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Multi-criteria selection of manufacturing processes in the conceptual process planning

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A B S T R A C T

Process planning is one of the most difficult tasks in product development caused by the large number of technical, technological, economic, environmental and other criteria. Accordingly, the selection of manufacturing processes is a complex multi-criteria decision making problem since it considers a number of possible alternative manufacturing processes in addition to a large number of specified criteria. This paper represents the computer-aided methodology for the multi-criteria evaluation and selection of manufacturing processes at the stage of conceptual process planning. The developed methodology is primarily focused on the mapping of product design and manufacturing requirements. Manufacturing processes that fail to meet the given conditions on the basis of 10 criteria such as materials, production volume, productivity, dimensional accuracy, surface finish, etc., are eliminated according to the developed rules. Then, the multi-criteria evaluation and ranking of manufacturing processes is performed based on 5 criteria: manufacturing cycle time, process flexibility, material utilization, quality and operating costs. Based on this methodology, a system is developed for the multi-criteria selection of manufacturing processes, whose implementation is presented in the case of the hip joint endoprosthesis.

A R T I C L E I N F O

Keywords:
Manufacturing processes
Conceptual process planning
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Process selection

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1. Introduction

A central place in the product life cycle is allocated to the product development, where all activities are defined, from an idea to the product placement on the market [1]. The influence of the stages of product development on the total product cost, time and quality depends on the product type, production type, environment and many other techno-economic factors. Generally, the influence of the conceptual product development is around 5-10 % in the total manufacturing cost, and wrong decisions in this stage can affect the increase in manufacturing cost in more than 60 % [2]. It is therefore necessary to consider the production problem as early as possible, in the stage of product design, i.e. the development of product concept, because the costs are even higher due to product changes if they are made in the later stages of product development [2-4]. Product development is a multi-dimensional problem determined by product exploitation conditions, product function and market requirements on one hand, and conditions and constraints of the manufacturing process on the other hand, Fig. 1.

The selection of manufacturing processes is a complex issue that depends on a number of different criteria, such as material, geometric characteristics of the product, production volume, cost, time, quality, accuracy, and others [5-8]. The main goal of designers is the selection of an optimal manufacturing process which considers a large number of alternatives in addition to a large number of criteria. Thus, the problem has to be observed as a multi-criteria problem, i.e. it requires the implementation of methods for multi-criteria decision-making (MCDM) [9].

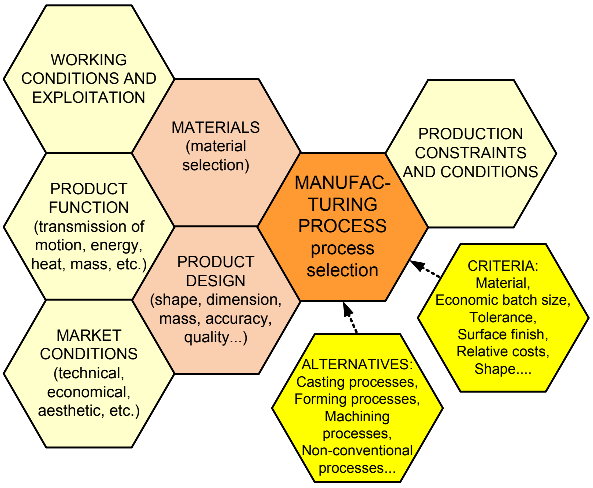


Fig. 1 Manufacturing process selection within the product development

The following chapter represents a literature review in the field of conceptual process planning with emphasis on the activity of manufacturing process selection. The structure of the developed system for multi-criteria selection of primary manufacturing processes and the explanation of the system stages are shown in the third chapter. Within the fourth chapter of the paper the verification of the developed system is performed with the representation of given results. Finally, some conclusions and outlook are given in the chapter five.

2. Literature review and research

Process planning is a complex activity divided into several hierarchical levels. The first level (the highest level) represents a preliminary or conceptual process planning (CPP). The basic task at this level is a support in the early stages of product development in optimizing the design of products from the standpoint of manufacturability, selection of preliminary process plans, and manufacturing cost and time estimation. Output results of this stage of process planning are used at the stages of product design as well as at the stage of detailed process planning, Fig. 2.

