

Mechanisms and Machine Science

Milan Rackov  
Radivoje Mitrović  
Maja Čavić *Editors*

# Machine and Industrial Design in Mechanical Engineering

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# Mechanisms and Machine Science

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Editors

# Machine and Industrial Design in Mechanical Engineering

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# Contents

## Part I Invited Keynote Lectures

<b>1 Analytical Model for Spur Gears with Profile Modification: Simulation of the Meshing Stiffness, Load Sharing, and Transmission Error</b> .....	3
José I. Pedrero	
<b>2 Lifetime Mechanics of Machines as Cluster of Classical Mechanics, Reliability Theory and Digital Twin Concept</b> .....	27
Vladimir Algin	
<b>3 Mechanism Applications in Robotics</b> .....	51
Erwin-Christian Lovasz	
<b>4 Robotics as Assistive Technology for Treatment of Children with Developmental Disorders—Example of Robot MARKO</b> .....	69
Branislav Borovac, Mirko Raković, Milutin Nikolić, Vlado Delić, Srđan Savić, Marko Penčić, and Dragiša Mišković	
<b>5 Development of Terminology for Gearing: IFToMM Notions, Reference-Dictionary Book, Tooth Failure Modes</b> .....	77
Victor E. Starzhinsky	

## Part II Design, Manufacturing and Management of Machine Elements, Equipment and Systems

<b>6 The Self-Compensation Approach for Backlash on Gear Train</b> .....	85
Bahadır Karba, Nihat Yıldırım, Mert Vardar, Fatih Karpat, and Milan Rackov	
<b>7 The Modification Effects of the Sum of Pitch Angles in Case of Bevel Gear Pairs Having Straight Teeth for the TCA</b> .....	97
Sándor Bodzás and Gyöngyi Szanyi	

<b>8</b>	<b>Influence of Wear on Load Sharing and Transmission Error of Spur Gears with Profile Modifications</b> .....	111
	Miguel Pleguezuelos, José I. Pedrero, Miryam B. Sánchez, and Elena Vicente	
<b>9</b>	<b>Service Life of Universally Loaded Deep Groove Ball Bearing Depending on Internal Clearance</b> .....	121
	Tatjana M. Lazović, Ivan M. Simonović, and Aleksandar B. Marinković	
<b>10</b>	<b>Investigation of Low to Medium Load Operating Regimes for Roller Bearings in Heavy Industrial Equipment</b> .....	131
	Radomir Karakolev and Lubomir Dimitrov	
<b>11</b>	<b>Performance of Water Lubricated Journal Bearings Under Elastic Contact Conditions</b> .....	141
	Juliana Javorova and Alexandru Radulescu	
<b>12</b>	<b>Influence of Low Temperature on the Pumping Rate of Radial Lip Seals</b> .....	151
	Sumbat Bekgulyan, Simon Feldmeth, and Frank Bauer	
<b>13</b>	<b>Design of an Automated Handling System</b> .....	161
	Pavol Varga and Andrej Smelík	
<b>14</b>	<b>Analysis of Two-Stage Cycloid Speed Reducers Dimensions and Efficiency</b> .....	171
	Milos Matejic, Vladimir Goluza, Milan Vasic, and Mirko Blagojevic	
<b>15</b>	<b>Balancing Rotating Parts. A New Method and Device</b> .....	183
	Mircea-Viorel Dragoi, Marius Daniel Nasulea, Milos Matejic, and Gheorghe Oancea	
<b>16</b>	<b>Machine Retrofitting for Tissue Paper Industry—INTERFOLDER Case</b> .....	191
	Milos Milivojevic, Bozica Bojovic, Vladimir Babic, and Djordje Djuric	
<b>17</b>	<b>Equipment for Catalytic Water Purification with a Gas-Saturated Reactor</b> .....	201
	Aliaksandr Ph. Ilyushchanka, Aleksey R. Kusin, Iryna M. Charniak, Dzmityri I. Zhehdryn, Ruslan A. Kusin, Natalia V. Rutkovskaya, Evgeniy N. Eremin, and Tsanka D. Dikova	
<b>18</b>	<b>Mechanical Design of the Bicycle Inner Tube Assembly Tool Based on the Reverse Engineering Methodology</b> .....	207
	Dušan Ćirić, Aleksandar Miltenović, Jelena Mihajlović, and Miroslav Mijajlović	



