem različitih dijagrama

$t/\sqrt{A}$ - Volume / Volumen	Complexity level - Size, kg / Razina složenosti-Veličina, kg	Tolerance - Roughness / Tolerancija - Hrapavost	Hardness - Melting temp. / Tvrdoća –Temperatura lijevanja
machining, cold working, hot working, electro forming, powder methods, pressure die casting, investment casting, sheet working, polymer molding, micro fabrication, gravity casting / obrada odvajanjem čestica, , hladni rad, rad na vruće, elektro oblikovanje, metode obrade praha, tlačno lijevanje, precizni lijev, obradalima, lijevanje polimera, mikro obrada, kokilni lijev	machining, polymer molding, pressure die casting, investment casting, deformation processing, molecular methods / obrada odvajanjem čestica, lijevanje polimera, tlačno lijevanje, precizno lijevanje, deformacijski proces, molekularna metoda	machining, cold deformation, pressure casting, investment casting, closed die forging, hot deformation / obrada odvajanjem čestica, hladna deformacija, tlačno lijevanje, precizno lijevanje, kovanje u ukovnju, vruća deformacija	machining, vacuum casting, warm working, e-beam casting, powder methods, hot working, cold working, electroforming, conventional casting / obrada odvajanjem čestica, lijevanje pod vakumom, topla obrada, e-beam lijevanje, metode obrade praha, vruća obrada, hladna obrada, elektrooblikovanje, konvencionalno lijevanje

The processes that appear in all chart combinations are machining, investment casting, cold working (deformation) and hot working (deformation). Selection does not include batch size, production rate and process accessibility. Also, the final selection should consider production costs which can be estimated according to the expression (2) [5].

$$C = \text{material costs} + \frac{\text{labour cost}}{\text{batch rate}} + \frac{\text{capital cost}}{\text{batch size}}. \tag{2}$$

The problem is that in the early stage of process planning, costs are not well known to give a good estimation. Therefore, further process elimination based on such cost prediction could lead to wrong decisions. It should be mentioned that Boothroyd in [4] presented equations for early cost estimation.

3. New challenges in education in manufacturing

It has been observed that high education does not fully reflect the real needs of the industry that faces problems of integrative nature across the traditional disciplines, such as: a) working globally in a multicultural environment, b) working in interdisciplinary, multi-skill teams, c) sharing of work tasks on a global level, d) working with digital tools for communication, e) working in a virtual environment [11].

Therefore, special efforts have been made in integration of technical field, humanistic field (sociology, economy, history, culture, psychology, etc.), with IT skills and web technologies.

Over a longer time, a decreased interest in studying technical and natural sciences has been observed (especially in developed countries – the northeast part of Europe). Serious efforts have been made in developing questionnaires on the attitude of future students towards attractiveness of possible studies, data collecting and analysis and development of new curricula taking into account students' interests, motivation, self-learning [12], multimedia, Internet, IT and web technologies (Projects PISA, ROSE) [13]. A new approach to learning, quality assessment of the learned material, personal communication between users and tutors, and importance of psychological relationship between user and tutor ("blindly'') has been accepted. Choice of material and design solution as part of simultaneous engineering cannot be done on purely technical and economical criteria, but must also take into account recycling, pollution and disassembly and reuse concerns.