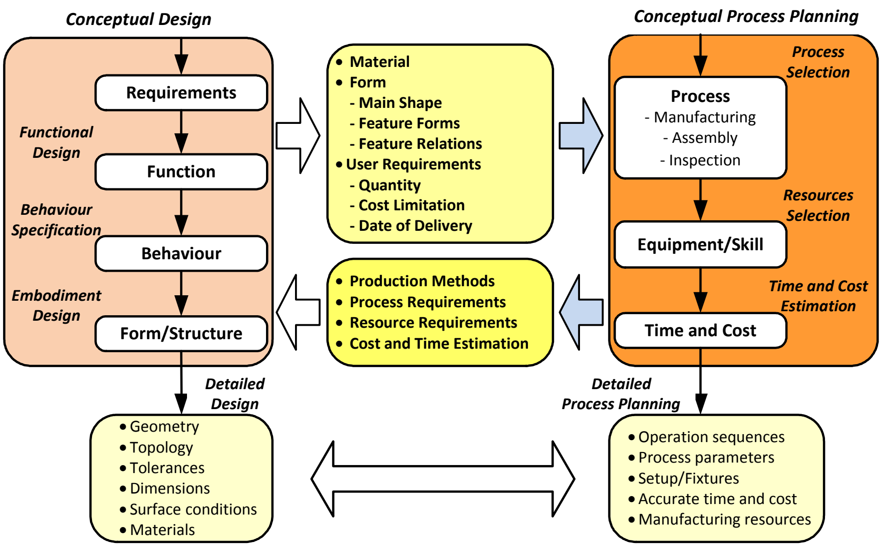


Fig. 2 The place and role of conceptual process planning [10]

Conceptual process planning is in the literature recognized under the terms Meta Process Planning [11], Low-level Process Planning [12], High-level Process Planning [13], Preliminary Process Planning [10], while some consider this stage as a part of the Macro Process Planning [14]. Of course, the content and the sequence of activities that are resolved within the specified stages of process planning are not formulated in the same way, but essentially, tasks that are solved are mutual to a significant degree.

The first activity of conceptual process planning is related to the manufacturability analysis for which the appropriate systems are developed. These systems are designed to identify potential problems in the process of product development and manufacturing, as well as in providing recommendations to designers on how to eliminate or reduce those problems. According to [15], the systems for manufacturability analysis are divided by approach, manufacturability evaluation and level of automation.

Selection of manufacturing processes is the subject of many studies, and some of the most significant are listed below. Dargie et al. [16] developed a system for the selection of materials and processes, named MAPS 1. This research was continued by Shea et al. [17] who developed a system called CAMPS (Computer-Aided Material and Process Selection). The CAMPS is focused on the selection of primary manufacturing processes for casting, forging, material removal and sheet metal processing. Chan et al. [11] built up the COMPASS (Computer Oriented Material, Processes and Apparatus Selection System) system. The system is focused on the selection of primary manufacturing processes while considering available shopfloor resources, which makes this system more interesting for practical uses. Farris [18] generated the expert system for the selection of processing sequence under the name EPSS (Expert Processing Sequence Selector). The procedures in this system are divided into four parts: input data on product geometry, selection of manufacturing process, selection of material and data update. Yu et al. [19] developed the system for the selection and ranking of manufacturing processes (Computer-Aided Design for Manufacturing Process Selection) which is focused on net-shape processes. The geometry is described by the classification of product shape and size. Esawi and Ashby [20] built a system for the selection of materials and processes which included CMS and CPS systems. First, the CMS (Cambridge Materials Selector) for material selection is included, and then the CPS (Cambridge Process Selector) system for the process selection is integrated. The system for material selection is concentrated on the aspect of representing data in the graph form. Data on the selected material are subsequently used for the process selection within the CPS system. Giachetti [21] developed the MaMPS (Material and Manufacturing Process Selection) system that integrates formal multi-attribute decision-making model with the relation database. Smith [22] generated the system for the selection of manufacturing processes and materials under the name MAS (Manufacturing Advisory Service). This system works through a dialogue with the designer based on which the data on product and manufacturing characteristics are defined; after each step, a ranking list of possible processes and materials is updated.

Activities within the conceptual process planning are greatly consistent with the activities related to the design for manufacturing (DfM). Therefore, the group of systems for conceptual process planning that includes the aspects of manufacturing process selection may also include the corresponding DfM software, such as DFMA® [6].

Determination of manufacturing time and cost represents the basis for a better decision-making process in manufacturing practice [23]. The inability of enterprises to determine costs in a quick and efficient manner can significantly endanger their economic survival on the market. In the initial stages, cost and time estimation is usually performed, while the later stages consider the detailed cost and time calculation [24].