<b>19</b>	<b>Product Redesign Using an Innovative Process: Application to a Case Study</b> .....	<b>217</b>
	Pedro Agustín Ojeda Escoto, Miguel Ángel Zamarripa Muñoz, and Gerardo Brianza Gordillo	
<b>20</b>	<b>Product Design Involving Culture, Sustainability and User Experience</b> .....	<b>227</b>
	Branislav Petrovic and Djordje Kozic	
<b>21</b>	<b>Design Recommendations for FFF Parts</b> .....	<b>237</b>
	Jelena Djokikj, Tatjana Kandikjan, and Ile Mircheski	
<b>22</b>	<b>Adaptive Neuro Fuzzy Estimation of Processing Parameters Influence on the Performances of Plasma Arc Cutting Process</b> .....	<b>249</b>
	Dalibor Petković and Milos Milovancevic	
<b>23</b>	<b>Identification of Important Parameters for Laser Photoresist Removal Process by ANFIS Methodology</b> .....	<b>257</b>
	Milos Milovancevic and Dalibor Petković	
<b>24</b>	<b>Identifying the Structure and Tribological Characteristics of the Material of Uncoated and Coated Model Single-Tooth Hob Milling Tools Using the Original Modular Fixture</b> .....	<b>267</b>
	Ivan Sovilj-Nikić, Bogdan Sovilj, Sandra Sovilj-Nikić, Bojan Podgornik, Matijaž Godec, and Radomir Đokić	
<b>25</b>	<b>Investigation of Machined Surface Roughness and Cutting Tool Wear from Prepared Tool Geometry</b> .....	<b>279</b>
	Róbert Straka and Jozef Peterka	
<b>26</b>	<b>Residual Stress in Pipe Joints Welded with Base and Cellulose Coated Electrode</b> .....	<b>289</b>
	Amna Bajtarević, Nedeljko Vukojević, Fuad Hadžikadunić, Josip Kačmarčik, and Amra Talić-Čikmiš	
<b>27</b>	<b>Comparison Analysis Between Different Technologies for Manufacturing Patient-Specific Implants</b> .....	<b>299</b>
	Georgi Todorov, Yavor Sofronov, and Krasimira Dimova	
<b>28</b>	<b>Effects of Additives on the Mechanical Properties of Aluminum Foams</b> .....	<b>307</b>
	Szilvia Gyöngyösi, András Gábora, Gábor Balogh, Gábor Kalácska, Tamás Bubonyi, and Tamás Mankovits	
<b>29</b>	<b>The Influence of the Hardening and Tempering Heat Treatment on the Strength of the CuZn39Pb3 Brass to Cavitation Erosion</b> .....	<b>315</b>
	Iosif Lazar, Ilare Bordeasu, Liviu Daniel Pirvulescu, Mihai Hluscu, Dumitru Viorel Bazavan, Lavinia Madalina Micu, and Cristian Ghera	

