Multi-criteria Robot Selection Problem for an Automated Single-Sided Lapping System

Norbert Piotrowski and Adam Barylski

Abstract Flat lapping is a crucial process in a number of precision manufacturing technologies. Its aim is to achieve extremely high flatness of the workpiece. Single-sided lapping machines have usually standard kinematic systems and are used in conjunction with conditioning rings, which are set properly between the centre and the periphery of the lapping plate. In this paper, instead of conventional single-sided lapping machine, an automated lapping cell is introduced. The object of the robotic lapping system is to provide improved means for controlling the position of conditioning rings on lapping plate, so as to enable the flatness of the plate and consequently of the workpieces to be controlled. What is more, this innovative solution allows to fully automate a single-disc lapping process. Selection of a robot is one of a number of challenges in designing automated manufacturing systems. This problem has become very demanding due to the increasing specifications and the complexity of the robots. This study aims to solve a robot selection difficulty for conditioning ring positioning, workpieces handling and loading tasks in the lapping cell. For this reason, analytic hierarchy process (AHP), which is one of the multi-criteria decision-making (MCDM) methods, is used to select the most convenient robot.

Keywords Abrasive machining · Lapping kinematics · Robot application · Analytic hierarchy process · Robot selection

1 Introduction

The lapping process is a significant technology among various precision manufacturing applications. It has a broad scope of application, mostly in technical ceramics, medical devices, electro optics, data storages, and aerospace and

N. Piotrowski (✉) · A. Barylski
Gdańsk University of Technology, Gdańsk, Poland
e-mail: np.piotrowski@gmail.com

A. Barylski
e-mail: abarylsk@pg.gda.pl

© Springer International Publishing Switzerland 2016

J. Awrejcewicz et al. (eds.), *Mechatronics: Ideas, Challenges, Solutions and Applications*, Advances in Intelligent Systems and Computing 414,
DOI 10.1007/978-3-319-26886-6_1

automotive industries [1]. Moreover, this type of machining can be used both in optical mirrors and lenses. Lapping process is conducted by implementing loose abrasive grains between two surfaces and causes a relative motion between them resulting in a finish of multi-directional lay [2].

Flat lapping is one of the most commonly used types of the lapping process which objective is to achieve extremely high flatness of the workpiece. Single-sided lapping machines are usually used along with conditioning rings, which are situated precisely between the centre and the periphery of the lapping plate [3].

Previously conducted studies put the main emphasis on the mechanisms of material removal, the effects of input parameters and the thermal measurements. The main aim of the research was to optimize the machining conditions in order to boost the surface quality and to improve the efficiency of the process. However, issue such as behaviour of lap flatness in lapping process when the standard input parameters—relative velocity of workpiece as well as the velocity of lapping plate—are carefully controlled, and a conventional kinematic system is changed and has not been closely scrutinized. The investigation of new kinematic systems should be continued in order to improve the flatness of lapping plate and consequently the surface quality of workpiece [4].

The main object of the automated lapping system is to provide the improved means for controlling the position of conditioning rings on lapping plate so as to enable the flatness of the plate to be controlled. This innovative solution enables an automation of a single-sided lapping process. A remarkable point in the process is a robot that helps automating the lapping process with such available options as multi-step programmable rings speed, down pressure, slurry feed as well as quick machine loading and unloading.

One of the challenges in designing automated manufacturing systems is selecting a robot. This issue has become very demanding due to increasing specifications and complexity of the industrial robots. The study aims to solve a robot selection difficulty for conditioning ring positioning, workpieces handling and loading tasks in the lapping cell. To meet the mentioned requirements the author chose one of multi-criteria decision-making (MCDM) methods in order to select the most beneficial robot.

2 Robot Selection

2.1 Industrial Robots Parameters

Recent developments in information technology and information technology have been the main reason for the increased utilization of manipulators in a variety of advanced manufacturing facilities. Nowadays there are many types of industrial robots of various applications. Leading industrial robots producers are KUKA (Germany), ABB (Switzerland), Comau (Italy), Fanuc (Japan), Kawasaki (Japan).

According to the application, the engineers must be able to select the perfect robot. This is only possible, if the engineers are well known about the technical parameters of every robot. The basic technical features of such robots are:

– configuration of a robot,
– number of axes of a robot,
– type of control system,
– drive system,
– permissible working load (kN),
– total weight of a robot (kg),
– working volume (mm^3),
– floor space (m^3),
– range of joints motion (°),
– maximum speed (°/rad),
– repeatability that ensures the precision of a motion (mm),
– work area temperature (°C),
– recommended relative operating humidity (% + °C),
– versions of the robot installations,
– additional information and equipment.