3.1. E-Lapp Application Description

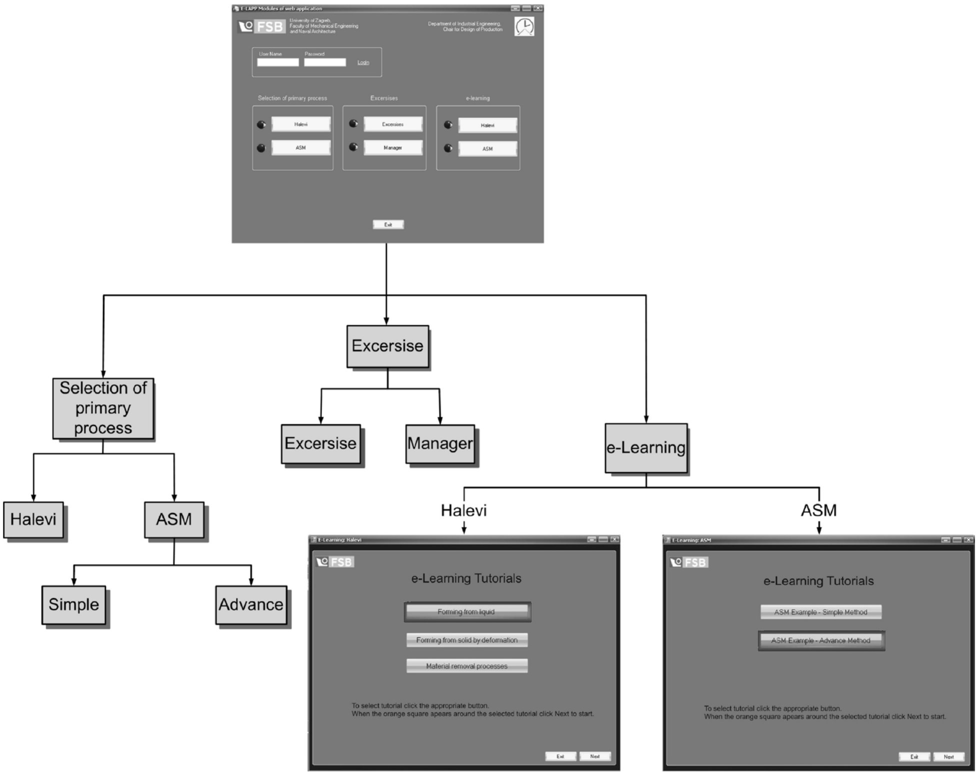
E – *learning application for process planning* (E – LAPP) [7] has been created to help students better understand material that is taught at our university. It is conceived in three different modules: *Selection of Primary Process*, *Exercises*, and *E-learning* as it is shown in the flowchart below (Figure 3.).

The first module named *Selection of Primary Process* enables students to determine an appropriate primary process for manufacturing the required part. There are two different methods available to select the primary process. The first method is named after the author Gideon Halevi. During the development of application for the second method, ASM Handbooks [7] were used, so it is called ASM [14] (http://ptp.fsb.hr).

The *Halevi* method enables students to select a primary process only by knowing material, shape complexity and required quantity. Based on input parameters the application lists a process sequence. The first listed forming process is the most acceptable, but if there are some reasons why this process cannot be used, a student is allowed to choose the next one on the list.

Application e-LAPP [15] also offers a student the possibility to infiltrate deeper into the chosen process. For example, if the student clicks on 'Forming from Solid by Material Removal' and presses the button 'Next' a new window will open where the student can input required data about the part. By pressing the button 'Calculate' the application will list required process sequences and dimensions of the considered part with tolerances and surface roughness.

The *ASM* method offers students the choice between two different approaches of primary process selection: *Simple Process Planning Method* and *Advanced Process Planning Method*.



To select tutorial click the appropriate button.
When the orange square apears around the selected tutorial click Next to start.

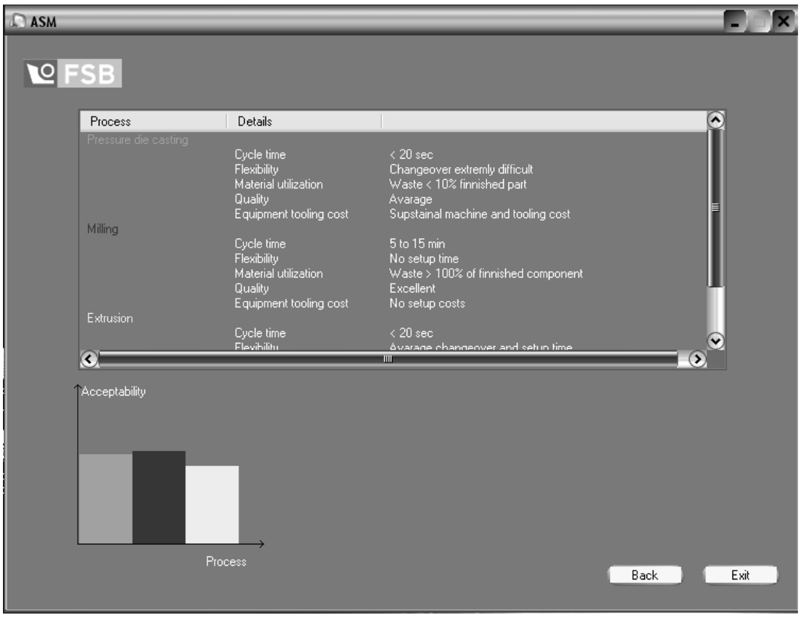
To select tutorial click the appropriate button.
When the orange square apears around the selected tutorial click Next to start.