<b>30</b>	<b>MCDM Approach in Choosing the Optimal Composite Shaft Material—Application of SAW Method</b> .....	<b>323</b>
	Zorica Djordjevic, Sasa Jovanovic, Sonja Kostic, Amra Talic-Cikmis, and Danijela Nikolic	
<b>31</b>	<b>Experimental Analysis for Defining Mechanical Properties of Steel Sheet Metal on Different Material Thickness</b> .....	<b>331</b>
	Florinda Sejfullai, Tasuli Taleski, Bojan Mitev, and Atanas Kochov	
<b>32</b>	<b>Determination of LCF Plastic and Elastic Strain Components of Steel</b> .....	<b>341</b>
	Vujadin Aleksić, Ljubica Milović, Srđan Bulatović, Bojana Zečević, and Ana Maksimović	
<b>Part III Management and Monitoring of Manufacturing Processes</b>		
<b>33</b>	<b>Energy and Utility Management Maturity Model for Sustainable Industry</b> .....	<b>353</b>
	Milena Rajic, Milan Banic, Rado Maksimovic, Marko Mancic, and Pedja Milosavljevic	
<b>34</b>	<b>Fundamental Ideas About Intelligent Manufacturing Systems</b> .....	<b>363</b>
	Vanessa Prajova, Peter Košťál, Sergiu-Dan Stan, and Štefan Václav	
<b>35</b>	<b>Material Flow in the Flexible Manufacturing</b> .....	<b>371</b>
	Peter Košťál, Vanessa Prajova, Erika Hrušková, and Miriam Matúšová	
<b>36</b>	<b>Example of Good Maintenance Practice for Maintaining the Health of a Hydraulic System</b> .....	<b>379</b>
	Mitar Jocanović, Slađan Andrić, Milovan Lazarević, and Dejan Lukić	
<b>37</b>	<b>Development of Portable IoT Diagnostic Device for Particle Contamination Monitoring</b> .....	<b>389</b>
	Goran Rodić, Velibor Karanović, and Dragana Oros	
<b>38</b>	<b>New Method for Evaluation of Corrosive Resistivity of Impregnants</b> .....	<b>399</b>
	Miroslav Ďuračka, Tomáš Dérer, Zuzana Filová, Katarína Kocúrová, Alena Kozáková, and Michal Šišťák	
<b>39</b>	<b>Analysis of Pressure Force in Robot Supported Sheet Metal Forming</b> .....	<b>407</b>
	Malik Čabaravdić, Dennis Möllensiep, Bernd Kuhlenkötter, and Alfred Hypki	

**40 Optimization of Gears Production Processes by Application of Material Flow Simulation** ..... 415  
 Dragana Radakovic, Dejan Lukic, Sanja Bojic, and Mijodrag Milosevic

**Part IV Applied Modelling, Industrial Design and Virtual Engineering**

**41 Influence of Active Vehicle Suspension to Maintain Transverse Stability in Bends** ..... 427  
 Hristo Uzunov, Stanimir Karapetkov, Lubomir Dimitrov, Silvia Dechkova, and Vasil Uzunov

**42 Mechanical Mathematical Modelling of Two-Vehicle Collisions** .... 439  
 Stanimir Karapetkov, Lubomir Dimitrov, Hristo Uzunov, and Silvia Dechkova

**43 Checking the Validity of the Simulation for a Vehicle Test Collision** ..... 449  
 Dan-Marius Mustață, Attila-Iuliu Gönczi, Ioana Ionel, and Ramon Mihai Balogh

**44 Mechanical Metastructure in Structural Engineering: A Short Review** ..... 459  
 Livija Cveticanin and Sinisa Kraljevic

**45 Numerical Investigation of 3D Lattice Infill Pattern Cellular Structure for Orthopedic Implant Design** ..... 467  
 Rashwan Alkentar, Dávid Huri, and Tamás Mankovits

**46 Euler Buckling and Minimal Element Length Constraints in Sizing and Shape Optimization of Planar Trusses** ..... 473  
 Nenad Petrovic, Nenad Marjanovic, and Nenad Kostic

**47 Modeling and Simulation of High-Voltage Transmission Line Insulators in a Virtual and Laboratory Environment** ..... 483  
 Bojan Mitev, Monika Fidanchevska, Marko Naseski, Kristina Miceva, and Atanas Kochov

**48 Application of the Finite Element Method for Analysis of Piston Characteristics** ..... 491  
 Dalibor Feher, Jovan Dorić, and Nebojša Nikolić

**49 Numerical and Analytical Analysis Methods for Radial Response of Flexible Ring Dampers** ..... 499  
 Mykola Tkachuk, Andriy Grabovskiy, and Anton Tkachuk

**50 Developing a Methodology for Design of Patient-Specific Plate Type Implants and Defining the Relative Deformation of the Implant** ..... 507  
 Yavor Sofronov and Krasimira Dimova