The problem of integrating product design and manufacturing processes has been the topic of a number of projects. The SIMA (Systems Integration for Manufacturing Applications) project is focused on the integration of software applications in the area of design, manufacturing and assembly of electromechanical components (parts). The main goal of DPPI (Design and Process Planning Integration) project refers to the realization of communication and integration between conceptual process planning and manufacturing processes [10].

Significant research efforts in the scientific world are dedicated to the development of CAPP (Computer Aided Process Planning) systems that are mainly developed for the detailed process planning stage. This research showed that this is a very complex task that is characterized by many technically and technologically dependent and operating parameters. This is the reason for the lack of adequate universal CAPP system which would enable easy and broad use in industry [25, 26]. It is familiar that the development and application of CAPP systems is falling behind the CAD and CAM systems, which is a major problem in the integration of manufacturing activities [27].

Certainly, there are other studies related to the considered area of research, and some of them are represented in Wang et al. [9], Febransyah [13], Nguyen and Martin [28], Boral and Chakraborty [29], Klancnik et al. [30], and others.

Based on the literature analysis, it can be concluded that the field of conceptual process planning, i.e. manufacturing process selection, has been the research subject in the world for many years. It is identified that there is no universal methodology for manufacturing process selection and that a limited number of different processes and criteria for their selection are covered in recent studies. The main reason for this is the complexity of research in this area. This complexity is caused by a huge amount of data about the characteristics of numerous manufacturing processes, the influence of different criteria on process capabilities (material, surface finish, surface accuracy, time, cost and others), or the emergence of new processes and materials whose characteristics are not sufficiently tested, etc.

Within the covered research, a methodology for the evaluation and selection of manufacturing processes is defined as a synthesis of previously analyzed literature information and research. The first part of the methodology is focused on the elimination of inadequate processes on the basis of established rules and given criteria, while the second part is focused on the application of multi-criteria decision making for the selection of most suitable manufacturing processes on the basis of appropriate criteria for process evaluation. Based on this methodology, an appropriate system is developed. Its main goal is the optimization of manufacturing processes in the conceptual stage of product development, through the selection of possible manufacturing processes on the basis of a large number of product attributes and finally, their multi-criteria evaluation and ranking. AHP (Analitic hierarchy process) method as one of the most important MCDM methods is used for defining weight coefficients (weights) [31-34]. Verification of the system was performed in the case of selecting the best primary manufacturing process for hip joint endoprosthesis body.

3. Developing the system for the multi-criteria evaluation and selection of primary manufacturing processes

In the paper [34], there is a general and functional model for the technological preparation of production, whose integral part is the stage of conceptual process planning. This stage includes four activities, as appropriate CAPP system:

- Manufacturability analysis,
- Evaluation and selection of manufacturing processes,
- Selection of manufacturing resources and
- Manufacturing time and cost estimation.

By analyzing the considered research in the field of manufacturing process selection, the methodology for the evaluation and selection of manufacturing processes is defined, and then implemented for the development of the considered system by following this procedure:

1. *Mapping requirements for the product design*. This phase defines the requirements expected in the manufacturing process, as well as the constraints related to the class of materials, shape, accuracy, production quality, etc. Likewise, a number and type of the optimization criteria (objective functions) is defined here.

2. *Feasibility phase or elimination phase*. This phase evaluates the given manufacturing constraints, and eliminates the processes which fail to meet these constraints.
3. *(Multi-criteria) Optimization phase*. This phase is determined by the evaluation and ranking of manufacturing processes according to the adopted optimization criteria.
4. *Analysis of the obtained results.* In this phase, the detailed analysis of the possibilities for applying the best ranking process is performed.

The structure of the developed system for the multi-criteria selection of primary manufacturing processes is presented in Fig. 3.

Within the feasibility phase, the rules for the process elimination are established. These are based on the possibilities for material/process combinations, economic process application for adequate production volumes, productivity, dimension accuracy and surface finish quality, according to [3-7, 13, 34-37] and others.

There were over 40 different processes considered, and clustered into five groups: Casting processes, Plastic and composite processes, Metal forming processes, Machining processes and Non-conventional processes.

