ISSN 1330-3651
UDC/UDK [658.512.2 : 621.791-52] : 519.816

WELDING ROBOTS KINEMATIC STRUCTURES EVALUATION OF BASED ON CONCEPTUAL MODELS USING THE POTENTIAL METHOD

Željko Ivandić, Todor Ergić, Milan Kljajin

Original scientific paper

The article presents a new systematic approach to evaluate kinematic structures of the robot for welding in the application of certain conceptual solutions in different welded forms of product design. Generated conceptual solutions of the welded structure are independent of the eight kinematic structure models of the robots. Conceptual solutions of welded structures are defined according to the possibility of their practical performance as shown in models of product design in welded form. Five groups of welded structures have been analysed with three characteristic examples in each group of products designed at the conceptual level (such an approach makes 15 varieties of solutions) in the form of welded structures. In the paper we shall described a new model of evaluation by the application of the Potential method (one of the decision making tools) as appropriate choice for the concept of kinematic structures of robots for welding in welding technology of steel structures. Selection is carried out based on the list of requirements with twelve independent parameters. These parameters must define the welding robot in fifteen models of welded structures. List of requirements is determined by types of design products (fifteen variant solutions) in welded form. The originality of the proposed evaluation procedure lies mainly in special application of the potential method for evaluating weight factors of kinematic structures of welding robots based on conceptual welded forms of product design. A model for linking a criteria and alternatives of kinematic structures for robot welding is also shown and described. Introduced is the model to determine the criteria to evaluate kinematic structures according to the criteria for welding the fifteen models of welded structures. These two sets of parameters (parameters of the set of kinematic structures and the set of welded forms of product design) make possible the estimation acceptability for application. In the article is calculated the weighted value of solutions of kinematic structures of welding robot that fully satisfies the theoretical settings and/or practical variants solution of a robot with the highest technical performance. Moreover, in order to implement a thorough evaluation process such as decision making based on defined list of requirements in examples in this paper, we suggest and show the procedure that can serve as a procedure for evaluation of other systems for the same purpose using the Potential method.

Key words: *Product design, robot, welding, evaluation, Potential method*

Vrednovanje kinematičkih struktura robota za zavarivanje na temelju koncepcijskih modela primjenom metode potencijala

Izvorni znanstveni članak

Članak predstavlja novi sustavni pristup ocjenjivanju kinematičkih struktura robota za zavarivanje u primjeni određenih koncepcijskih rješenja različitih oblika zavarene konstrukcije proizvoda. Generirana koncepcijska rješenja zavarene konstrukcije ne ovise o osam modela kinematičkih struktura robota. Koncepcijska rješenja zavarene konstrukcije definirana su prema mogućnosti njihove praktične izvedbe kao što je prikazano u modelima proizvoda u zavarenom obliku. Analizirano je pet skupina zavarenih konstrukcija s tri karakteristična primjera u svakoj grupi oblikovanog proizvoda na razini koncepcije (takav pristup daje 15 varijanti rješenja) u obliku zavarenih konstrukcija. U radu je opisan novi model vrednovanja primjenom metode potencijala (jedan od alata za donošenja odluka), prikladan za izbor koncepcije kinematičke strukture robota za zavarivanje u tehnologiji zavarivanja čeličnih konstrukcija. Izbor se provodi na temelju liste zahtjeva s dvanaest neovisnih parametara. Ovi parametri moraju definirati robot za zavarivanje za petnaest modela zavarene konstrukcije. Originalnost predloženog postupka ocjenjivanja nalazi se uglavnom u posebnoj aplikaciji metode potencijala za procjenu težinskih faktora kinematičkih struktura robota za zavarivanje na temelju koncepcije zavarenih oblika proizvoda. Također, prikazan je i opisan model povezivanja kriterija i alternativa kinematičkih struktura robota za zavarivanje. Predstavljen je model za utvrđivanje kriterija za ocjenu kinematičkih struktura prema kriterijima za zavarivanje petnaest modela zavarenih konstrukcija. Ta dva seta parametara (parametri skupa kinematičkih struktura i skup zavarenih oblika proizvoda) čine mogućnost čvrste ocjene prihvatljivosti za primjenu. U članku je određena ponderirana vrijednost rješenja kinematičkih struktura robota za zavarivanje koji u potpunosti zadovoljava teorijske postavke i/ili inačice praktičnog rješenja robota s najvišom tehničkom dobrotom. Štoviše, kako bi se obavila temeljita provedba procesa kakvo je odlučivanje na temelju definirane liste zahtjeva u primjerima ovog rada, predlaže se i pokazuje postupak koji može poslužiti kao postupak za ocjenu drugih sustava za istu svrhu, korištenjem metode potencijala.

Ključne riječi: *Oblikovanje proizvoda, robot, zavarivanje, vrednovanje, Metoda potencijala*

1 Introduction
Uvod

Selection of robot type, which is suitable for arc welding, depends on a number of requirements that need to meet such a robot in the application. This paper does not analyze all the different parameters that are important and have influence on the choice alternative of robots for welding, and more details about this can be found in the literature [1, 2, 3, 4, 5], which does not reduce their importance. It is quite clear that the majority of the requirements on the selection of robots for welding arise from the form of products design. The second part of application requirements arises from the production technology and management of the production process. The complexity of problems because of technical and economic criteria requires a serious approach. Possible irregularities in the application of robots for welding: choice of the wrong type of robot welding; wrong design of the product as unsuitable for welding robot; inaccessible spot welding or a choice of technology for an unacceptable model for robot welding. All of the above and more than this create major problems in the process of production and economic losses. Therefore, the aim of this paper will be to demonstrate the procedure of choosing a robot for welding technologies, which can improve production by applying new technologies and reduce production costs and the humanization of labour in the production end ecological development. The starting point for the selection of types of robots for welding is a list of selected requests that should satisfy the selected type of robot [5].

The selection problem is especially relevant bearing in mind the likely lack of experience of prospective users in robots for welding application. Various methods of robot selection for different purposes are known. Some authors have studied the robots for welding as separate complex systems. Authors Liang and Wang [6] proposed a fuzzy TOPSIS method for robot selection. Author Goh CH [7] proposed a revised procedure for defined weighted sum decision model. That model took into account both objective and subjective attributes of the robots under consideration. The model incorporated values assigned by a group of experts on different attributes in selecting the robots. Parkan and Wu [8] presented a procedure called operational competitiveness rating (OCRA) and a multiple attribute decision making method (TOPSIS).

To the best knowledge of authors the Potential method in the choice of the robots for welding has not been observed. In the paper we shall describe the new model evaluation by the application of the Potential method. The Potential method is one of the decision making tools. But the method is as appropriate for the choice of the concept kinematic structures of robots for welding in welding technology. Contribution of this work has originality of the proposed evaluation procedure through a specially applications based on the potential method for evaluating weight factors of welding robots kinematic structures, based on conceptual welded forms of product design. This method, shown in the paper, giving the final solution in the choice of kinematic robots for welding structure based on the defined list of requirements, which is an approach that has so far not used in this goal.

The paper is organized as follows. In Section 2, eight most-often used kinematic structures of robotic manipulators are presented and requirements which should be fulfilled considering five different conceptual models of welding structures are listed. In Section 3, a brief description of the Potential method is given and in Section 4 its application to the evaluation of different kinematic structures is described based on the aforementioned requirements. The paper ends with conclusions and some ideas for future work.