Various technical features are needed in different applications. For example, machine loading need a polar, cylindrical or revolute robot with four to five axes. It should be equipped with a limited sequence or point-to-point (PTP) control system. For heavy weights the drive system must be hydraulic. Otherwise electric drive type is sufficient. In case of assembly operations a robot should be either Cartesian or revolute. It must be incorporated with three to six axes and must have an electrical drive system. Continuous path or PTP control system is required. To perform various machining process, a revolute will be the appropriate selection. The number of axes must be more or equal to five. It can have either electric or hydraulic drive system. It must possess a continuous path control system [5].

2.2 Robot Selection Methods

The selection of robots to suit a certain application and production environment form among the large number available in the market is a difficult challenge. Different approaches were used by previous researchers to solve the robot selection problem.

Khouja and Booth [6] used a statistical procedure known as robust fuzzy cluster analysis that can select the robots with the best compilation of specifications based on various performance parameters. Moreover, Khouja [7] is the author for two-phase decision model for problems according to the robot selection. The first phase consists of employing data envelopment analysis (DEA) for identifying the robots with the best combination of vendor specifications with regard to the robot performance parameters. The second phase applies a multi-attribute decision-making (MADM) method in order to choose the best robot among those which were identified in the first phase.

Revised weighted sum decision model was developed by Goh et al. [8]. The model takes into account the objective as well as subjective attributes while choosing the industrial robots.

Rao and Padmanabhan [9] introduced the diagraph and matrix methods to assess and rank the alternative robots for a specific industrial application, applying the similarity and dissimilarity coefficient values.

Karsak [10] is the author of a decision model for robot selection. It is based both on quality function deployment (QFD) and fuzzy linear regression methods while combining the user demands with the technical parameters of the robots.

Zhao et al. [11] introduced a multi-chromosome genetic algorithm with first-fit bin packing algorithm in order to choose a robot and workstation assignment problem for a computer integrated manufacturing system.

Among numerous multiple-criteria decision analysis (MCDA) or MCDM methods developed to solve real-world decision problems by supporting the subjective evaluation of a finite number of decision alternatives under a finite number of performance criteria, technique for order preference by similarity to ideal solution (TOPSIS) can be found. TOPSIS was developed by Hwang and Yoon in 1981. This ranking method is simple in conception and application. The fundamental logic of TOPSIS method is to determine the positive-ideal solution (PIS) and the negative-ideal solution (NIS). The convenient alternative is the one with the shortest distance from the positive solution and the farthest distance from the negative solution and preference order is ranked. The PIS maximizes the benefit criteria and minimizes the cost criteria, whereas the NIS maximizes the cost criteria and minimizes the benefit criteria. However, attribute values must be numeric, monotonically increasing or decreasing to apply this technique [12].

2.3 Analytical Hierarchy Process

One of the most common MCDM techniques is analytic hierarchy process (AHP). It was developed in 1970 by Thomas L. Saaty. However, AHP is still improved by other decision makers. Solving difficult decision problems using this method is based on their decomposition into components; objective, criteria (sub-criteria) and alternatives. These elements are then linked into a model with a multi-level (hierarchical structure). The goals can be found at the top of this structure and the main criteria at the first level. Criteria can be broken down into sub-criteria, and at the lowest level given are the alternatives. Another important component of the AHP method is the mathematical model that calculates the priorities of the elements that are at the same level of the hierarchical structure [13]. AHP has been used in many applications with various risks. Using this method allows to:

– make a selection of alternatives (e.g. robot selection),
– evaluate a quality (e.g. Computer software),
– estimate design solutions,
– assist financial decisions,
– determine the suitability of a technical equipment,
– introduce amendments.

General algorithm for the AHP method is shown in Fig. 1. It consists of several steps. The first one is defining the unstructured problem and criteria. Then pairwise comparisons and rating scale must be employed and relative importance weights at each level of the hierarchy must be evaluated. Next step is to check the consistency property of the matrix. Consistency index (1) and consistency ratio (2) parameters should not be greater than 0.1. Finally, the results can be made into a hierarchical structure [14].

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1} \leq 0.1 \quad (1)$$

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \leq 0.1 \quad (2)$$

where: $\lambda_{\max}$—maximum eigenvalue, n—order of matrix, RI—random index (Table 1).