Materials are divided into 14 groups according to the main structural and technological features: iron, carbon steel, alloy steel, stainless steel, Al alloys, Cu alloys, Zn alloys, Mg alloys, Ti alloys, Ni alloys, thermoplastics, thermosets, composite and ceramic materials.

After the automated elimination of processes that fail to meet the previously set criteria, the following step is the overview of the level on which the processes are satisfied for additional criteria: shape complexity, relative costs (workers, equipment and tools), part mass, cross section thickness, as well as shape (surface projection).

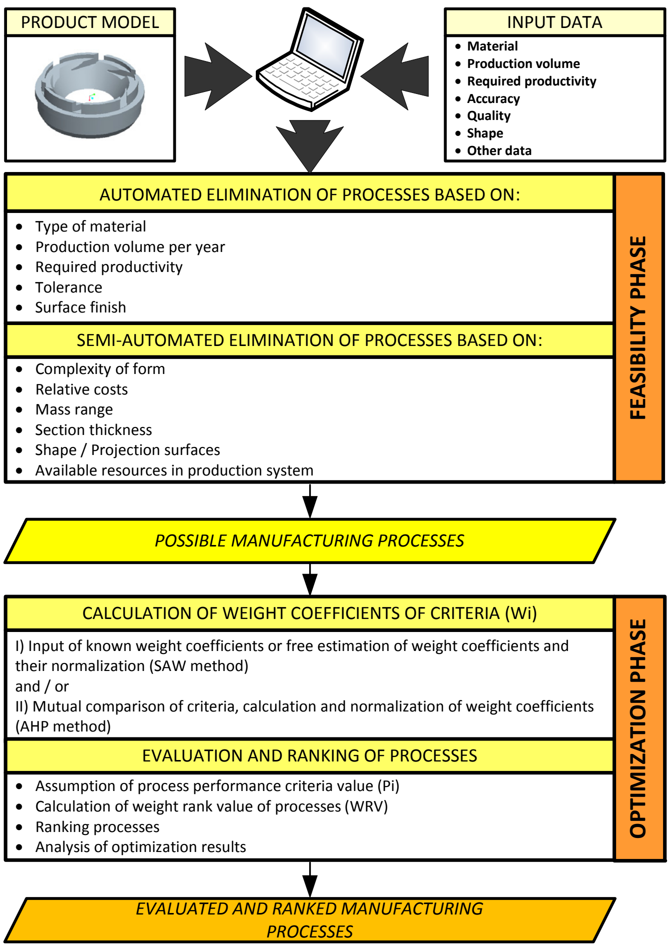


Fig. 3 Structure of the developed system for the multi-criteria selection of primary manufacturing processes

Table 1 Keys to the evaluation of set criteria for the selection of manufacturing processes

No	Criteria	Criteria levels for the selection of manufacturing processes (key evaluation)						Units
1	Combination of material/process	0 – applicable			X – not applicable			-
2	Economic volumes	1-100	100-1000	1000-10000	10000-100000	> 100000	All Quantity	prt/year
3	Productivity	< 10 (N – Low)		10-100 (S –Medium)		> 100 (V – High)		prt/h
4	Dimensional accuracy	> 1.3 (N – Low)		0.13-1.3 (S – Medium)		< 0.13 (V – High)		mm
5	Surface finish (R_a)	> 6.3 (N – Low)		1.6-6.3 (S – Medium)		< 1.6 (V – High)		µm
6	Shape complexity	N – Low		S – Medium		V – High		-
7	Relative costs	N – Low		S – Medium		V – High		-
8	Mass	Defined recommended limits of process capabilities						kg
9	Section thickness min – max	Defined recommended limits of process capabilities						mm
10	Shape (surface projection)	< 0.02 (N - Low)		0.02-0.5 (S - Medium)		> 0.5 (V – High)		m^2

Table 1 shows the defined levels, i.e. keys for the evaluation of the mentioned set of criteria (attributes). Based on these attributes, the elimination or the acceptance of the manufacturing process is performed afterwards.

After eliminating the processes that do not meet the criteria, the optimization phase is being realized. In this phase, the evaluation and ranking of manufacturing processes is conducted. In the observed study, the evaluation system for manufacturing processes according to the ASM (American Society for Metals) is adopted. It includes the following criteria for evaluation: *Cycle time (A), Process flexibility (B), Material utilization (C), Quality (D) and Operating costs (E)*, Fig. 4.