2 The list of requirements of kinematic structures of welding robots

Lista zahtjeva kinematičkih struktura robota za zavarivanje

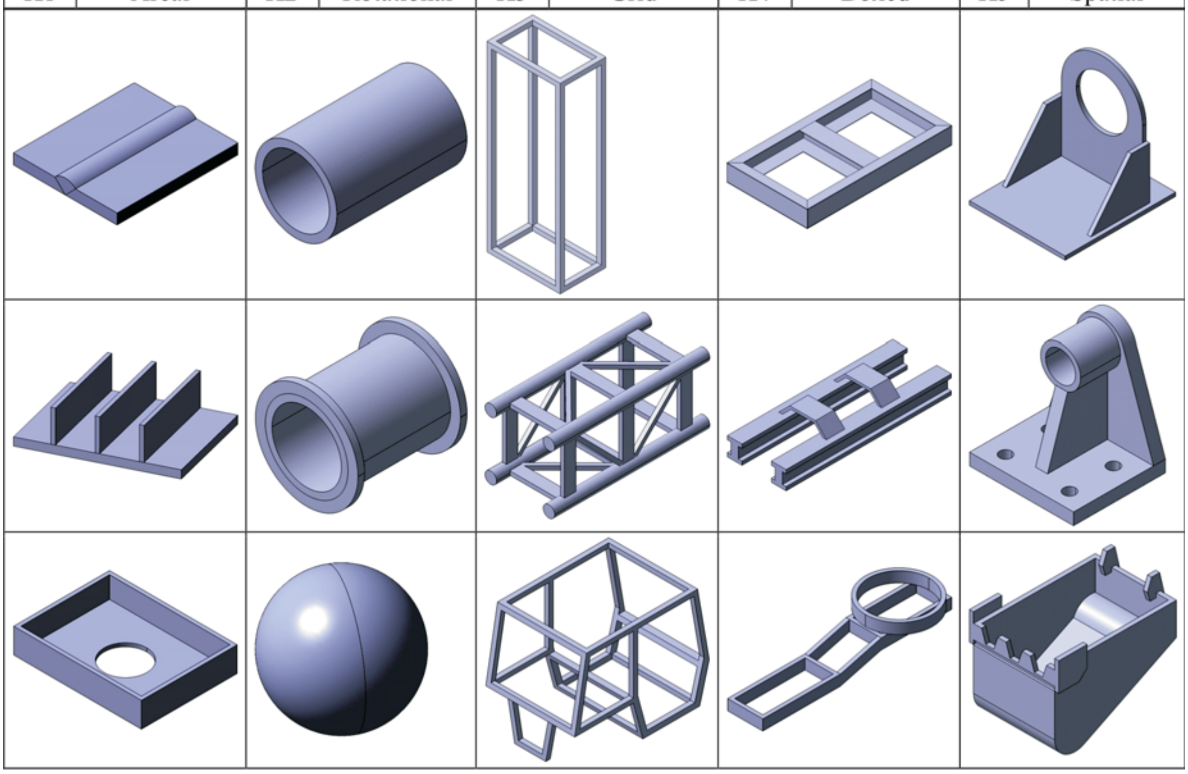
As a starting point for the selection of robot type a list of requirements is made. It should satisfy the selected kinematic structures of robot respecting the selected concept solution type of welded construction. These solutions are given taking into account the possibilities of practical realization. Model evaluation presents the most appropriate argument choice of kinematic structure for welding robot, depending on the group of five selected conceptual welded products design. A requirement to meet the kinematic structure suited to the application of automated welding technology depends on construction performance of products. Five groups of different conceptual solutions of welded structures are shown in Tab. 1.

Areal structure of the product in welded performance: Prevails butt weld, welding lines are straight, long and uninterrupted. Products have relatively large or medium-sized dimension and weight, and navigation tool for welding is unchanged during the process of welding. Places of welding are accessible by a positive influence of gravity on welding which does not require frequent reorientation of the product.

Rotational structure of the product in the welded performance: Prevails butt weld, welding lines are rotary or straight, long and continuous with the ability to simplify the process of welding (rotary devices and other ancillary equipment). Products have a relatively large or medium-sized dimension and weight. Navigation tool for welding process during welding is irreversible, and places for

Table 1 *Groups of conceptual structure models of the product in welded construction* [3, 5, 9]
Tablica 1. *Grupe modela koncepcijskih struktura proizvoda u zavarenoj konstrukcijskoj izvedbi* [3, 5, 9]

Conceptual structure of the product models									
K1	Areal	K2	Rotational	K3	Grid	K4	Boxed	K5	Spatial



welding are accessible. Favourable position of weld due to the influence of gravity does not require the position change of products for welding and reorientation.

Lattice structure of the product in the welded performance: Prevails corner weld, welding lines are straight, short and discontinuous. Many of the same welds recur by the length and orientation. Products have a relatively large or medium-sized dimension and weight. Navigation tool for welding process during welding is unchanged, and access to the location of welding can be complicated. Adverse position of the weld due to the influence of gravity on welding requires frequent reorientation of the product.

Boxed structure of the product in the welded performance: Prevails corner weld, welding lines are straight and linear, a relatively large number of the short and broken welds. Products have a relatively large or medium-sized dimension and weight. Navigation tool for welding process during welding is unchanged, and access to the location of welding is typically complicated. Adverse position of the weld due to the influence of gravity on the welding requires frequent reorientation of the product.

Spatial structure of the product in the welded performance: Prevails corner weld, welding lines are straight and curved a relatively large number of the short and broken welds. Products have a relatively large or medium-sized dimension and weight. Navigation tool for welding process during welding is floating, and access to the location of welding is typically primitive. Adverse position of the weld due to the influence of gravity on the welding requires frequent reorientation of the product. In addition to these features of products that results from construction and they have other requests, some of which can be systematically shown in Tab. 2.

To reach any point in three-dimensional manipulation space three degrees of freedom of motion of the open kinematic chain robot are necessary (but not always sufficient). For orientation in attain point three degrees of freedom of motion are necessary. Therefore, most modern industrial robot has six degrees of freedom of movement, of which the last three rotations around the axes that intersect at most one point. As each degree of freedom of motion can be translation (T) or rotary (R), the kinematic chain can be built on eight different ways, which corresponds to the number of variations with repetition of the third row with two elements (which is 8). Each rotary and translation degree of freedom of motion can be selected in three ways, and each variation can be written in as many ways as there are variations with repetition of three elements of the third row (which is 27).

Therefore, it can be for an open kinematic chain with three degrees of freedom of motion to get a total of 216 different combinations of kinematic structure (8 × 27 = 216). Among these 216 kinematic structures dimensional space manipulation is not possible. In general, despite its three-dimensionality it can be achieved only by the motion of the line or plane, or just make one-dimensional or two-dimensional space. Such structures are not spatial, and they occur when in the structure occur: two similar translations, three similar rotations, two non-similar translations and rotation around the third axis, and the two similar rotations and translation along one of the remaining two axes.

Using these starting points, from 216 theoretically possible kinematic structures, 87 are not spatially buildable. It means that the requested space by setting coordinates can be achieved with 129 buildable kinematic structures of manipulators/robots. If you adopt the recommendations that result from the dynamic analysis, that the first article of the robot needs to be compulsory vertical, then the number of theoretically possible structures is reduced to 72. Applying the criteria for the number of probable spatial buildable structures that number is reduced to 43, whereof 40 are symmetrical and rotated for $\pi/2$ about the axis z.

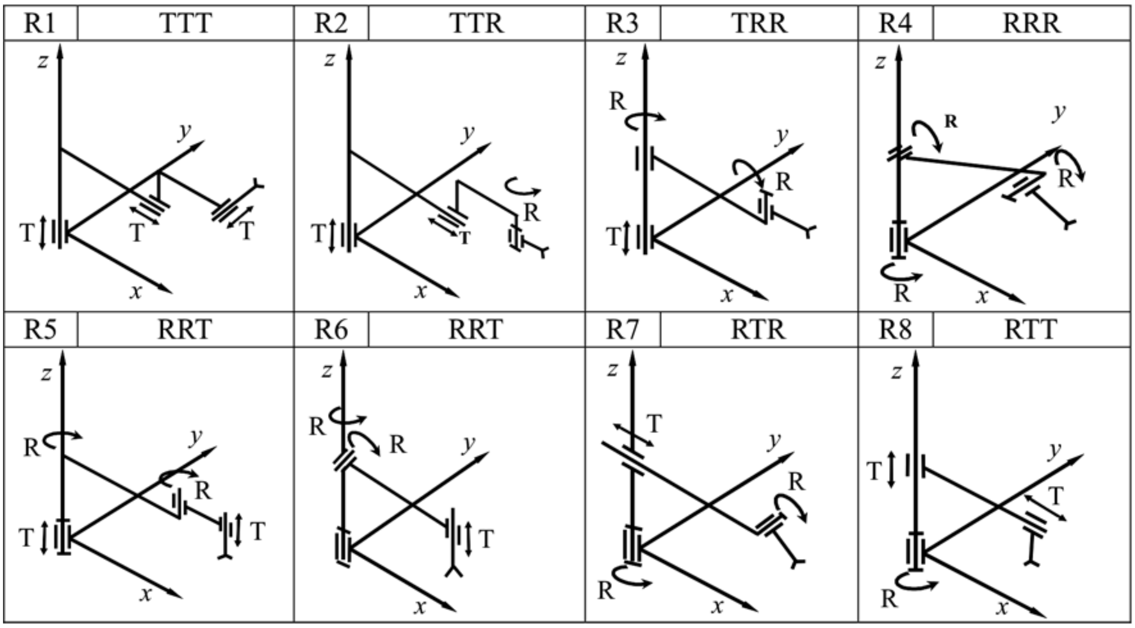
Practically, there are 23 different buildable spatial structures, of which the eight analyzed are schematically shown in Tab. 3. Rating of each type of robot performance is given in Tab. 3.