Figure 3. E-LAPP flowchart [7]

Slika 3. E-LAPP dijagram tijeka [7]

The *Simple Process Planning Method* is conceived in a way that on the basis of input parameters such as material, surface roughness, dimensional accuracy, complexity, production rate, production run, relative costs and size (projected area) the first selection and a list of possible operations is made.

In the next step the application asks a student to rank the offered criteria: cycle time, flexibility, quality, material utilization and operating costs and demand the last condition in order to make the last selection. The required condition is 'shape'. After the last selection is made, the application lists possible solutions in a table with adequate explanations. There is also a graph of process acceptability. It is important to mention that the graph only suggests to the student which process is the most acceptable, but it is up to the student and his knowledge to judge if that process is really the most acceptable (Figure 4.).



Process	Details	
Pressure die casting		
	Cycle time	< 20 sec
	Flexibility	Changeover extremly difficult
	Material utilization	Waste < 10% finnished part
	Quality	Avarage
	Equipment tooling cost	Supstainal machine and tooling cost
Milling		
	Cycle time	5 to 15 min
	Flexibility	No setup time
	Material utilization	Waste > 100% of finnished component
	Quality	Excellent
	Equipment tooling cost	No setup costs
Extrusion		
	Cycle time	< 20 sec
	Flexibility	Avarage changeover and setup time

Figure 4. Suggested primary process (ASM) – Simple Process Planning

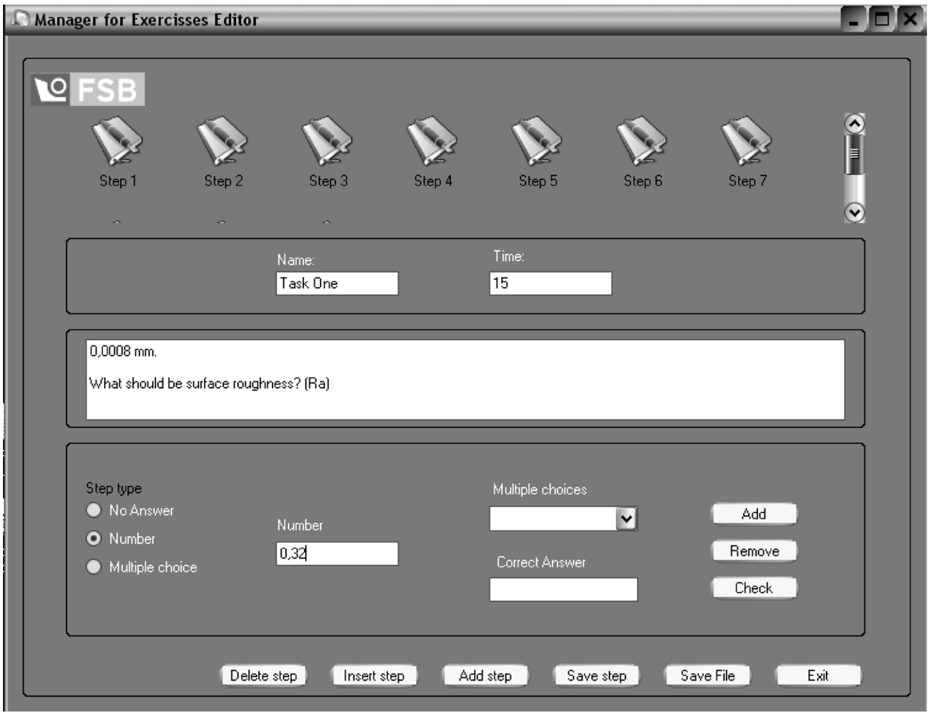
Slika 4. Sugeriran primarni proces po ASM-u- Jednostavan proces planiranja