**51 Assessment of Aircraft Cylinder Assembly Lifetime at Elevated Temperature** ..... 515  
 Nikola Vučetić, Ranko Antunović, and Lazar Šarović

**52 Dynamic Simulation of a Planetary Gearbox with Double Satellite** ..... 523  
 Imre Zsolt Miklos, Cristina Carmen Miklos, and Carmen Inge Alic

**53 Design and Simulation of a Multi-pole, Multi-layer, Double-Sided Magnetorheological Brake** ..... 531  
 Aleksandar Poznić and Boris Stojić

**54 Comparative Analysis of Rotation Welding Positioners Based on Friction Forces** ..... 539  
 Marija Matejic, Lozica Ivanovic, and Milos Matejic

**55 Wear Analysis of IC Engine Crankshaft Bearings Depending on the Connecting Rod Length** ..... 549  
 Nebojša Nikolić, Jovan Dorić, and Dalibor Feher

**56 Application of Techniques and Systems for Additive Manufacturing in Rapid Tooling** ..... 557  
 Marko Popovic, Vesna Mandic, and Marko Delic

**Part V Mechatronics and Robotics: Design, Kinematics and Dynamics**

**57 L-CaPaMan Design and Performance Analysis** ..... 569  
 Alexander Titov and Marco Ceccarelli

**58 Walking Robot with Modified Jansen Linkage** ..... 577  
 Lucian Alexeev, Andreea Dobra, and Erwin Lovasz

**59 Sensor System and Control of a 3D Printed Bionic Hand** ..... 585  
 Toni Duspara and Hasan Smajić

**60 Sensors in Self-Driving Car** ..... 595  
 Livija Cveticanin and Ivona Ninkov

**61 High Speed Spindle Simulation Using Multibody Siemens NX MCD** ..... 605  
 Hasan Smajić, Milos Knezev, Aleksander Stekolschik, and Aleksandar Zivkovic

<b>Part VI Quality Engineering and Management/Economical Aspects of Construction of Technological Equipment and Systems</b>	
<b>62 Influence of Maintenance Practice on MTBF of Industrial and Mobile Hydraulic Failures: A West Balkan Study</b> .....	617
Marko Orošnjak, Milan Delić, and Sandra Ramos	
<b>63 Automated MIG Welding Application: An Industrial Case Study</b> .....	627
Miguel Ángel Zamarripa Muñoz, Pedro Agustín Ojeda Escoto, and Gerardo Brianza Gordillo	
<b>Part VII Ecology, Ergonomics, Energy Efficiency, Environment Protection, Safety and Health at Work</b>	
<b>64 Application of Ergonomic Principles in Solving Workplaces in Industrial Enterprises in the Slovak Republic</b> .....	639
Petra Marková and Vanessa Prajová	
<b>65 Impact of Long-Term Sitting on Productivity, Burnout, and Health: Employees' View on Workplace Ergonomics</b> .....	649
Mihalj Bakator, Eleonora Desnica, Milan Nikolić, and Ivan Palinkaš	
<b>66 Geometrical Considerations of Air-Conditioner Vent Arrangement in a Farm Tractor Cab</b> .....	657
Dragan Ružić and Tanasije Jojić	
<b>67 Energy Efficiency of Food Cooling and Freezing Plants in Serbia</b> .....	665
Marko Mančić, Dragoljub Živković, Milena Rajić, Milena Mančić, Milan Đorđević, Bojana Vukadinović, and Milan Banić	
<b>68 Preliminary Research Concerning the Pollution Generated by a Diesel Engine in Order to Higher Its Performance</b> .....	675
Cosmin Constantin Suciú, Daniel Ostoia, Nicolae Stelian Lontis, Ion Vetres, Sorin Vlad Igret, and Ioana Ionel	
<b>69 A Bayesian Analysis of CO<sub>2</sub> Emissions and National Industrial Production in Romania</b> .....	683
Carmelia Mariana Bălănică Dragomir, Geanina Podaru, and Cristian Munteniță	
<b>70 Environmental Impact of Minimal Order Quantity Constraint in (R, s, S) Inventory Policy</b> .....	691
Jasmina Žic and Samir Žic	