Due to capability of applications for welded structure as in Tab. 1 it can be determined.

***Table 2** List of requests for different kinematic structure for welding robot*
***Tablica 2.** Lista zahtjeva za različite kinematičke strukture robot za zavarivanje*

Number	Requirements due to the kinematic structure of the robot able to use in the welding technology for typed products according to Table1.	Size, units, tolerances	Description of application	
			Request	Wish
1	Robot is designed for arc welding		T✓	
2	Type of kinematic structure should be universal (suitable for all five groups of conceptual product structure in welded construction)		T✓	
3	The size of the product fits into a certain shape			
	• Max. length	≤ 5000 mm	F✓	
	• Max. width	≤ 2000 mm	F✓	
	• Max. height	≤ 1000 mm	F✓	
4	Simple performance			O,E✓
5	Very mobile structure		F✓	
6	A good working range		F✓	
7	Satisfactory speed and acceleration of welding	$v \leq$ 1,5 m/s	F✓	
8	Satisfactory accuracy	≤ 0,25 mm	F✓	
9	Load (mass)	≤ 10 kg	F✓	
10	Is easily programmed			O,T✓
11	Easy to maintain			O,E✓
12	Price is justified considering the size of a series production	$2{,}5\times10^6$ pieces/year		E✓
Notes: F - functionality, T - Technologically, E - Economically, O - Maintenance,				

Table 3 *Schematic overview of the kinematic structures of welding robots that will be analyzed in terms of suitability for welding*
Tablica 3. *Shematski prikaz kinematičkih struktura robota za zavarivanje koji će biti analizirani u pogledu prikladnosti za zavarivanje*



3
Brief description of the Potential method
Kratki opis Metode potencijala

By author L. Čaklović [10, 11, 12, 13] let us suppose that a decision maker makes pair wise comparisons on the set of alternatives V. A pair $\alpha=(u, v)\in V\times V$ is declared to be an arc of a directed graph if v is more preferred than u. An un-compared pair is not adjacent in the graph. The set of all arcs is denoted by A. A function $F{:}A\rightarrow\Re$ which assigns to each arc $\alpha\in A$ α its weight of preference is called a preference flow. Evidently, preference flow is always non-negative and can be represented as an $m\times 1$ matrix. Directed graph (V, A) is called a preference graph. The preference graph is complete if each pair of alternatives is compared i.e. if for each pair $\{i, j\}$ of vertices $(i, j)\in A$ or $(j, i)\in A$. For a given flow F on the preference graph (V, A) and $\alpha\in A$ we use a convention $F(-\alpha){:}=-F(\alpha)$. Let us denote by n and m the cardinality of V and A respectively. Incidence matrix of the preference graph is denoted by B and it is $m\times n$ matrix defined by [10, 11, 12, 13]:

$$B_{\alpha,i}=\begin{cases}-1\rightarrow \text{if the arc}\,\alpha\text{ leaves the node i}\\ 1\rightarrow \text{if the arc}\,\alpha\text{ enters the node i}\\ 0\rightarrow \text{otherwise}\end{cases}\tag{1}$$

Let F be a given preference flow, and B incidence matrix of the graph. Moreover, let us assume that the graph is weakly connected (connected in the sequel). System [13]:

$$B^{\tau}BX=B^{\tau}F,\ \sum_{i=1}^{m}X_i=0\,.\tag{2}$$

Has a unique solution called normal integral of F. One can think of the first equation in (1) as the normal equation associated to $BX=F$. The potential difference BX of *normal integral* is the best approximation of F by column space of incidence matrix. In a network flow context, a function $X{:}V\rightarrow\Re$ is called potential and that is the reason why the method gets its name: Potential Method. One can think of X as a utility function and this is true in consistent situation when $BX=F$. If the graph is not connected, the normal integral is unique on each connected component of the graph. To obtain a ranking, after having X, the following formula can be used [13]:

$$w=\frac{a^X}{\left\|a^X\right\|_1},\ a\succ 0\tag{3}$$

Where exponential function of X is defined component wise, i.e. $(a^X)_i=a^{X_i}$, and $\|\cdot\|_1$ is l_1 norm. Parameter a can be arbitrary, currently we use value $a=2$.

If more than one criterion is present then, each criterion C_i generates its own graph (V, A_i) and its own flow F_i. Let us denote the weight of the i-th criterion by w_i. We are going to describe a procedure of making a consensus graph (V, A) and consensus flow F for the group of all criteria. First, for a given pair $\alpha=(u, v)$ we calculate [13]:

$$F_\alpha:=\sum_{\substack{i=1\\ \pm\alpha\in A_i}}^{k}w_iF_i(\alpha)\,,\tag{4}$$

where the term $w_iF_i(\alpha)$ contributes if and only if $\pm\alpha\in A_i$ i.e. . if and only if $F_i(\alpha)$ or $F_i(-\alpha)$ is defined. If this sum is non-negative, then we put α in the set of arcs A and $F(\alpha){:}=F_\alpha$. Otherwise, we define $-\alpha=(v, u)$ as an arc in A and $F(-\alpha){:}=F_\alpha$. The flow F becomes a non-negative flow that is called consensus flow. It can happen that consensus graph has a cycle. Anyway, normal integral of F exists and it is unique. The presence of cycles can only generate bigger inconsistency. For more details please consult [13].

Table 4 *Tags, content and level of criteria in a hierarchical structure for the specified model*
Tablica 4. *Oznake, sadržaj i razina kriterija u hijerarhijskoj strukturi za navedeni model*

Number of criteria	Designation of criteria	Content of criteria	Level of criteria
1	C_{100}	Evaluation to select according to the hierarchical structure of criteria simple kinematics structure that is suitable for multipurpose use, simple programming, reliable in operation and easy maintenance	1
2	C_{110}	Multi (flexible) solution	2
3	C_{120}	Model of optimal variants kinematic structure	2
4	C_{130}	Easy programming	2
5	C_{140}	High reliability	2
6	C_{150}	Easy maintenance	2
7	C_{121}	Mobility (redundantly)	3
8	C_{122}	Good working volume	3
9	C_{123}	Easily taking the position in space	3
10	C_{124}	Simple structure	3

4
The evaluation process by the Potential method of welding robot kinematic structures
Proces vrednovanja metodom potencijala kinematičkih struktura robota za zavarivanje

Most importantly and simultaneously the first step in evaluation is identification criteria of evaluation and determining the hierarchical structure which results from the most important requirements and wishes from the list of requirements (Tab. 2). In determining the system of criteria we have to meet the following requirements [4, 5, 9]:

- The system of criteria should be complete, so it does not happen to the fundamental valuation point view or boundary conditions remain non-account
- Individual partial criteria, against which evaluation is conducted, must be mutually independent.

This means that activities undertaken in terms of increasing the degree of goodness or meeting the criteria of variant solutions with respect to one partial one criterion may not have a partial impact on other criteria. Each criterion in an assessment of the level assigns relevance to the criteria and levels. The task of evaluation is to select one kinematic structure of the robot for automated welding technology, these conceptual structures of the product as expensive solution $K=\{K_1,..., K_5\}$, which has a simple concept, which is suitable for multipurpose use, simple programming, reliable in operation and easy maintenance. If we define the criteria and sub criteria as follows in Tab. 4, we uniquely determine the direction of the process of evaluation activities.

In this way the hierarchical structure can in this case be graphically represented as oriented graphs – a hierarchical tree structure of the criteria defined by the three levels of systems.

Hierarchic structure of evaluation model (Fig. 1) is given with finite levels number (for more details please consult [4]):

$$H_c, \forall c = 1,..., g\,. \tag{5}$$

The hierarchical structure of criteria (Fig. 1) to directly test through the kinematic structures R_1,..., R_8 for welding robot as well as the fourth level, in order to determine the most acceptable for the selection and application of welding

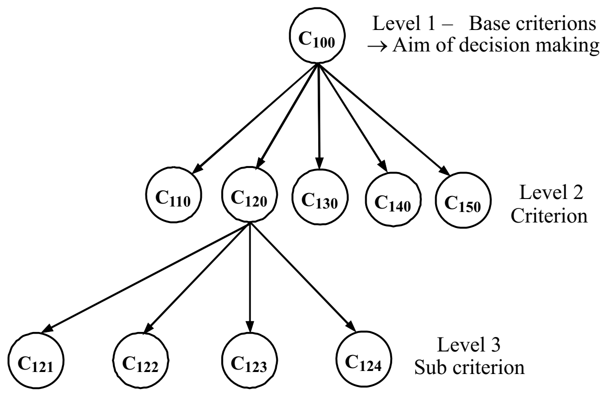


Figure 1 *The hierarchical structure of criteria in the evaluation procedure of kinematic structures for welding robot*
Slika 1. *Hijerarhijska struktura kriterija u proceduri vrednovanja kinematičkih struktura robota za zavarivanje*

robots in welding technology. In this way, the defined equipment is very complex relation ρ_{nk} between space design variant solutions kinematic structures of welding robots in reference to set of criteria presentation in Fig. 2.