3 Automated Lapping System

Lapping is one of the finishing methods that allows very high surface qualities, form accuracies and very close dimensional tolerances. Since now, various types of lapping machines have been developed. However, there are only two kinematic systems, which are commonly used. Plane and parallel surfaces are lapped on double-disc lapping machines with a planetary kinematic system. In case of flat surfaces machining, single-sided lapping machines are used. They are usually used in conjunction with conditioning rings. In the standard lapping machines, relative movements of lapping plate and workpieces are induced from respective rotations and reciprocal movements.

Nowadays modern lapping machines became more efficient than those in the past. The basic constructions are supplied with additional components. As a result of the automation of lapping machines some of the supporting operations were eliminated. Lapping machines for flat and parallel surfaces are supplied with feeding tables, loading and unloading systems of rings, which form mini-production lines (Fig. 2).

The Peter Wolters Company developed a solution for a micro lapping lines that provides greater efficiency and precision (Fig. 3). In these machines, a five-axis robot functions as a workpieces feeder. The robot is able to handle the workpieces

Fig. 1 Analytical hierarchy process algorithm [14]

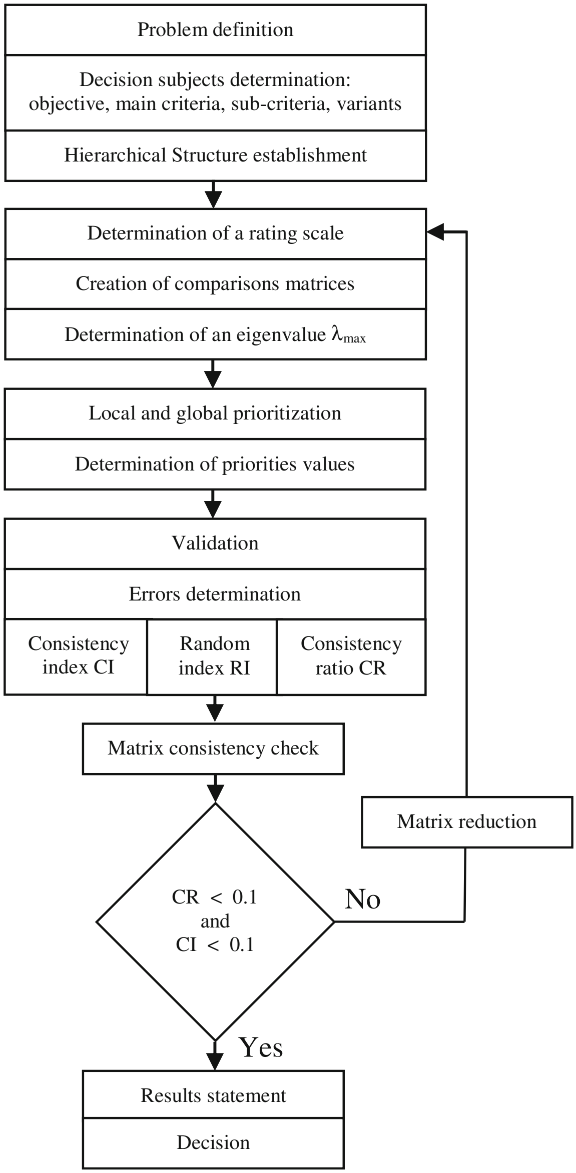

Table 1 Random inconsistency indices RI [14]

n	1	2	3	4	5	6	7	8
RI	0.0	0.00	0.58	0.9	1.12	1.24	1.32	1.41

Fig. 2 Lapping machine with feeding table [15]

Fig. 3 Robot as a feeder in Peter Wolters lapping machine [15]