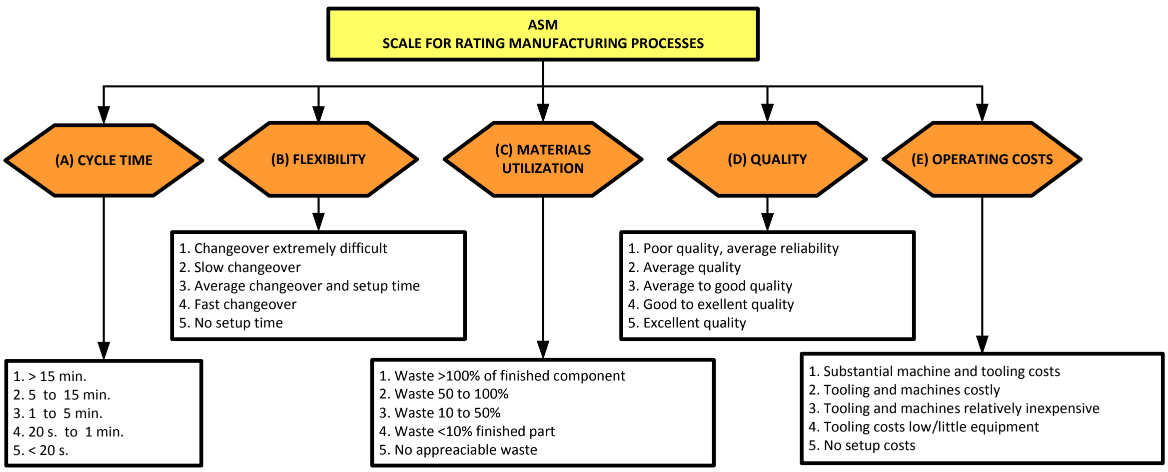


Fig. 4 Criteria for the evaluation of manufacturing process in the metalworking industry (Rank: 1 – poorest; 5 – best) [3]

The evaluation of processes is performed by using the weighted value (P_i), from 1 to 5. Based on the literature data [3-7] and some others as well, the weighted values of processes for the observed criteria are defined. Table 2 shows an example of the evaluation for specific processes.

Table 2 Examples of process performance criteria value P_i

Processes	Criteria for process evaluation				
	A	B	C	D	E
Sand Casting (SC)	2	5	2	2	1
Investment Casting (IC)	2	4	4	4	3
Gravity Die Casting (GDC)	4	2	2	3	2
Pressure Die Casting (PDC)	5	1	4	2	1
Centrifugal Casting (CC)	2	3	5	3	3

Process evaluation is performed according to the expression (1); afterwards, the order of process significance, i.e. process ranking, is determined:

$$WRV = \sum_{i=1}^{n} (P_i) \cdot (W_i) \tag{1}$$

where:

WRW	–	weighted rank value of the process
i = 1 to n	–	total number of criteria (A, B, C, D, E)
P_i	–	process performance criteria value and
W_i	–	weight coefficient of criteria

In the developed application, defining the weight coefficients of the specified criteria (W_i) can be performed in two ways (methods):

<u>I Method:</u> Normalization of the estimated weighted values for weight coefficients, by applying the SAW (simple addition weighting) method (2):

$$W_i = \frac{w_i}{\sum_{i=A}^{E} w_i} \tag{2}$$

where W_i is normalized value of the estimated weight coefficient w_i.

<u>II Method:</u> Mutual comparison of all criteria and the calculation of normalized values of weight coefficients using the methodology that is applied in the AHP method [9, 31, 32, 34].

The matrix A is the matrix in which the mutual comparison of the criteria is done. For n = 5 criteria (A, B, C, D, E), the matrix A has the form according to the Eq. 3.

$$A = \begin{bmatrix} \frac{w_A}{w_A} & \frac{w_A}{w_B} & \cdots & \frac{w_A}{w_E} \\ \frac{w_B}{w_A} & \frac{w_B}{w_B} & \cdots & \frac{w_B}{w_E} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{w_E}{w_A} & \frac{w_E}{w_B} & \cdots & \frac{w_E}{w_E} \end{bmatrix} = \begin{bmatrix} a_{AA} & a_{AB} & \cdots & a_{AE} \\ a_{BA} & a_{BB} & \cdots & a_{BE} \\ \vdots & \vdots & \ddots & \vdots \\ a_{EA} & a_{EB} & \cdots & a_{EE} \end{bmatrix} \tag{3}$$