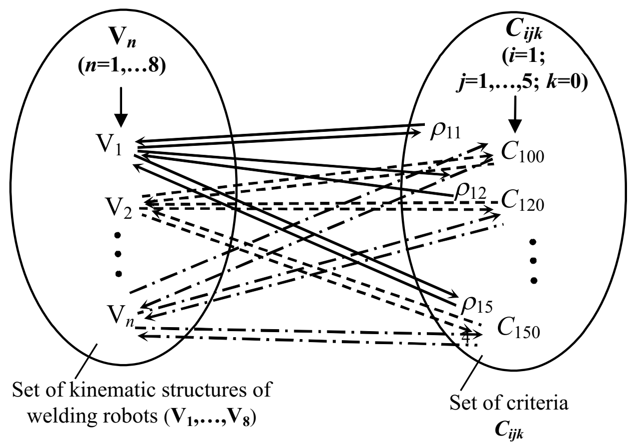


Figure 2 *The graphical representation of relations of kinematic structure and criteria for second-level (C_{100},..., C_{150})*
Slika 2. *Grafički prikaz relacijskih odnosa kinematičkih struktura i kriterija druge razine (C_{100},..., C_{150})*

The model (Fig. 2) equipment relation ρ_{np} of set kinematic structures $[V]_n$ in identification with set criteria $[C]_{ijk}$ as such as second level in example (i=1; j=1,…,5; k=0). So for the second level i=1; j=1,..,5; k=0 of simplified relations can be written $R=V_n x C_p$ (where p takes the value of variable index of a plane that is evaluated) from the Relation in Fig. 2 can be shown:

$$[R(V(n=1,...,8)\leftrightarrow C(i=1, j=1,...,5; k=0))]= \tag{6}$$
$$=[R(V(n=1,...,8)\leftrightarrow C(p=j=1,...,5;))]=$$
$$=[R(V_n x \leftrightarrow C_p)]=\begin{Bmatrix}\rho_{11} & \rho_{12} & \cdot & \rho_{1p}\\ \rho_{21} & \rho_{22} & \cdot & \rho_{2p}\\ \cdot & \cdot & \cdot & \cdot\\ \rho_{n1} & \rho_{n2} & \cdot & \rho_{np}\end{Bmatrix}=\begin{Bmatrix}\rho_{11} & \rho_{12} & \cdot & \rho_{15}\\ \rho_{21} & \rho_{22} & \cdot & \rho_{25}\\ \cdot & \cdot & \cdot & \cdot\\ \rho_{81} & \rho_{82} & \cdot & \rho_{85}\end{Bmatrix}$$

Relational matrix R has a component of the relationship as the relation between criteria of second level and alternative solutions (analogously for the other levels will be determined, for more details, pleas consult [4]). The task is to make assessment of the degree of realization of a set of criteria to set the level of alternative solutions. In this procedure starting from the base element, which is the rating:

$$o_{np}, n=1,...,r; p=1,...,t. \tag{7}$$

Rating is a numerical value and determines how each variant solution is to meet the set criteria. Key role in all components of a process is to determine the rating matrix by designers or the expert development team. Development team regularly consists of a number of experts of various fields (the team of evaluators). Its task is to make decisions about estimate and grades of the principal varieties of solutions. General decision making about estimate can be written as [4, 14, 15, 16]:

$$R=\mathbf{E}\cdot\mathbf{C}, \tag{8}$$

where is:
E - the set of evaluators in process of evaluation,
C - a set of criteria
R - a set of relationship between **E** and **C**.

For the general case of group decision-making by decision makers to set criteria for the matrix of relations R is a process of evaluation as decision making about estimate of second level in example (absolute selection of level criteria is general shown):

$$[R(Q)]\rightarrow\left[Q\left(\begin{Bmatrix}E_1\\E_2\\ \cdot\\E_n\end{Bmatrix}\times\begin{Bmatrix}C_1\\C_2\\ \cdot\\C_k\end{Bmatrix}\right)\right]=\begin{Bmatrix}o_{11} & o_{12} & \cdot & o_{1k}\\ o_{21} & o_{22} & \cdot & o_{2k}\\ \cdot & \cdot & \cdot & \cdot\\ o_{n1} & o_{n2} & \cdot & o_{nk}\end{Bmatrix}. \tag{9}$$

Then taking into account the rating based on estimate the already defined access for n evaluators to second level of H_c in relation to each criterion i, j, k can be defined matrix of estimate (for more details, please consult [4]), as follows:

$$Q_{cp}{}^{N}\left(o_{ijk}\left(\begin{Bmatrix}C_{110}\\C_{120}\\C_{130}\\C_{140}\\C_{150}\end{Bmatrix}\right)\right)=Q_{2p}{}^{N}\left(o_{1jk}\left(C_{1jk}\right)\right). \tag{10}$$

Of course, when we know the matrix of estimate for second level (10) toward (6, 7, 8, 9) or each level H_c (5) and for evaluation of individual criteria, the value of grades for the individual criteria set of solutions with respect example of second level and N=1, can be defined (Tab. 5).

Table 5 *The estimate for the sub set criteria C_{110}, ..., C_{150}*
Tablica 5 *Ocjene za podskup kriterija C_{110}, ..., C_{150}*

Rating: C_{110},.., C_{150}	Criteria: C_{110}	Criteria: C_{120}	Criteria: C_{130}	Criteria: C_{140}	Criteria: C_{150}
$Q_{cp}(o_{ijk}(C_{1jk}))$ c=2; p=j; i=1; j=1,…, 5; k=0	4	5	1	3	2

The matrix of estimate from (10) for second level in example has the form for sub set C_{110},…, C_{150}:

$$Q_{cp}\left(o_{ijk}\left(\begin{Bmatrix}C_{110}\\C_{120}\\C_{130}\\C_{140}\\C_{150}\end{Bmatrix}\right)\right)=Q_{2p}\left(o_{1jk}\left(C_{1jk}\right)\right)=\begin{bmatrix}Q_{21}(o_{121}(C_{110}))\\Q_{22}(o_{122}(C_{120}))\\Q_{23}(o_{123}(C_{130}))\\Q_{24}(o_{124}(C_{140}))\\Q_{25}(o_{125}(C_{150}))\end{bmatrix}=\begin{bmatrix}4\\5\\1\\3\\2\end{bmatrix} \tag{11}$$

Matrix of estimate criteria is derived from the rating Table 4. In this way a hierarchical structure to resolve the problem set is fully defined and described. Defining the hierarchical structure of criteria, the list of requirements and rating matrix in example of second levels, provides second-level implementation in the process of evaluation for each of the next levels of criteria. Later in this work follows the original version of evaluation procedures for the election of acceptable kinematic structure of the robot/manipulator for welding of selected 5 types of welded products from three sub groups in each primary group. For full implementation of the model evaluation it is necessary to establish the following matrix, as shown in the following equations and tables (more details may be seen in [3, 4, 5]). Matrix rating criteria C_{121},…, C_{124} is derived from the rating Tab. 6.