The *Advanced Process Planning Method* offers students a different approach to the problem. The first selection is here made on the basis of material. Based on the type of material, the application lists the basic operation for process planning: Forming from Solid by Material Removal, Welding, Forging, Forming from Solid by Deformation, and Forming from Liquid (Casting, Molding). Once the basic operation is chosen, all other calculations are made for that basic operation. First, the application offers the student to choose an adequate shape according to the table. Next, the application requires the student to input other necessary parameters and then a final, deeper selection is made. The results are presented in a graph of acceptability. It is important to mention that, as in the case of the *Simple Process Planning Method*, the graph only suggests to the student which process is the most acceptable, but it is up to the student and his knowledge to decide if that process is really the most acceptable.

The second module is Exercises. It is divided into two entities: Exercise and Manager. Manager (Figure 5.) enables tutors and students to create tasks that can be time limited. When the tutor creates a task, he uploads it on to the internet on a page created for E-LAPP [14]. The task can be created as an exercise. After the tutor uploads the task on the web page, students can download it and input it in the application. Running the option Exercise, the student can solve the task that has been given by the tutor or another student. After each solved task, the student gets feedback information about how successful he/she has been, i.e. he/she wins points. For each correctly solved step the student gets one point. When the application is connected to the internet and the student is logged on, the application saves results that can be later reviewed by both the student and the tutor (Self learning as formative learning).

The third module is e-learning. It enables students to understand the core of the task problem, because the aim of this application is not to teach students how to input values into the software and get a solution. The application is created, in the first place, to help students to better understand problems that occur in production almost every day.

The module is divided into two entities: Halevi and ASM [3,7]. Each entity has a few solved examples that show background of the task. The examples are created as short tutorials (Figure 6.) that present step by step task solution with all necessary explanations and tables used in the process of decision making. Each step is no longer than a minute so that the student can stay focused on the subject if he/she misses something and has to play the step again. There is a high possibility of students losing interest in this type of learning if the e-learning tutorials are too long, especially if they have to repeat them several times. During the tutorial development special attention was paid to duration and dynamics. Students are able to stop, pause, rewind and fast forward the tutorial so that they can scrutinize every aspect of it.



Name: Task One

Time: 15

0,0008 mm.

What should be surface roughness? (Ra)

Step type
- ○ No Answer
- ● Number
- ○ Multiple choice

Number: 0,32

Multiple choices:

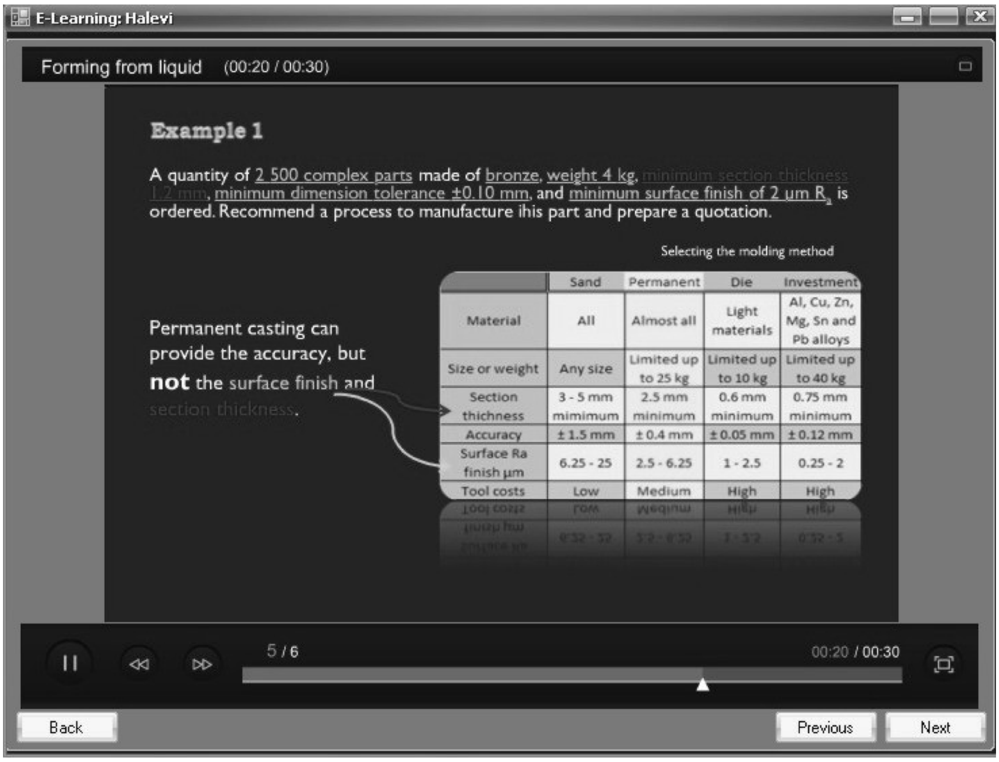
Correct Answer:

Figure 5. Example of Manager Module work

Slika 5. Primjer Upravljanja Module rada

4. Influence of shape complexity

In terms of manufacturing processes, production costs and quality of final product, complexity plays an important role in the selection of the most suitable manufacturing process. The objective is to research the relation between shape complexity, production time and costs, technology used to produce such part, group technology, etc [7]. Shape complexity metrics will be targeted as an appraisal of the fundamental purpose of the manufacturing analysis.



Example 1

A quantity of 2 500 complex parts made of bronze, weight 4 kg, minimum section thickness 1.2 mm, minimum dimension tolerance ±0.10 mm, and minimum surface finish of 2 µm R_a is ordered. Recommend a process to manufacture ihis part and prepare a quotation.

Permanent casting can provide the accuracy, but **not** the surface finish and section thickness.

Selecting the molding method

	Sand	Permanent	Die	Investment
Material	All	Almost all	Light materials	Al, Cu, Zn, Mg, Sn and Pb alloys
Size or weight	Any size	Limited up to 25 kg	Limited up to 10 kg	Limited up to 40 kg
Section thichness	3 - 5 mm mimimum	2.5 mm minimum	0.6 mm minimum	0.75 mm minimum
Accuracy	± 1.5 mm	± 0.4 mm	± 0.05 mm	± 0.12 mm
Surface Ra finish µm	6.25 - 25	2.5 - 6.25	1 - 2.5	0.25 - 2
Tool costs	Low	Medium	High	High

Figure 6. E-learning tutorial

Slika 6. E-učenje priručnik

To do so we need some kind of criterion for part shape complexity. The aim is to compute the shape complexity number of a 2D shape (in the future also for 3D surface). This is an attempt to produce some sort of quantification, thus considerable further research is required to make complexity a practically useful concept. Figure 7 shows a general procedure for determining shape complexity of closed 2D shapes.

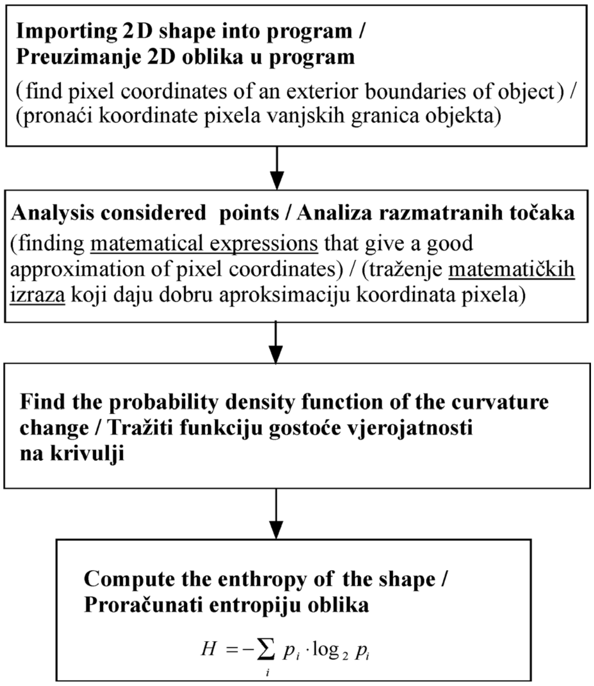


Figure 7. General procedure for shape complexity of 2D shapes og product

Slika 7. Opća procedura za određenje složenosti 2D oblika proizvoda

4.1. Mathematical description of shape

In order to ensure geometry analysis initial data are needed. For this purpose an algorithm is written, which analyzes bitmap image and traces pixel coordinates on the contour of the shape. These "points" are used later to define lines and curves that fit them well enough. Figure 8 shows a plot of these "points" in a graph.