**71 Cabin Safety Prediction in a Selected Group of Mobile Working Machines** ..... 699  
Adam Vincze, Ladislav Gulan, Roman Ižold, and Andrej Korec

**72 Determination of Zipline Braking Distance** ..... 707  
Tanasije Jojić, Jovan Vladić, and Radomir Đokić

**73 Risk and Safety of Cylindrical Tank Exposed to Fire** ..... 713  
Mirko Đelosević and Goran Tepić

**Part VIII Academic and Mechanism Education and History of MMS**

**74 Education 4.0 for Industry 4.0** ..... 723  
Biljana Marković and Aleksija Đurić

**75 Cyber Physical Systems in Manufacturing Engineers Education** ..... 735  
Zivana Jakovljevic and Dusan Nedeljkovic

**76 Teaching Methodology for Designing Smart Products** ..... 745  
Tatjana Kandikjan, Ile Mircheski, and Elena Angeleska

# Chapter 30

## MCDM Approach in Choosing the Optimal Composite Shaft Material—Application of SAW Method



Zorica Djordjevic, Sasa Jovanovic, Sonja Kostic, Amra Talic-Cikmis, and Danijela Nikolic

**Abstract** In this paper, the selection of materials for production of shafts is considered from the aspect of the influence of a large number of parameters (mechanical characteristics of the material, density or mass of the shaft, fiber orientation angle in composite materials, shaft bending displacement values, free frequencies, etc.). In order to include all the above criteria in the selection of materials, the approach of Multi-Criteria Decision-Making (MCDM) using the Simple Additive Weighting Method (SAW) was applied. The analysis was performed for four different shaft materials (steel, aluminum, Carbon Fiber Reinforced Polymers CFRP and Glass Fiber Reinforced Polymers GFRP). The results of the analysis showed that the best characteristics, in addition to steel shafts, have composite shafts made of CFRP and GFRP with fiber orientation  $0^\circ$  and that they can be their adequate replacement, especially in systems where the weight of the structure is to be as small as possible.

**Keywords** Composite materials · Shafts · SAW method

### 30.1 Introduction

Composite materials are a combination of two or more materials with different mechanical and physico-chemical properties in order to obtain materials with improved characteristics in relation to the constituent components. Some of the advantages of composite concerning to traditional metallic materials are reflected in increased tensile strength, impact resistance, vibration, fatigue, temperature changes,

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reduced weight and the like. The specificity of composite materials is that these characteristics can vary depending on the amount and type of material used, and the angle of orientation of the fibers in the composite.

Composites consist of fibers and a matrix. Fibers (carbon, glass, aramid, etc.) form the supporting part of the composite, while the matrix (metal, polymer, ceramic, etc.) serves to bond and transfer loads between the fibers, gives shape to the structure, prevents damage to the fibers, etc.

Composite shafts, in comparison with steel, are characterized by increased load capacity, reduced weight, higher fatigue endurance, extremely harmonious vibration damping, the increased value of critical speed, etc. Carbon or glass fibers in combination with epoxy or polyester resin are most often used to make shafts. Also, hybrid shafts obtained by a combination of metal (steel or aluminum) and a composite material give good results.

When choosing an adequate material for the production of shafts, a large number of material characteristics, ie criteria must be taken into account (physical and mechanical characteristics should be maximum, while the weight, price and weightiness of the production organization should be minimal). Since the problem of material selection is very complex, it is recommended to apply some of the methods of MCDM.

Not so many researchers have proposed a specific analysis model to select the right material for a particular application. In study [1], the selection of suitable natural fibers for resin reinforcement for the production of roto molded product was analyzed, using the technique of MCDM. In particular, the MOORA and TOPSIS methods were used. It was concluded that, as far as natural fibers are concerned, the best properties for this purpose were shown by coconut fibers.