Table 6 *The estimate for the sub set criteria C_{121},…, C_{124}*
Tablica 6. *Ocjene za podskup kriterija C_{121},…, C_{124}*

Rating: C_{121}, ..., C_{124}	Criteria: C_{121}	Criteria: C_{122}	Criteria: C_{123}	Criteria: C_{124}
$Q_{cp}(o_{ijk}(C_{1jk}))$ c=3; p=j; i=1; j=2; k=1,..., 4	4	5	3	2

Matrix rating sub criteria C_{121},…, C_{124} in function of C_{120} is given by:

$$Q_{cp}\left(o_{ijk}\left(\begin{Bmatrix}C_{121}\\C_{122}\\C_{123}\\C_{124}\end{Bmatrix}\right)\right)=Q_{3p}\left(o_{1jk}\left(C_{1jk}\right)\right)=\begin{bmatrix}Q_{31}(o_{131}(C_{121}))\\Q_{32}(o_{132}(C_{122}))\\Q_{33}(o_{133}(C_{123}))\\Q_{34}(o_{134}(C_{124}))\end{bmatrix}=\begin{bmatrix}4\\5\\3\\2\end{bmatrix} \tag{12}$$

***Table** 7 The estimate for elements of set solutions $R_1, \dots, R_8$*
***Tablica** 7. Rezultati ocjena elemenata skupa rješenja $R_1, \dots, R_8$*

Criteria	Values of criteria	R1		R2		R3		R4		R5		R6		R7		R8	
C_{110}	4	3	12	1	4	1	4	5	20	2	8	1	4	1	4	4	16
C_{121}	1,42857143	1	1,4	1	1,4	4	5,7	5	7,1	4	5,7	1	1,4	1	1,4	4	5,7
C_{122}	1,78571429	1	1,8	2	3,6	3	5,4	5	8,9	3	5,4	4	7,1	4	7,1	3	5,4
C_{123}	1,07142857	5	5,4	2	2,1	5	5,4	5	5,4	3	3,2	5	5,4	2	2,1	5	5,4
C_{124}	0,7142857	4	2,8	4	2,8	1	0,7	5	3,6	4	2,8	4	2,8	4	2,8	2	1,4
C_{130}	1	5	5	4	4	3	3	5	5	4	4	5	5	4	4	4	4
C_{140}	3	3	9	3	9	4	12	4	12	3	9	4	12	3	9	3	9
C_{150}	2	3	6	3	6	4	8	4	8	2	4	4	8	3	6	3	6
Non norm	**15**	**25**	**43,4**	**20**	**33**	**25**	**44,1**	**38**	**70**	**25**	**42,1**	**28**	**45,8**	**22**	**36,6**	**28**	**52,8**
Utility	**3,06607143**	**25**	**2,9**	**20**	**2,2**	**25**	**2,9**	**38**	**4,6**	**25**	**2,8**	**28**	**3,1**	**22**	**2,4**	**28**	**3,5**
X Potential		**25**	**-0,1708**	**20**	**-0,866**	**25**	**-0,12321**	**38**	**1,6006**	**25**	**-0,25655**	**28**	**-0,014**	**22**	**-0,628**	**28**	**0,4577**
w Rang		**25**	**0,0962**	**20**	**0,0594**	**25**	**0,09941**	**38**	**0,32836**	**25**	**0,090634**	**28**	**0,1073**	**22**	**0,07006**	**28**	**0,1487**

Preferences defined in a way that all criteria are in relation to each other in order to determine the degree of importance as the preferences targeted at the same level. Defining the table to address the criteria for each principle and component determine the matrix-targeted preference. Matrix of rating the kinematic structure $R_1, \dots, R_8$ is derived from the rating Tab. 7.

The value of the utility function of each variant is given in the last row. For R1 is scalar product between the first and second column. In the column under R1 is validity of R1 for each criterion in the last row of the value across all criteria Then the matrix of rating kinematic structures $R_1, \dots, R_8$ related to $C_{110}, \dots, C_{150}, C_{121}, \dots, C_{124}$ can be given by (see Tab. 7):

$$Q_{cp}\left(o_{ijk}\left(\left\{\left\{\begin{matrix} C_{110} \\ \cdot \\ C_{150} \\ C_{121} \\ \cdot \\ C_{124} \end{matrix}\right\} \rightarrow \left\{\begin{matrix} R_1 \\ \cdot \\ R_8 \end{matrix}\right\}\right\}\right)\right) = \begin{bmatrix} 3 & 1 & 1 & 5 & 4 & 5 & 3 & 3 \\ 1 & 1 & 2 & 2 & 4 & 4 & 3 & 3 \\ 1 & 4 & 3 & 5 & 1 & 3 & 4 & 4 \\ 5 & 5 & 5 & 5 & 5 & 5 & 4 & 4 \\ 2 & 4 & 3 & 3 & 4 & 4 & 3 & 2 \\ 1 & 1 & 4 & 5 & 4 & 5 & 4 & 4 \\ 1 & 1 & 4 & 2 & 4 & 4 & 3 & 3 \\ 4 & 4 & 3 & 5 & 2 & 4 & 3 & 3 \end{bmatrix} \quad (13)$$

Then the components of the matrix rating $R_1, \dots, R_8$ are completely and unequivocally defined. Of course, when we know the matrix evaluation of individual criteria between set of kinematic structures and set of criteria we can define the preference for individual decision criteria set by the appreciation of the value of preference. Preferences are defined in a way that in each level hierarchical structures face rating matrix components in order to determine the degree of importance of targeted preference at the same level. Relations between the criteria are shown in Tab. 8 (i=1; j=1,…, 5; k=0) [3, 4, 5].

***Table 8** Relations between the criteria in order to determine the preference*
***Tablica 8.** Relacijski odnos kriterija međusobno u cilju određivanja prednosti*

$R(Q(C_{jk}))$	C_{110}	C_{120}	C_{130}	C_{140}	C_{150}
C_{110}	ρ_{11}	ρ_{12}	ρ_{13}	ρ_{14}	ρ_{15}
C_{120}	ρ_{21}	ρ_{22}	ρ_{23}	ρ_{24}	ρ_{25}
C_{130}	ρ_{31}	ρ_{32}	ρ_{33}	ρ_{34}	ρ_{35}
C_{140}	ρ_{41}	ρ_{42}	ρ_{43}	ρ_{44}	ρ_{45}
C_{150}	ρ_{51}	ρ_{52}	ρ_{53}	ρ_{54}	ρ_{55}

Therefore, the relation matrix is a matrix of preference:

$$[R] \rightarrow \left[\vec{P}\left(\left\{\begin{matrix} C_{110} \\ C_{120} \\ \cdot \\ C_{150} \end{matrix}\right\} \times \left\{\begin{matrix} C_{110} \\ C_{120} \\ \cdot \\ C_{150} \end{matrix}\right\}\right)\right] = \left\{\begin{matrix} \alpha_{11} & \alpha_{12} & \cdot & \alpha_{15} \\ \alpha_{21} & \alpha_{22} & \cdot & \alpha_{25} \\ \cdot & \cdot & \cdot & \cdot \\ \alpha_{n1} & \alpha_{n2} & \cdot & \alpha_{nn} \end{matrix}\right\}. \quad (14)$$

Then the matrix-oriented preference $\vec{P}_{C110,\dots,C150}$ of the criteria $C_{110}, \dots, C_{150}$ is given by [3, 4, 5]:

$$\left[\vec{P}\left(\left\{\begin{matrix} C_{110} \\ C_{120} \\ C_{130} \\ C_{140} \\ C_{150} \end{matrix}\right\} \times \left\{\begin{matrix} C_{110} \\ C_{120} \\ C_{130} \\ C_{140} \\ C_{150} \end{matrix}\right\}\right)\right] = \vec{P}_{C110,\dots,C150} = \begin{bmatrix} 0 & -1 & 3 & 1 & 2 \\ 1 & 0 & 4 & 2 & 3 \\ -3 & -4 & 0 & -2 & -1 \\ -1 & -2 & 2 & 0 & 1 \\ -2 & -3 & 1 & -1 & 0 \end{bmatrix} \quad (15)$$

Then the matrix-oriented preference $\vec{P}_{C121,\dots,C124}$ of the criteria $C_{121}, \dots, C_{124}$ is given by [3, 4, 5]:

$$\left[\vec{P}\left(\left\{\begin{matrix} C_{121} \\ C_{122} \\ C_{123} \\ C_{124} \end{matrix}\right\} \times \left\{\begin{matrix} C_{121} \\ C_{122} \\ C_{123} \\ C_{124} \end{matrix}\right\}\right)\right] = \vec{P}_{C121,\dots,C124} = \begin{bmatrix} 0 & -1 & 1 & 2 \\ 1 & 0 & 2 & 3 \\ -1 & -2 & 0 & 1 \\ -2 & -3 & -1 & 0 \end{bmatrix} \quad (16)$$