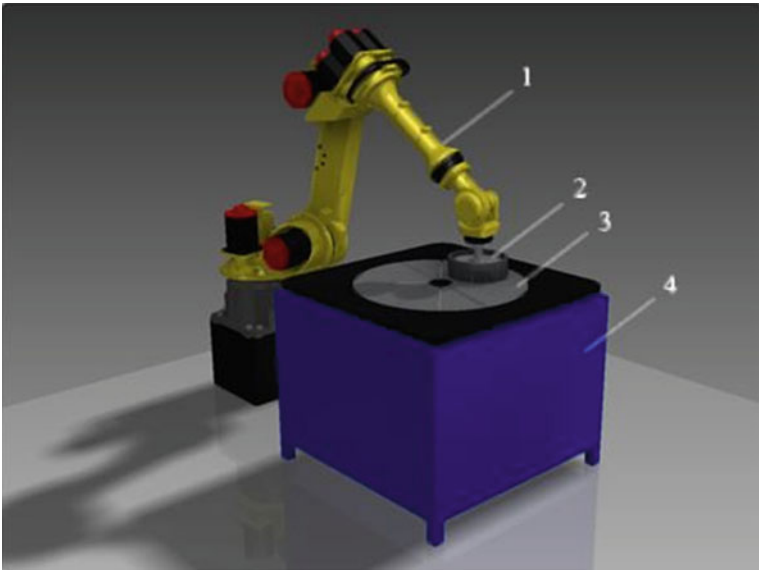

Fig. 4 Idea of robotic single-sided lapping machine

from the storeroom with a magnetic or vacuum holder, put them in the conditioning rings and shift the whole ring. The system reduces the auxiliary process time, increases the flow capacity and makes the unmanned machining possible [15].

After a careful analysis of numerous offers of many lapping machines producers, it has emerged that none of them has a system where the ring is led by the manipulator, during the machining. The robot functions as a feeder in the Peter Wolters lapping machines and moreover, it can support the machining. It is complicated and in some cases impossible to create a universal mechanism that makes the ring move at any path. Thanks to the robot that moves an effector from point to point, it is possible to change the ring trajectory at any moment. Owing to this solution, it is possible to apply any lapping kinematics, which causes a regular wear of lapping disc at its ray [1–4].

The idea of how single-sided lapping machine and the robot working together is presented in Fig. 4. There is a robot 1 situated next to the lapping machine 2. Primarily sorted workpieces are handled from the table to the separator, located in conditioning ring 3. Then ring griped by the robot moves on the plate 4, which is propelled with angular velocity ωt. The machining is executed by the robot. It shifts the ring with workpieces in such a way to keep the flatness of the plate along the radius. The turning motion ω2 of the ring can be forced by the robot (same or oppositional rotational direction) or it can be affected by the friction force. After lapping process, robot shifts conditioning ring to another table and workpieces fall into the box with finished parts. Finally the flatness of the plate is controlled and fixed in case an error occurs.

4 AHP Methodology for Lapping Robot Selection

Application of AHP method was carried out for robot selection. An automated lapping system was examined. The selection of a robot to perform material handling tasks and lapping process were decided. After initial selection, three robots R1, R2 and R3 were chosen for further evaluation (Table 2). These articulated robots have six degrees of freedom and are powered by an electrical drive. Continuous path or PTP control system is required.

Thus, the robot selection problem consists of three main criteria and nine sub-criteria. These criteria are as follows: Physical (P): weight (P1), total height (P2), Specification (S): load (S1), speed (S2), range (S3), repeatability (S4) and Cost (C): purchase cost (C1), maintenance cost (C2), insurance (C3).

The first step in the AHP procedure is to make pairwise comparisons between each criterion. Results of the comparison are described in term of integer values from 1 to 9, where higher number means the chosen factor is considered more important than other factor being compared with. $N \times N$ matrix with compared criteria can be composed, where N means number of criteria. It can be noticed that the diagonal elements of the matrix are always 1. Next step is to sum every column and every row (Table 3). Each element of the matrix is divided by a sum of the corresponding column. The result is saved in new matrix (Table 4). The weights of criteria are obtained by adding all the elements in a row. Weights are allowed to develop a ranking of criteria. It may be noted that a sum of each column of the Table 4 equals 1.

Table 2 Chosen parameters for industrial robots

Parameters	R1	R2	R3
Weight (kg)	380	130	280
Height (mm)	1564	1340.5	1630
Load (kg)	16	12	10
Speed (°/s) Joint 1 Joint 2 Joint 3 Joint 4 Joint 5 Joint 6	360 210 125 400/∞ 240 800 /∞	360 250 445 380 380 720	160 140 160 330 330 500
Reach (mm)	1550	1420	1852
Repeatability ± (mm)	0.04	0.08	0.10
Purchase cost (PLN)	220,800	260,000	185,000
Maintenance cost (PLN)	80,000	85,000	65,000
Insurance cost (PLN)	40,000	20,000	35,000

Table 3 A pairwise comparison of criteria

	P	S	C	Sum
P	1.00	0.14	0.20	1.343
S	7.00	1.00	3.00	11.000
C	5.00	0.33	1.00	6.333
Sum	13.00	1.48	4.20	

Table 4 Criteria importance

	P	S	C	Weight	Rank
P	0.08	0.10	0.05	0.074	3
S	0.54	0.68	0.71	0.643	1
C	0.38	0.23	0.24	0.283	2
Sum	1.00	1.00	1.00	1.00	