Researchers in [2] dealt with the analysis of mechanical properties of polyamide-based composites in combination with carbon fibers from the aspect of engineering application. An integrated multicriteria approach in material selection was applied, using the fuzzy best–worst method and the fuzzy G-VIKOR method.

The analysis of polymer composite materials reinforced with sugar palm fibers using three different multicriteria methods (AHP, TOPSIS and ELECTRE) was performed by researchers in [3].

Researchers have shown that the application of the method of MCDM can significantly facilitate the choice of materials in the automotive industry [4]. For this purpose, they used the methods of MOORA, TOPSIS and VIKOR.

## 30.2 Selection of the Composite Shaft Material

The analyzed shaft has an annular cross section 1 m long, 0.05 m middle radius, and 0.005 m wall thickness. The influence of the shaft material and the angle of orientation of the composite fibers on the values of maximum displacements due to bending and free frequencies of the shaft is considered.



**Table 30.1** Material property values

Material	Elastic modulus, $E_1$ (MPa)	Elastic modulus, $E_2$ (MPa)	Shear modulus, $G_{12}$ (MPa)	Density, $\rho$ (kg/m <sup>3</sup> )	Max. deflection, $f$ (mm)	Free frequencies, $f_s$ (Hz)
Steel	210,000	210,000	83,000	7830	0.087	277.6
Aluminum	70,000	70,000	2800	2600	0.262	278.2
CFRP(0) <sub>4</sub>	130,000	10,000	7000	1500	0.440	426.7
GFRP(0) <sub>4</sub>	40,300	6200	3000	1900	0.984	232.4
CFRP(90) <sub>4</sub>	130,000	10,000	7000	1500	1.495	139.8
GFRP(90) <sub>4</sub>	40,300	6200	3000	1900	2.521	111.7
Type of criteria	Max	Max	Max	Min	Min	Max

The results were obtained numerically using the software FEMAP and NeNastran. The shaft is modeled by isoparametric quadrangular finite elements in the form of multilayer shells. Composite shafts are made as laminates consisting of 4 layers—lamina.

The analysis was performed for the following materials: steel, aluminum, CFRP and GFRP. Composite shafts were considered with a fiber orientation angle of 0° (CFRP(0)<sub>4</sub> and GFRP(0)<sub>4</sub>) and 90° (CFRP(90)<sub>4</sub> and GFRP(90)<sub>4</sub>).

The mechanical characteristics of the analyzed materials as well as the obtained values of maximum displacements and free frequencies of the shaft, are given in Table 30.1.

### 30.2.1 Application of MCDM Methods in the Selection of Optimal Material

The decision-making process is used in management theory as part of the process of solving a certain problem. Many authors of management theory consider decision-making to be one of the most important tasks, both at the strategic and operational levels. Multi-criteria decision-making (MCDM) is a relatively new discipline, which through its development, should provide support to decision makers who face numerous and very often conflicting influencing factors. This method aims to maximize the quality of the decision following the selected criteria.

Methods of multi-criteria decision-making in the conceptual sense are not particularly complex and are easier to understand than classical single-criteria optimization. The most common division of MCDM procedures presupposes the existence of two basic groups of these methods [5–8], namely the Multiple Attribute Decision Making method (MADM) and the Multiple Objective Decision Making method (MODM). As the choice of one (best) of alternatives (materials) from a limited number of alternatives (materials) is sought within the set problem analyzed in this paper, we opted

for the SAW method, which belongs to the group of MADM methods. The SAW (Simple Additive Weighting Method) method is a relatively simple method of multi-criteria decision-making, which takes into account the weight of the selected criteria. For each possible alternative solution, the so-called summary characteristic ( $A_i$ )—the value obtained by summing the products of relative weighting factors ( $W_j'$ ) and normalized performance values according to all selected criteria ( $r_{ij}$ ). The alternative that corresponds to the highest calculated value of the summary characteristic ( $A^*$ ) is the optimal solution:

$$A^* = \left\{ A_i \mid \max_i \sum_{j=1}^n W_j' r_{ij} \right\} \tag{30.1}$$

### 30.2.2 Multicriteria Analysis of Material Characteristics

The paper analyzes a total of six different materials (alternatives, solutions) for six different characteristics (criteria), in fact for four materials, two of which have different fiber orientations. In the Table 30.2, the values of the selected characteristics for the considered materials are presented. At the same time, the types of criteria-characteristics are indicated and classified into those of maximization (max, the higher the value, the better the material characteristic) and minimization (min, the smaller the value, the better the material characteristic). Table 30.2 shows the values of normalized factors  $r_{ij}$ , obtained by one of the pre-ordered methods of data normalization.

The values of weight coefficients were determined using the Seaty procedure (Tables 30.3, 30.4 and 30.5). In order to examine the stability of the solution—the

**Table 30.2** of normalized values of material characteristics ( $r_{ij}$ )

material	Elastic modulus, $E_1$ (MPa)	Elastic modulus, $E_2$ (MPa)	Shear modulus, $G_{12}$ (MPa)	Density, $\rho$ ( $\text{kg/m}^3$ )	Max. deflection, $f$ (mm)	Free frequencies, $f_s$ (Hz)
Steel	1	1	1	0	1	0.53
Aluminum	0.18	0.31	0	0.83	0.93	0.53
CFRP(0) <sub>4</sub>	0.53	0.02	0.05	1	0.85	1
GFRP(0) <sub>4</sub>	0	0	0	0.94	0.63	0.38
CFRP(90) <sub>4</sub>	0.53	0.02	0.05	1	0.42	0.09
GFRP(90) <sub>4</sub>	0	0	0	0.94	0	0
Type of criteria	1	1	1	0	1	0.53

**Table 30.3** Values of weighting coefficients (Seaty scale-procedure), variant 1

	Variant 1 ( $W_{i1}'$ )							$\sum$	$W_{i1}'$
	$k_1$	$k_2$	$k_3$	$k_4$	$k_5$	$k_6$			
$k_1$	1	3	3	1	0	1	9	0.15	
$k_2$	0	1	1	0	0	0	2	0.033333	
$k_3$	0	1	1	0	0	0	2	0.033333	
$k_4$	1	3	3	1	0	1	9	0.15	
$k_5$	5	7	7	5	1	5	30	0.5	
$k_6$	1	3	3	1	0	1	8	0.133333	
$\sum$							60	1	

**Table 30.4** Values of weighting coefficients (Seaty scale-procedure), variant 2

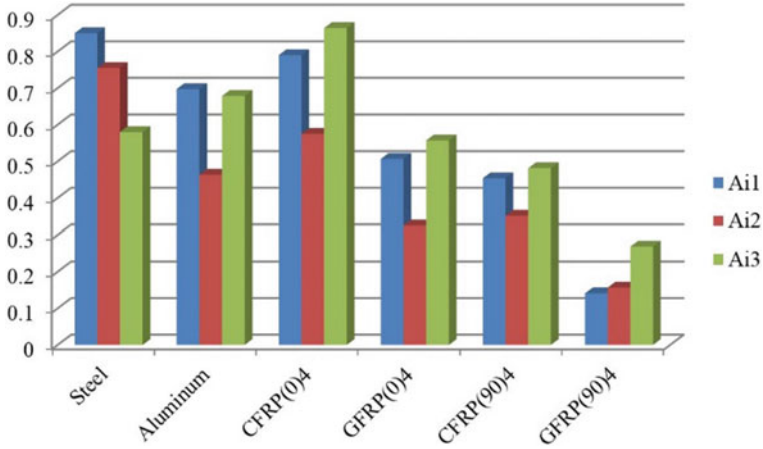
	Variant 2 ( $W_{i2}'$ )							$\sum$	$W_{i2}'$
	$k_1$	$k_2$	$k_3$	$k_4$	$k_5$	$k_6$			
$k_1$	1	1	1	1	1	1	6	0.166667	
$k_2$	1	1	1	1	1	1	6	0.166667	
$k_3$	1	1	1	1	1	1	6	0.166667	
$k_4$	1	1	1	1	1	1	6	0.166667	
$k_5$	1	1	1	1	1	1	6	0.166667	
$k_6$	1	1	1	1	1	1	6	0.166667	
$\sum$							36	1	