By calculating the Eqs. 4 and 5, normalized weight coefficients of the criteria W_i can be obtained; $i \in \{A, B, C, D, E\}$. S_{ci} represents the sum of column i of matrix A.

$$|A| = \begin{bmatrix} \frac{a_{AA}}{S_{C1}} & \frac{a_{AB}}{S_{C2}} & \cdots & \frac{a_{AE}}{S_{C5}} \\ \frac{a_{BA}}{S_{C1}} & \frac{a_{BB}}{S_{C2}} & \cdots & \frac{a_{BE}}{S_{C5}} \\ \vdots & \vdots & & \vdots \\ \frac{a_{EA}}{S_{C1}} & \frac{a_{EB}}{S_{C2}} & \ddots \cdots & \frac{a_{EE}}{S_{C5}} \end{bmatrix} \tag{4}$$

$$W_i = \begin{bmatrix} \frac{\sum row_1}{5} \\ \frac{\sum row_2}{5} \\ \frac{\sum row_3}{5} \\ \frac{\sum row_4}{5} \\ \frac{\sum row_5}{5} \end{bmatrix} = \begin{bmatrix} W_A \\ W_B \\ W_C \\ W_D \\ W_E \end{bmatrix} \tag{5}$$

4. Multi-criteria selection of manufacturing processes – Case study

Conforming to time period, implants used in medical prosthetics can be temporary or permanent. According to their design and manufacturing method, implants can be individual or "custom made", following the characteristics of each patient individually, and modular or "ready made", which are usually produced in batches [38]. Modern production of implants is based on the application of flexible manufacturing technologies, such as the processes of casting, forging, machining, as well as direct manufacturing technologies, such as rapid tooling, rapid prototyping and rapid manufacturing, with the support of the corresponding CAx systems.

This paper represents the multi-criteria evaluation and selection of manufacturing processes for the body of modular hip joint endoprosthesis made of the stainless cobalt-chromium-molybdenum (CoCrMo) steel alloy.

In order to select the possible alternatives of the primary manufacturing process for endoprosthesis parts, the following input data are entered in the system, Fig. 5:

- Type of material: Stainless steel,
- Production volume: batch (100-300 part/year),
- Required productivity: low (up to 10 part/hour),
- Dimensional accuracy: medium (0.13-1.3 mm) and
- Surface finish: medium (Ra = 1.6-6.3 µm).

Based on the input data, possible alternatives of primary manufacturing processes are automatically obtained, while possible processes in the appropriate manufacturing conditions are selected for evaluation. Afterwards, weight coefficients of the criteria for process evaluation are determined and the multi-criteria selection is performed. Fig. 6 presents the relative criteria evaluation and the calculated weight coefficient values for evaluating the alternative manufacturing processes for body endoprosthesis according to the abovementioned method (II). When comparing different criteria, the market demands, manufacturing constraints and conditions are also taken into consideration.

After the definition of weight coefficients for the process evaluation, the calculation of weighted rank value of processes (WRV) is completed according to the expression (1). Fig. 7 shows the output results of the evaluation of alternative manufacturing processes for the considered endoprosthesis body with its rank importance.

Fig. 8 represents the overall synthesis of the problem of multi-criteria evaluation and selection of the primary manufacturing process for body endoprosthesis by using both methods for the determination of weight coefficients of the criteria (W_i).

Figs. 9(a) and 9(b) show the influence of some criteria on the rank of the given manufacturing processes for the methods I and II for defining weight coefficients of the criteria.

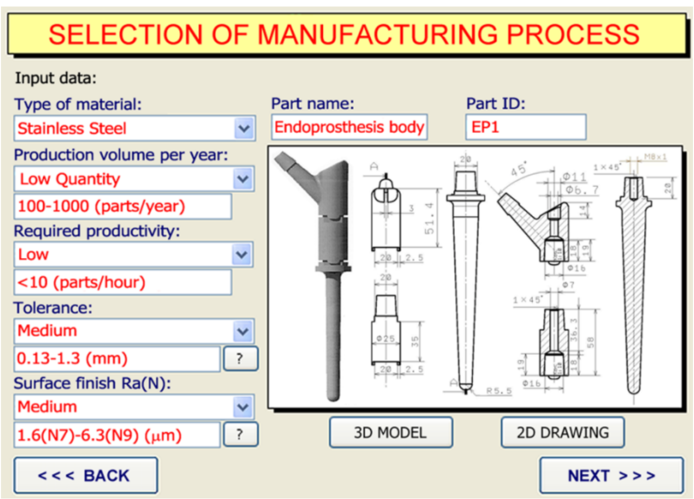


Fig. 5 Representation of the input data for the computer-aided manufacturing process selection