Apart from the relative weight, consistency has to be checked. To do that, principal eigen value $\lambda_{\max}$ is needed. It is obtained from the summation of multiplication products between each weights and the sum of columns of the matrix with comparison. Then conditions (1) and (2) are checked:

$$CI = \frac{3.097 - 3}{3 - 1} = 0.048 \le 0.1 \tag{3}$$

$$CR = \frac{0.048}{0.58} = 0.083 \le 0.1 \tag{4}$$

In the same manner as criteria, sub-criteria are calculated. Local weights of sub-criteria are obtained by multiplying global weights by a weight of corresponding criteria. The results of the Specification (S) sub-criteria calculations are shown in Tables 5 and 6, respectively. The matrix consistency is checked as well in (5) and (6).

Table 5 A pairwise comparison of sub-criteria specification (S)

	S1	S2	S3	S4	Sum
S1	1	0.20	0.33	0.14	1.68
S2	5	1	1	0.2	7.20
S3	3	1	1	0.33	5.33
S4	7	5	3	1	16
Sum	16	7.20	5.33	1.68	

Table 6 Sub-criteria (S) importance

	S1	S2	S3	S4	Global weight	Local weight	Rank
S1	0.06	0.03	0.06	0.09	0.060	0.038	4
S2	0.31	0.14	0.19	0.12	0.190	0.122	2
S3	0.19	0.14	0.19	0.20	0.178	0.115	3
S4	0.44	0.69	0.56	0.60	0.573	0.369	1
Sum	1.00	1.00	1.00	1.00	1.00	0.643	

$$\mathrm{CI} = \frac{4.227 - 4}{4 - 1} = 0.076 \leq 0.1 \tag{5}$$

$$\mathrm{CR} = \frac{0.076}{0.9} = 0.084 \leq 0.1 \tag{6}$$

In Tables 7 and 8 as example, the calculations of the Repeatability (S4) of R1, R2, R3 robots are shown. They were implemented in the same way as calculations of sub-criteria importance. Moreover, the necessary conditions are checked (7) and (8).

$$\mathrm{CI} = \frac{3.111 - 3}{3 - 1} = 0.056 \leq 0.1 \tag{7}$$

$$\mathrm{CR} = \frac{0.056}{0.58} = 0.096 \leq 0.1 \tag{8}$$

Finally, the last step of robot selection with AHP method is to develop a hierarchical structure (Fig. 5). Furthermore, results were presented in Table 9.

Table 7 A pairwise comparison of repeatability (S4)

	R1	R2	R3	Sum
S4	0.04	0.08	0.1	
R1	1	5.00	7.00	13.00
R2	0.20	1	3.00	4.20
R3	0.14	0.33	1	1.48
Sum	1.34	6.33	11.00	

Table 8 Repeatability (S4) importance

	R1	R2	R3	Global weight	Local weight	Rank
R1	0.74	0.79	0.64	0.724	0.01779	1
R2	0.15	0.16	0.27	0.193	0.00475	2
R3	0.11	0.05	0.09	0.083	0.00205	3
Sum	1.00	1.00	1.00	1.00	0.025	