The matrix-oriented preferences $\vec{P}_{R_{1,..,}R_8}$ for a hierarchical system of evaluation have as many elements as the criteria and from them derived sub criteria (more details may be seen in [3, 4, 5]). It is sufficient to show only one of them, as a function of criteria C_{110}:

$$\vec{P}_{R_1,...,R_8}\left(\begin{Bmatrix} R_1(C_{110}) \\ \cdot \\ R_8(C_{110}) \end{Bmatrix} \times \begin{Bmatrix} R_1(C_{110}) \\ \cdot \\ R_8(C_{110}) \end{Bmatrix}\right) = \begin{bmatrix} 0 & 2 & 2 & -2 & 1 & 2 & 2 & -1 \\ -2 & 0 & 0 & -4 & -1 & 0 & 0 & -3 \\ -2 & 0 & 0 & -4 & -1 & 0 & 0 & -3 \\ 2 & 4 & 4 & 0 & 3 & 4 & 4 & 1 \\ -1 & 1 & 1 & -3 & 0 & 1 & 1 & -2 \\ -2 & 0 & 0 & -4 & 1 & 0 & 0 & -2 \\ -2 & 0 & 0 & -4 & 1 & 0 & 0 & -2 \\ 1 & 3 & 3 & -1 & 2 & 2 & 2 & 0 \end{bmatrix} \quad (17)$$

Analogous to determine the matrix and other benefits:

$$\vec{P}_{R_{1,..,}R_8}(C_{130}),..., \vec{P}_{R_{1,..,}R_8}(C_{150}), ..., \\ ..., \vec{P}_{R_{1,..,}R_8}(C_{121}),..., \vec{P}_{R_{1,..,}R_8}(C_{124}). \quad (18)$$

Procedure was conducted to determine the ratings and benefits of a comprehensive evaluation system. Achieved unambiguous identification of the assessment process with the process of determining the preference as the transformation matrix of relationships matrix of ratings and targeted preference. In the matrix of advantages are given all the relations between criteria, sub criteria and evaluation facilities, and the direction is defined by algebraic sign in front of component matrix of preference. Then we define a graph G as a completely oriented graph. The graph presents the relationships of comprehensive relational hierarchical structure of criteria $C_{110},\ldots, C_{150}, C_{121},\ldots, C_{124}, R_1,\ldots, R_8$ with components of matrix-oriented preferences:

$$\vec{P}_C(C_{110},...,C_{150},C_{121},...,C_{124}), \\ \vec{P}_{R_1,...,R_8}(C_{110},...,C_{150},C_{121},...,C_{124}). \quad (19)$$

Based on the matrix of the advantages $\vec{P}_C(C_{110},...,C_{150})$ the graph is a homogeneous first-level hierarchical structure of criteria $G_C(C_{110},\ldots, C_{150})$. It is given as:

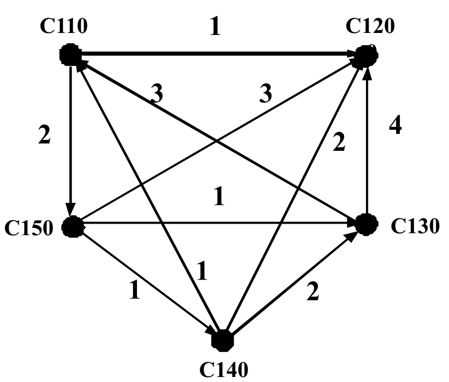


***Figure 4** The graph $G_C(C_{110},\ldots, C_{150})$ in the interpretation of the first level of homogeneous hierarchical structure of criteria and content-oriented preferences*
***Slika 4.** Graf $G_C(C_{110},\ldots, C_{150})$ u interpretaciji prve razine homogene hijerarhijske stukture kriterija i sadržaja usmjerenih prednosti*

Then we have a set of all criteria with components of the individual criteria that we can show as matrix:

$$\left[X_{C_{110},...,C_{150}}\right] = \begin{bmatrix} X_{C_{110}} \\ X_{C_{120}} \\ X_{C_{130}} \\ X_{C_{140}} \\ X_{C_{150}} \end{bmatrix} = \begin{bmatrix} 1{,}00 \\ 2{,}00 \\ -2{,}00 \\ 0{,}00 \\ -1{,}00 \end{bmatrix} \quad (20)$$

Then the incidence matrix is:

$$B_{C_{110},...,C_{150}} = \begin{bmatrix} -1 & 1 & 0 & 0 & 0 \\ 1 & 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & -1 & 0 \\ 1 & 0 & 0 & 0 & -1 \\ 0 & 1 & -1 & 0 & 0 \\ 0 & 1 & -1 & 1 & 0 \\ 0 & 1 & 0 & 0 & -1 \\ 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & -1 & 0 & 1 \\ 0 & 0 & 0 & 1 & -1 \end{bmatrix} \quad (21)$$

Transpose incidence matrix is given in the form:

$$B^T_{C_{110},...,C_{150}} = \begin{bmatrix} -1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & -1 & -1 & 0 & -1 & -1 & 0 \\ 0 & 0 & -1 & 0 & 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & -1 & 0 & 0 & -1 & 0 & 1 & -1 \end{bmatrix} \quad (22)$$

Matrix A is defined as [4, 10, 11, 13]:

$$A_{C_{110},...,C_{150}} = B^T{}_{C_{110},...,C_{150}} \cdot B_{C_{110},...,C_{150}} = \\ = \begin{bmatrix} 4 & -1 & -1 & -1 & -1 \\ -1 & 4 & -1 & -1 & -1 \\ -1 & -1 & 4 & -1 & -1 \\ -1 & -1 & -1 & 4 & -1 \\ -1 & -1 & -1 & -1 & 4 \end{bmatrix}. \quad (23)$$

With $C_{110},..., C_{150} \rightarrow C$ the equation $B_C^T{\cdot}B_C{\cdot}X_C{=}\Delta F_C$ turns into the equation $A_C{\cdot}X_C{=}\Delta F_C$ of the form [4, 10, 11, 13]:

$$A_C \cdot X_C = \Delta F_C \rightarrow \\ \begin{bmatrix} 4 & -1 & -1 & -1 & -1 \\ -1 & 4 & -1 & -1 & -1 \\ -1 & -1 & 4 & -1 & -1 \\ -1 & -1 & -1 & 4 & -1 \\ -1 & -1 & -1 & -1 & 4 \end{bmatrix} \cdot \begin{bmatrix} 1{,}00 \\ 2{,}00 \\ -2{,}00 \\ 0{,}00 \\ -1{,}00 \end{bmatrix} = \begin{bmatrix} 5{,}00 \\ 10{,}00 \\ -10{,}00 \\ 0{,}00 \\ -5{,}00 \end{bmatrix} = \Delta F_C \quad (24)$$

After checking the consistency and determination of graph we can determine analytical factors and weight as a function of the potential that each criterion is on its level relative to the total potential of all the criteria and levels. Matrix of factor weights of criteria $C_{110},\ldots, C_{150}$ can be displayed as:

$$\left[W_{C_{110},\dots,C_{150}}\right]=\begin{bmatrix} w_{C_{110}} \\ w_{C_{120}} \\ w_{C_{130}} \\ w_{C_{140}} \\ w_{C_{150}} \end{bmatrix}=\begin{bmatrix} 0{,}258 \\ 0{,}516 \\ 0{,}032 \\ 0{,}129 \\ 0{,}065 \end{bmatrix}. \tag{25}$$

Accordingly to the analytical procedure for criteria $C_{110},\dots, C_{150}$ we calculate the criteria important factor as a factor weighing on the observed level hierarchical structure. By analogy, procedure can be applied to determine the elements of the evaluation process for all sub criteria systems. Based on the matrix of advantages $\ddot{P}_C(C_{121},\dots,C_{124})$ of homogeneous hierarchies of sub criteria graph $G_{C_{121},\dots,C_{124}}$ is given as:

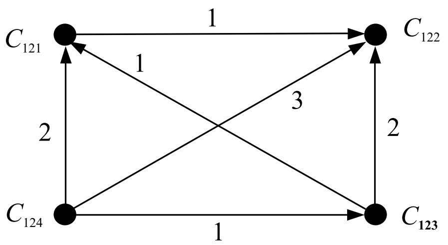


***Figure 5** Graph $G_{C_{121},\dots,C_{124}}$ in the interpretation of a homogeneous hierarchical structure of sub criteria $C_{121},\dots, C_{124}$ and content-oriented preferences*

***Slika 5.** Graf $G_{C_{121},\dots,C_{124}}$ u interpretaciji homogene hijerarhijske stukture podkriterija $C_{121},\dots, C_{124}$ i sadržaju usmjerenih prednosti*