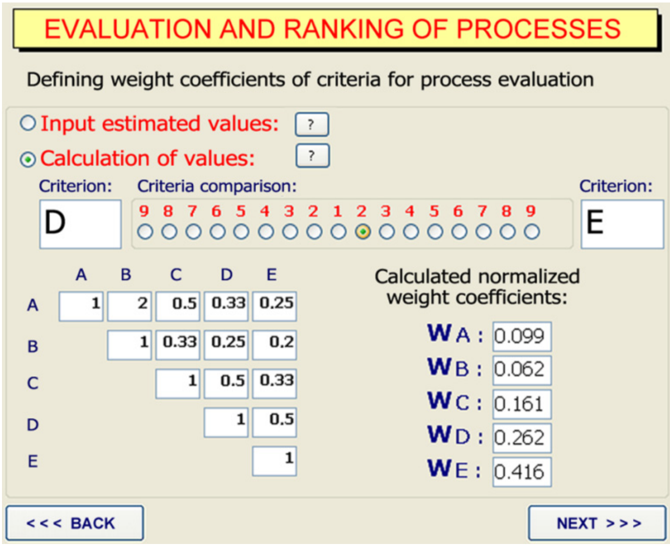
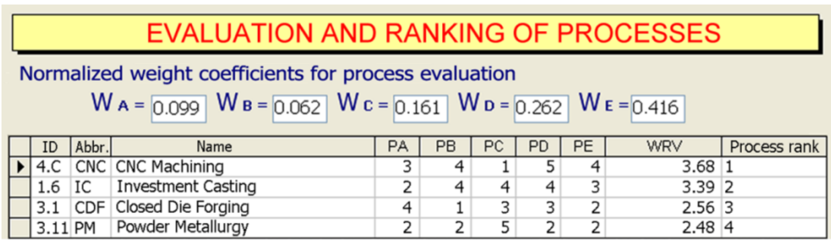


Fig. 6 Calculation of weight coefficients of criteria



ID	Abbr.	Name	PA	PB	PC	PD	PE	WRV	Process rank
4.C	CNC	CNC Machining	3	4	1	5	4	3.68	1
1.6	IC	Investment Casting	2	4	4	4	3	3.39	2
3.1	CDF	Closed Die Forging	4	1	3	3	2	2.56	3
3.11	PM	Powder Metallurgy	2	2	5	2	2	2.48	4

Fig. 7 Results for the evaluation and ranking of alternative primary manufacturing processes for body endoprosthesis

Based on the obtained results, it can be concluded that the most suitable alternative of a primary manufacturing process for the given conditions is CNC machining from blanks, and then precision casting etc., which is also verified using modules for the manufacturing cost estimation in the mentioned conceptual CAPP system.