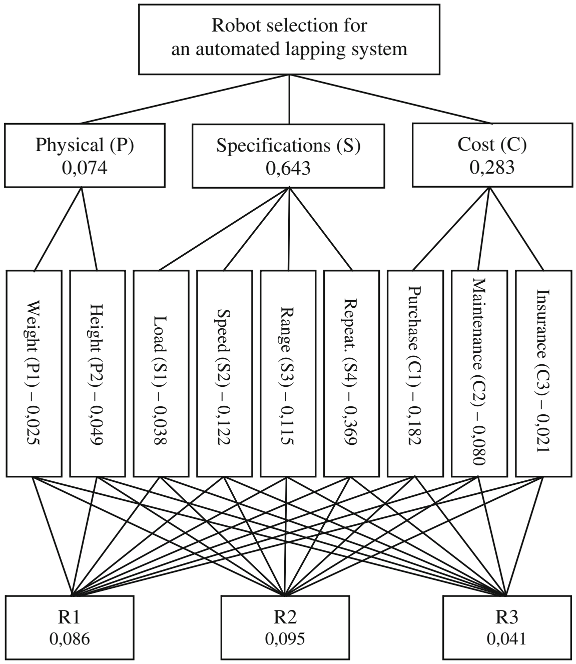

Fig. 5 Hierarchical structure of the robot selection

Table 9 Results of robot selection

Parameters	R1	R2	R3
Weight (kg)	0.00261	0.01557	0.00641
Height (mm)	0.00696	0.01582	0.00181
Load (kg)	0.01557	0.00641	0.00261
Speed (°/s)	0.01644	0.00598	0.00217
Reach (mm)	0.00475	0.00205	0.01779
Repeatability ± (mm)	0.01779	0.00475	0.00205
Purchase cost (PLN)	0.00598	0.01644	0.00217
Maintenance cost (PLN)	0.01118	0.01118	0.00224
Insurance cost (PLN)	0.00440	0.01685	0.00334
Sum	0.08568	0.09505	0.04059
Ranking	2	1	3

5 Conclusion

The aim of this paper is to solve the robot selection problem using one of MCDM methods. Selection problem refers to the automated lapping cell. A robot has to perform material handling tasks and assist lapping process. The most important attributes of the robot are described. The weights of the considered criteria and sub-criteria are calculated using analytical hierarchy process (AHP) method. The repeatability of robot is the leading sub-criteria in this case. According to the calculations, the ranking order of three robots is R2, R1 and R3 for the problem. However, there is not much difference between the first two robots.

References

1. Barylski, A.: Podstawy docierania jednotarczowego powierzchni płaskich. Zeszyty Naukowe Politechniki Gdańskiej. Mechanika nr 67, Gdańsk (1992)
2. Barylski, A., Gniot, M.: Analiza kinematyki docierania jednotarczowego powierzchni płaskich. Obróbka ścierna. Współczesne problemy, Katedra Technologii Maszyn i Automatyzacji Produkcji Politechnika Gdańska, Gdańsk (2011)
3. Barylski, A.: Problemy technologiczne docierania powierzchni płaskich w układach jednotarczowych. Presented at XXVI Szkoła Tribologiczna Problemy Tribologiczne w Przyrodzie i Technice oraz VI Konferencja Problemy Niekonwencjonalnych Układów Łożyskowych, Łódź-Niedzica (2003)
4. Barylski, A., Piotrowski, N.: Koncepcje niekonwencjonalnych układów kinematycznych docierania jednotarczowego z wykorzystaniem robota. XXXVII Naukowa Szkoła Obróbki Ściernej, Mechanik, nr 8-9 (2014)
5. Groover, M.P., Weiss, M., Nagel, R.N.: Industrial Robotics: Technology, Programming and Application. McGraw-Hill Higher Education, New York (1986)
6. Khouja, M., Booth, D.E.: Fuzzy clustering procedure for evaluation and selection of industrial robots. J. Manuf. Syst. **14**, 244–251 (1995)
7. Khouja, M.: The use of data envelopment analysis for technology selection. Comput. Ind. Eng. **28**, 123–132 (1995)
8. Goh, C.-H., Tung, Y.-C., Cheng, C.-H.: A revised weighted sum decision model for robot selection. Comput. Ind. Eng. **30**, 193–199 (1996)
9. Rao, R.V., Padmanabhan, K.K.: Selection, identification and comparison of industrial robots using digraph and matrix methods. Robot. Comput.-Integr. Manuf. **22**, 373–383 (2006)
10. Karsak, E.E.: Robot selection using an integrated approach based on quality function deployment and fuzzy regression. Int. J. Prod. Res. **46**, 723–738 (2008)
11. Zhao, L., Tsujimura, Y., Gen, M.: Genetic algorithm for robot selection and work station assignment problem. Comput. Ind. Eng. **31**, 599–602 (1996)
12. Behzadian, M., Khanmohammadi Otaghsara, S., Yazdani, M., Ignatius, J.: A state-of the-art survey of TOPSIS applications. Expert Syst. Appl. **39**:13051–13069 (2012)
13. Żurek, J., Ciszak, O., Cieślak, R., Suszyński, M.: Ocena i wybór robota przemysłowego metodą AHP. Arch. Mech. Technol. Autom. **31**, nr 2:201–211, Poznań (2011)
14. Downarowicz, O., Krause, J., Sikorski, M., Stachowski, W.: Zastosowanie metody AHP do oceny i sterowania poziomem bezpieczeństwa złożonego obiektu technicznego. Wybrane metody ergonomii i nauki o eksploatacji, Wydawnictwo Politechniki Gdańskiej, pp. 7–42, Gdańsk (2000)
15. http://www.peter-wolters.com. Accessed 29 Jan 2015