Graph $G_{C_{121},\dots,C_{124}}$ in Fig. 5 in direction of arrow clearly defines the benefits flow sub criteria of hierarchical structure in the selection of the optimal kinematic structure for robot welding 5 conceptual solutions welded product performance. Set resources of sub criteria $C_{121},\dots, C_{121}$ can be display by matrix:

$$\left[X_{C_{121},\dots,C_{124}}\right]=\begin{bmatrix} X_{C_{121}} \\ X_{C_{122}} \\ X_{C_{123}} \\ X_{C_{124}} \end{bmatrix}=\begin{bmatrix} 0{,}5 \\ 1{,}5 \\ -0{,}5 \\ -1{,}5 \end{bmatrix}. \tag{26}$$

Then the incidence matrix is:

$$B_{C_{121},\dots,C_{124}}=\begin{bmatrix} -1 & 1 & 0 & 0 \\ 1 & 0 & -1 & 0 \\ 1 & 0 & 0 & -1 \\ 0 & 1 & -1 & 0 \\ 0 & 1 & 0 & -1 \\ 0 & 0 & 1 & -1 \end{bmatrix}. \tag{27}$$

Transpose matrix of incidence is given in the form:

$$B^T{}_{C_{121},\dots,C_{124}}=\begin{bmatrix} -1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & -1 & 0 & -1 & 0 & 1 \\ 0 & 0 & -1 & 0 & -1 & -1 \end{bmatrix}. \tag{28}$$

The matrix A is defined as:

$$A_{C_{121},\dots,C_{124}}=B^T{}_{C_{121},\dots,C_{124}}\cdot B_{C_{121},\dots,C_{124}}=$$
$$=\begin{bmatrix} 3 & -1 & -1 & -1 \\ -1 & 3 & -1 & -1 \\ -1 & -1 & 3 & -1 \\ -1 & -1 & -1 & 3 \end{bmatrix}. \tag{29}$$

With $C_{121},\dots, C_{124} \rightarrow C'$ the equation $B^T_{C_i}\cdot B_{C_i}\cdot X_{C_i}=\Delta F_{C_i}$ turns into the equation $A_{C'}\cdot X_{C'}=\Delta F_{C'}$ of the form:

$$A_C\cdot X_C=\Delta F_C \rightarrow$$
$$\begin{bmatrix} 3 & -1 & -1 & -1 \\ -1 & 3 & -1 & -1 \\ -1 & -1 & 3 & -1 \\ -1 & -1 & -1 & 3 \end{bmatrix}\cdot\begin{bmatrix} 0{,}26 \\ 0{,}77 \\ -0{,}26 \\ -0{,}77 \end{bmatrix}=\begin{bmatrix} 1{,}03 \\ 3{,}10 \\ -1{,}03 \\ -3{,}10 \end{bmatrix}=\Delta F_C. \tag{30}$$

After checking the consistency and determination of graph we can determine analytical factors and weight as a function of the potential that each sub criteria $C_{121},\dots, C_{124}$ has on its level in relation to the total potential of all the criteria of that level. Matrix of factor weights sub criteria $C_{121},\dots, C_{124}$ can be show as (more details may be seen in [4]).

$$\left[W_{C_{121},\dots,C_{124}}\right]=\begin{bmatrix} w_{C_{121}} \\ w_{C_{122}} \\ w_{C_{123}} \\ w_{C_{124}} \end{bmatrix}=\begin{bmatrix} 0{,}266 \\ 0{,}533 \\ 0{,}133 \\ 0{,}066 \end{bmatrix}. \tag{31}$$

Matrix of preferences $\ddot{P}_{R_1,\dots,R_8}(C_{110})$ determines a graph $G_{R_1,\dots,R_8}(C_{110})$ as follows (for only one criterion C_{110}):

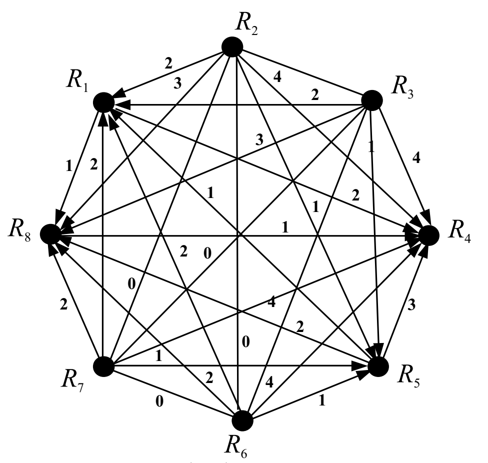


***Figure 6** Graph $G_{R_1,\dots,R_8}(C_{110})$ of kinematic structures $R_1,\dots, R_8$ and preferences*

***Slika 6.** Graf $G_{R_1,\dots,R_8}(C_{110})$ kinematičkih struktura $R_1,\dots, R_8$ i prednosti*

Graph in Fig. 6 is direction of arrows clearly defines benefits for the stream function criteria (Fig. 6. shows a graph of only one criterion C_{110} and analogous graphs are formed for all the criteria to variant solutions). Analogous to the way it defines:

$$\begin{aligned}
&\vec{P}_{R_1,\ldots,R_8}(C_{130}) \rightarrow G_{R_1,\ldots,R_8}(C_{130})\\
&\vec{P}_{R_1,\ldots,R_8}(C_{140}) \rightarrow G_{R_1,\ldots,R_8}(C_{140})\\
&\vec{P}_{R_1,\ldots,R_8}(C_{150}) \rightarrow G_{R_1,\ldots,R_8}(C_{150})\\
&\vec{P}_{R_1,\ldots,R_8}(C_{121}) \rightarrow G_{R_1,\ldots,R_8}(C_{121})\\
&\vec{P}_{R_1,\ldots,R_8}(C_{122}) \rightarrow G_{R_1,\ldots,R_8}(C_{122})\\
&\vec{P}_{R_1,\ldots,R_8}(C_{123}) \rightarrow G_{R_1,\ldots,R_8}(C_{123})\\
&\vec{P}_{R_1,\ldots,R_8}(C_{124}) \rightarrow G_{R_1,\ldots,R_8}(C_{124}).
\end{aligned} \tag{32}$$

Matrix of all potential elements of a set of solutions is given by (see tab. 7):

$$\left[X_{R_1,\ldots,R_8}(C_{110},\ldots,C_{150},C_{121},\ldots,C_{124})\right] = \begin{bmatrix} X_{R_1}\\ X_{R_2}\\ X_{R_3}\\ X_{R_4}\\ X_{R_5}\\ X_{R_6}\\ X_{R_7}\\ X_{R_8} \end{bmatrix} = \begin{bmatrix} 0{,}1708\\ -0{,}866\\ 0{,}12321\\ 1{,}6006\\ -0{,}25655\\ -0{,}014\\ -0{,}628\\ 0{,}4577 \end{bmatrix} \tag{33}$$

Control matrix of all potential $R=\{R_1,\ldots, R_8\}$ is performed for the well-known procedure, and in this example application is sufficient to determine only the incidence matrix. Incidence matrix $B_{R_1,\ldots,R_8}$ is as follows:

$$B_{R_1,\ldots,R_8} = \begin{bmatrix}
1 & -1 & 0 & 0 & 0 & 0 & 0 & 0\\
1 & 0 & -1 & 0 & 0 & 0 & 0 & 0\\
-1 & 0 & 0 & 1 & 0 & 0 & 0 & 0\\
1 & 0 & 0 & 0 & -1 & 0 & 0 & 0\\
1 & 0 & 0 & 0 & 0 & -1 & 0 & 0\\
1 & 0 & 0 & 0 & 0 & 0 & -1 & 0\\
-1 & 0 & 0 & 0 & 0 & 0 & 0 & 1\\
0 & 1 & -1 & 0 & 0 & 0 & 0 & 0\\
0 & -1 & 0 & 1 & 0 & 0 & 0 & 0\\
0 & -1 & 0 & 0 & 1 & 0 & 0 & 0\\
0 & 1 & 0 & 0 & 0 & -1 & 0 & 0\\
0 & 1 & 0 & 0 & 0 & 0 & -1 & 0\\
0 & -1 & 0 & 0 & 0 & 0 & 0 & 1\\
0 & 0 & -1 & 1 & 0 & 0 & 0 & 0\\
0 & 0 & -1 & 0 & 1 & 0 & 0 & 0\\
0 & 0 & 1 & 0 & 0 & -1 & 0 & 0\\
0 & 0 & 1 & 0 & 0 & 0 & -1 & 0\\
0 & 0 & -1 & 0 & 0 & 0 & 0 & 1\\
0 & 0 & 0 & 1 & -1 & 0 & 0 & 0\\
0 & 0 & 0 & 1 & 0 & -1 & 0 & 0\\
0 & 0 & 0 & 1 & 0 & 0 & -1 & 0\\
0 & 0 & 0 & 1 & 0 & 0 & 0 & -1\\
0 & 0 & 0 & 0 & 1 & -1 & 0 & 0\\
0 & 0 & 0 & 0 & 1 & 0 & -1 & 0\\
0 & 0 & 0 & 0 & -1 & 0 & 0 & 1\\
0 & 0 & 0 & 0 & 0 & 1 & -1 & 0\\
0 & 0 & 0 & 0 & 0 & -1 & 0 & 1\\
0 & 0 & 0 & 0 & 0 & 0 & -1 & 1
\end{bmatrix}. \tag{34}$$