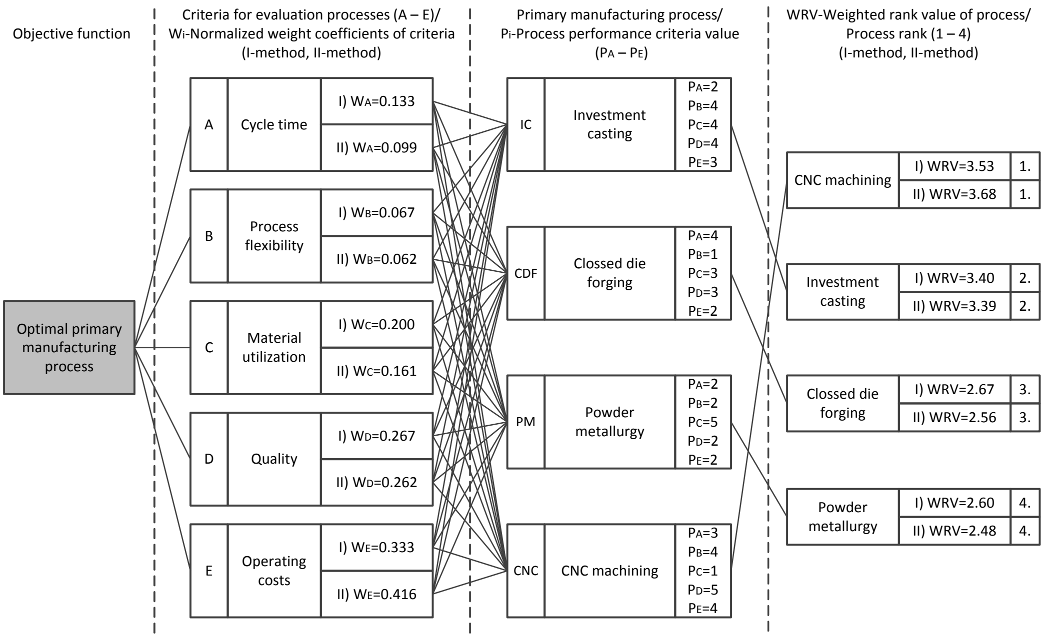
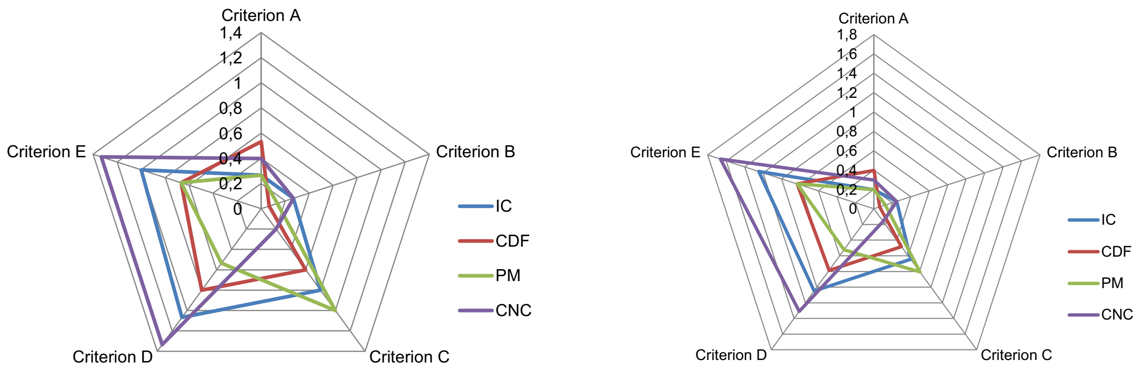


Fig. 8 Overall synthesis of the problem and results of the multi-criteria selection of the primary manufacturing process for body endoprosthesis



a) I method b) II method

Fig. 9 Influence of some criteria on the rank of the process

5. Conclusion

The main contribution of this research refers to the development of a methodology for the multi-criteria decision making of primary manufacturing processes that includes the selection of possible manufacturing processes and their multi-criteria evaluation and ranking. In addition, the contribution of this paper is a brief state of the art review in the field of conceptual process planning as a stage of product development which significantly affects the production cost and time.

Based on the given methodology and the corresponding structures, a system for multi-criteria selection of primary manufacturing processes is developed. The verification of this system is performed in the case of multi-criteria evaluation and selection of a manufacturing process for body endoprosthesis which showed simplicity and practicality of application.

The developed methodology and the corresponding system have the opportunity to be significantly implemented in industry, primarily in the selection of manufacturing processes in early/conceptual stage of product development. A number of researches showed that the majority of design engineers lack knowledge about various manufacturing processes and materials, primarily from their environment, which gives this research an additional value from the numerous techno-economic aspects.

When developing the system, the problems related to the possibility of developing a universal software system for process selection and evaluation were established:

- Lack of complete and systematized basis for the process selection.
- Inability of quantification of all interactions, i.e. influence of all manufacturing processes on the structure and properties of materials and vice versa.
- An increasing number of processes that are not fully examined and processes with incomplete knowledge of material behaviour and other criteria.
- Complexity of ''rule generation”, i.e. the development of knowledge base for process selection.

Selected primary manufacturing processes from the represented system are successfully used as the input data into the module of the system for the manufacturing cost estimation [34]. Within the represented system, the tasks for the selection of primary manufacturing processes are solved, while the issue about the selection of secondary and tertiary processes is not currently addressed. In order to increase the quality of solutions, considered tasks represent a logical continuation of the research which would, apart from the observed approaches to defining weight coefficients and evaluating manufacturing processes, significantly cover the use of AI methods as a support to the multi-criteria decision making process. In addition, the improvement of the system is planned through the development of Web-based system for the conceptual process planning, according to [39].

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