**Table 30.5** Values of weighting coefficients (Seaty scale-procedure), variant 3

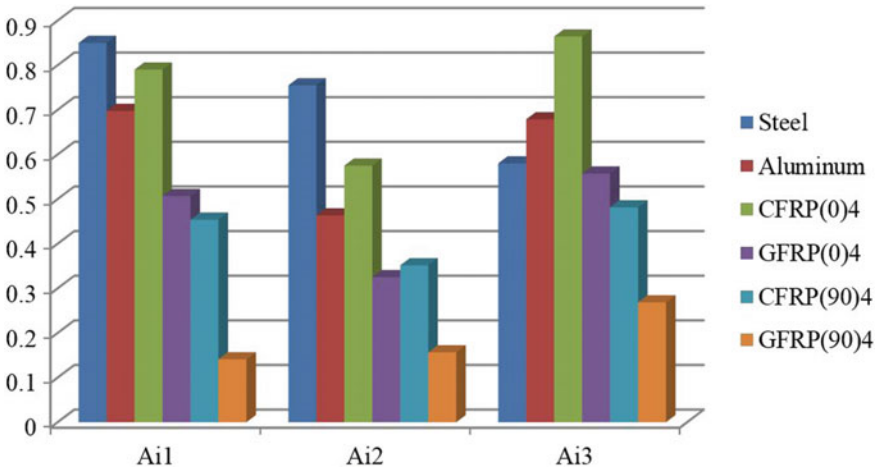
	Variant 3 ( $W_{i3}'$ )							$\sum$	$W_{i3}'$
	$k_1$	$k_2$	$k_3$	$k_4$	$k_5$	$k_6$			
$k_1$	1	3	3	0	0	0	7	0.090909	
$k_2$	0	1	1	0	0	0	2	0.025974	
$k_3$	0	1	1	0	0	0	2	0.025974	
$k_4$	5	7	7	1	1	1	22	0.285714	
$k_5$	5	7	7	1	1	1	22	0.285714	
$k_6$	5	7	7	1	1	1	22	0.285714	
$\sum$							77	1	

choice of the optimal material, an analysis was performed for three different variants of weight coefficients, depending on the preference of certain characteristics.

On Figs. 30.1 and 30.2 the summary characteristics ( $A_i$ ) for all three variants of weight coefficients for all six potential shaft materials are given. By analyzing both diagrams, it can be seen that steel has the best cumulative characteristic, in two



**Fig. 30.1** Diagram representation of summary characteristics for three variants of performance weights—criteria for six shaft materials



**Fig. 30.2** Diagram representation of summary characteristics for three variants of performance weights—criteria

of the three cases, but that the average value is very close to the material made of polymer-reinforced carbon fibers (CFRP(0)<sub>4</sub>).

### 30.3 Conclusion

The process of selecting the optimal material represents a significant and sensitive phase in the product design process. Within this phase, the constructor must, in accordance with the available material characteristics and the requirements of the potential construction, make an appropriate decision using an adequate method. Solving this type of design problem is most often done through the application of some of the methods of multi-criteria decision-making (MCDM). The paper specifically applies the method of additive weight factors known as the SAW method. Six selected materials (two “classic”, steel and aluminum and four composite) presented with six different characteristics were analyzed. The characteristics of the material were treated as criteria, which, depending on the assessment and affinity of the constructor, were assigned different weight coefficients in the three presented variants. Based on a comparative analysis of the distribution of weight coefficients, it was concluded that of the six materials considered, the best characteristics (observing all three variants with different weight coefficients), during bending, showed shafts made of steel and composite of carbon fibers reinforced with polymers (CFRP(0)<sub>4</sub>). In each of the three variants of weight coefficients these two materials showed better characteristics than the others.

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