The algorithm analyzes points and divides them into logical segments as shown in the example in Figure 9. The aim was to find vertices, straight segments, curved segments, places where *x* or *y* values change trend.

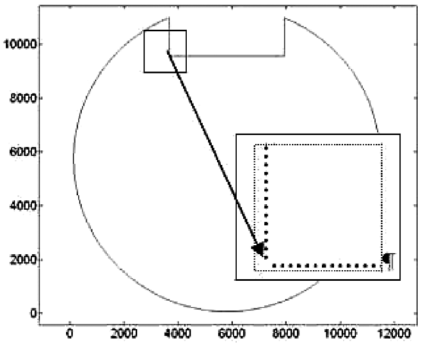


Figure 8. Shape imported in program

Slika 8. Oblik "preuzet" u aplikaciju

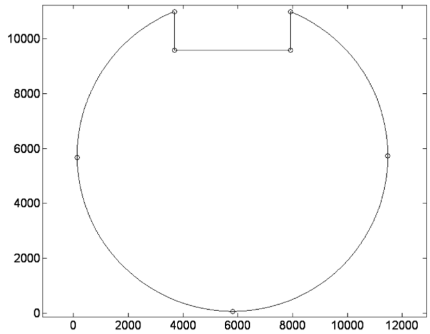


Figure 9. 2D shape divided into "logical" segments

Slika 9. 2D oblik podijeljen "logičkim" dijelovima

Points belonging to certain "logical" segment are approximated by curves/lines [16]. The result is that each "logical" segment is defined by a mathematical equation. Figure 10 visually shows fitness of this approximation for our example shape.

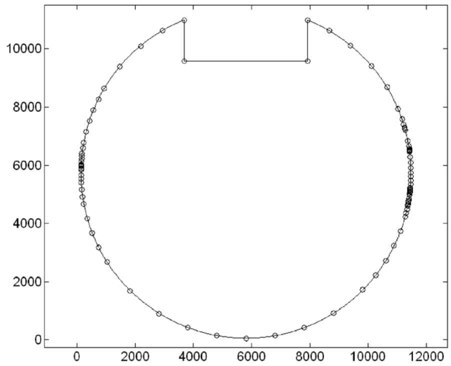


Figure 10. Splines and lines (with nodes) that approximate 2D shape

Slika 10. Spline krivulje (sa čvorovima) koje aproksimiraju 2D oblik

4.2. Shape analysis and complexity measure

After the shape has been defined by mathematical expressions, the curvature change along the curve is analyzed. Since the distance between adjacent sampling points is equal, i.e. sampling is uniform, the curvature change can be substituted with the angle change between tangents on the curve in each sample point (Figure 11).

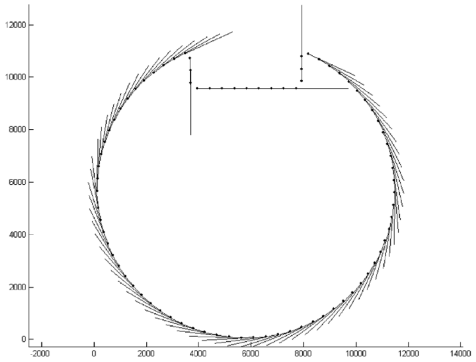


Figure 11. Tangents in points along the contour of the shape

Slika 11. Tangente u točkama uzduž konture oblika

An algorithm is used to analyze the values of the sampled angle changes and to find their probability distribution. Cluster analysis is used to group samples [17]. Figure 14 shows probability distribution of samples for the shape from Figure 13.