The matrix **A** is defined as follows:

$$A_{R_1,\ldots,R_8} = \begin{bmatrix}
7 & -1 & -1 & -1 & -1 & -1 & -1 & -1\\
-1 & 7 & -1 & -1 & -1 & -1 & -1 & -1\\
-1 & -1 & 7 & -1 & -1 & -1 & -1 & -1\\
-1 & -1 & -1 & 7 & -1 & -1 & -1 & -1\\
-1 & -1 & -1 & -1 & 7 & -1 & -1 & -1\\
-1 & -1 & -1 & -1 & -1 & 7 & -1 & -1\\
-1 & -1 & -1 & -1 & -1 & -1 & 7 & -1\\
-1 & -1 & -1 & -1 & -1 & -1 & -1 & 7
\end{bmatrix}. \tag{35}$$

Then equation $B_R^T \cdot B_R \cdot X_R = \Delta F_R$ turns into the equation $A_R \cdot X_R = \Delta F_R$ of the form [4, 10, 11, 13]:

$$A_R \cdot X_R = \Delta F_R \rightarrow$$
$$\begin{bmatrix}
7 & -1 & -1 & -1 & -1 & -1 & -1 & -1\\
-1 & 7 & -1 & -1 & -1 & -1 & -1 & -1\\
-1 & -1 & 7 & -1 & -1 & -1 & -1 & -1\\
-1 & -1 & -1 & 7 & -1 & -1 & -1 & -1\\
-1 & -1 & -1 & -1 & 7 & -1 & -1 & -1\\
-1 & -1 & -1 & -1 & -1 & 7 & -1 & -1\\
-1 & -1 & -1 & -1 & -1 & -1 & 7 & -1\\
-1 & -1 & -1 & -1 & -1 & -1 & -1 & 7
\end{bmatrix} \cdot \begin{bmatrix} -0{,}38\\ -0{,}75\\ -0{,}15\\ 1{,}76\\ -0{,}15\\ -0{,}15\\ -0{,}67\\ 0{,}48 \end{bmatrix} = \begin{bmatrix} -3{,}02\\ -5{,}99\\ -1{,}20\\ 14{,}11\\ -1{,}22\\ -1{,}16\\ -5{,}36\\ 3{,}84 \end{bmatrix} = \Delta F_R \tag{36}$$

Set of the weight matrices $R=\{R_1,\ldots, R_8\}$ amounts:

$$\left[W_{R_1,\ldots,R_8}(C_{110},\ldots,C_{150},C_{121},\ldots,C_{124})\right] = \begin{bmatrix} w_{R_1}\\ w_{R_2}\\ w_{R_3}\\ w_{R_4}\\ w_{R_5}\\ w_{R_6}\\ w_{R_7}\\ w_{R_8} \end{bmatrix} = \begin{bmatrix} 0{,}0962\\ 0{,}0594\\ 0{,}09941\\ 0{,}32836\\ 0{,}090634\\ 0{,}1073\\ 0{,}07006\\ 0{,}1487 \end{bmatrix} \tag{37}$$

5 Conclusion
Zaključak

Different authors propose different methods for goodness evaluating in technical problems. In this paper a new method of evaluation as a decision-making in the case of welding robots kinematic structures is presented. This new method is a method of potential. Analysis of all resources set from the set of relational structures and kinematic solutions of set criteria derive goodness of potentials solution of all decision elements. The work is performed in an original way to evaluate the application of mathematical formalism of graph theory in the methods of potentials. In the application this method is presented through analysis of 15 specific conceptual solutions in the different forms of welded product concepts. The method of potential, as a new method, applied in analysis of 8 welding robots kinematic structures. Therefore, in this case it can be an open kinematic chain with three degrees of motion freedom, and this gives a total of 216 different combinations of kinematic structures. It is also, shown and described a model linking criteria and alternatives of welding robots kinematic structures. The solution R_4 is the solution with the largest weight factor $w_{R_4} = 0{,}32836$ as the appropriate welding robot kinematic structure which is the best suited for use by all 15 conceptual welded design solutions. Applying the method in this paper, other factors for the weight of other types of kinematic structures are defined. This allows defining the order in the list of requirements to satisfy the degree of structural and technological parameters in manufacturing of welded structures using automated welding procedure. The review of multi-criteria decision-making applying the method of potential (expression 33 and 37) and assigning marks to the related activities of kinematic structure evaluation (see Tab. 7 and presented values). In this way, according to the criteria defined hierarchical structure is confirmed by the evaluation model with numerical results and the possibility to apply in the selection of acceptable kinematic structure of the robotized technologies for automated welding of different conceptual product structures is also confirmed.

The paper presents a general procedure of evaluation and possibility of application by different engineering problems, but this will be the subject of further research. It is particularly interesting the possibility to apply it in the field of group decision-making by product development, as well as the possibility of applying the method of potential.

6 References
Reference

[1] Timošenko, A.V.; Suhomlin, A.A. Robotizaciia svaročnvo proizvodstva, Tehnika, Kiev, 1988.
[2] Ergić, T. Konstrukcija specijalizirane manipulatorske šake za izradu malih spremnika, Magistarski rad, FSB, Zagreb, 1989.
[3] Kljajin, M.; Ergić, T.; Ivnadić, Ž. Choice of Welding Robots Conditioned by Product Design, Proceedings, CIM'95, Zagreb, 1995., C: 35-41.
[4] Ivandić, Ž. The conceptual evaluation of design parameters, PhD Thesis (in Croatian), University of Zagreb, 2002.
[5] Kljajin, M.; Ergić, T.; Ivandić, Ž.; Karakašić, M; Katalenić, Z. Practical Solution of Welding Robot Suitable for different Product Designs, Proceedings Cost Effective Application of Welding Process, Sl. Brod, 2007., pp. 147-156.
[6] Liang, G. H.; Wang, M. J. A fuzzy multi-criteria decision making approach for robot selection. Robot Computer Aided Manufacturing. 10(1993), 267–274.
[7] Goh, C. H. Analytic hierarchy process for robot selection. J Manuf Systems. 16(1997), 381–386.
[8] Parkan, C.; Wu, M.L. Decision making and performance measurement models with applications to robot selection. Comput Ind Eng. 36(1999), 503–23.
[9] Ergić, T.; Kljajin, M.; Ivandić, Ž.; Klarić, Š.; Jukić, R. Possibility to apply a welding robot in the ship's rudder manufacturing, The 5th International scientific-professional conference SBW 2009, Robotization and Automation in Welding and Other Techniques, Sl. Brod, November 11-13, 2009, pp. 255-264.
[10] Čaklović, L.; Šego, V. Potential Method applied on exact data. In K. Šorić, T. Hunjak, and R. Scitovski, editor, Proceedings of KOI 2002, pages 237–248. Croational Operational Research Society, Trogir, Croatia, October 2-4, 2002.
[11] Čaklović, L. Graph Distance in Multicriteria Decision Making context. Metodološki zvezki (Advances in Methodology and Statistics), 19, 1(2003), 25–34.
[12] Čaklović, L. Decision making by Potential Method. Int. J. of Pure and Appl. Math., (2005), 1-16.
[13] Čaklović, L. Decision making by potential method. Int. J. of Pure and Appl. Math. to appear.
[14] Veljan, D. Kombinatorna i diskretna matematika, Algoritam, 2001.
[15] Kurepa, S. Uvod u lineranu algebru, Školska knjiga, Zagreb, 1975.
[16] Blanuša, D. Viša matematika, I. dio, 1. svezak, Tehnička knjiga, Zagreb, 1989.

Authors' addresses
Adrese autora

doc. dr. sc. Željko Ivandić
doc. dr. sc. Todor Ergić
prof. dr. sc. Milan Kljajin
Sveučilište J. J. Strossmayera u Osijeku
Strojarski fakultet u Slavonskom Brodu
Trg Ivane Brlić-Mažuranić 2
35000 Slavonski Brod, Croatia
zivandic@sfsb.hr