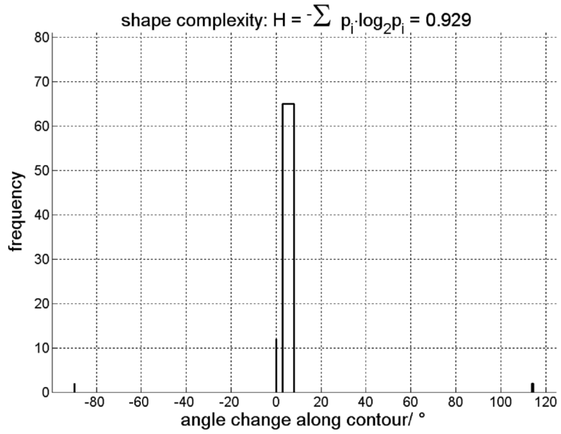


Figure 12. Analysis of angle change along the contour

Slika 12. Analiza promjene kuta uzduž konture

Shape complexity is defined through entropy as a measure of sample randomness [18]. The entropy is expressed as $H=-\Sigma p_i \cdot \log_2 p_i$, where p_i is the probability of a certain outcome (angle change along the contour in this case [19]. The ultimate goal is to calculate the shape entropy as a measure of shape complexity.

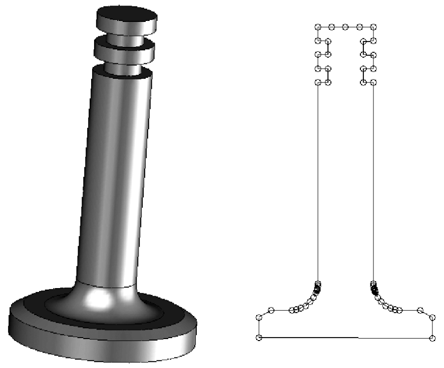


Figure 13. Contour of a valve approximated by splines and lines

Slika 13. Kontura ventila aproksimirana "slone" krivuljama i linijama

The entropy of a shape presented in Figure 10 is H=0.929. The shape shown in Figure 13 has the entropy of H=2.052. By observing these two shapes it is clear at a glance which one is more complex, but this analysis provides exact value suitable for quantitative comparison of different shapes.

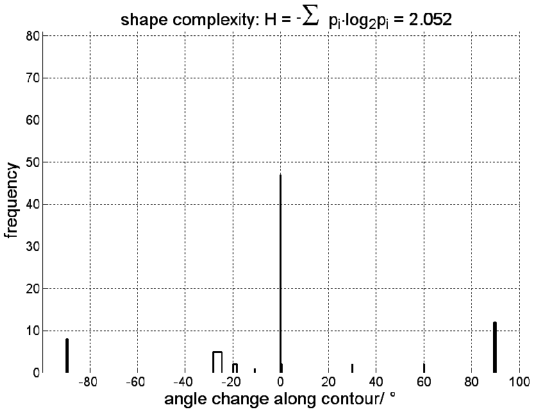


Figure 14. Analysis of angle change along the contour for the valve

Slika 14. Analiza promjene kuta uzduž konture za ventil

5. Conclusion

The problem of the workpiece shape recognition, and technological process selection and optimization always includes the possibility of shape complexity assessment, and selection of primary process and sequence of operations.

The article explains a general approach in writing an algorithm that calculates shape complexity for 2D shapes. Complexity was observed through curvature change along the shape contour. The complexity was calculated for two different shapes. It was shown that a more complex shape has a higher value of entropy.

A process planner has the responsibility to ensure that the design satisfies manufacturing process capabilities and to suggest alternatives which could reduce production costs. The first process selection strategy is capable of giving a unique answer concerning which process is optimal regarding its costs and capability, although elimination of processes in the 2nd step could be a bit inaccurate regarding limited information about particular process. Then the second strategy of candidate process "screening" is more precise but it usually provides more than one process and further reduction is not often possible in the early stage due to the lack of information.

We believe that education has to keep up with technology, so we decided to offer students from our university one modern aspect of learning. Writing tests and homework on computers are becoming an everyday practice, because it saves time for professors, results are available immediately and professor's prejudice is excluded. Also e-learning animated tutorials are quite a hit these days because people are mostly visual beings, so it is easier for us to learn something and understand it if it is vividly presented.

Some of the research results regarding process planning and operation sequencing selection have been also applied in the education software e-LAPP.

Acknowledgments

This project is a part of the scientific projects (2007-2009) titled Process Production Impacts to the Competitive and Sustainable Development 120-1521781-3116 financed by the Ministry of Science and Technology of the Republic of Croatia and Slovenian-Croatian project of bilateral cooperation in science and technology, (2007-2008) named Virtual Manufacturing – Step to Competiveness and Sustainable Development. We express gratitude for the financial support for these projects.

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